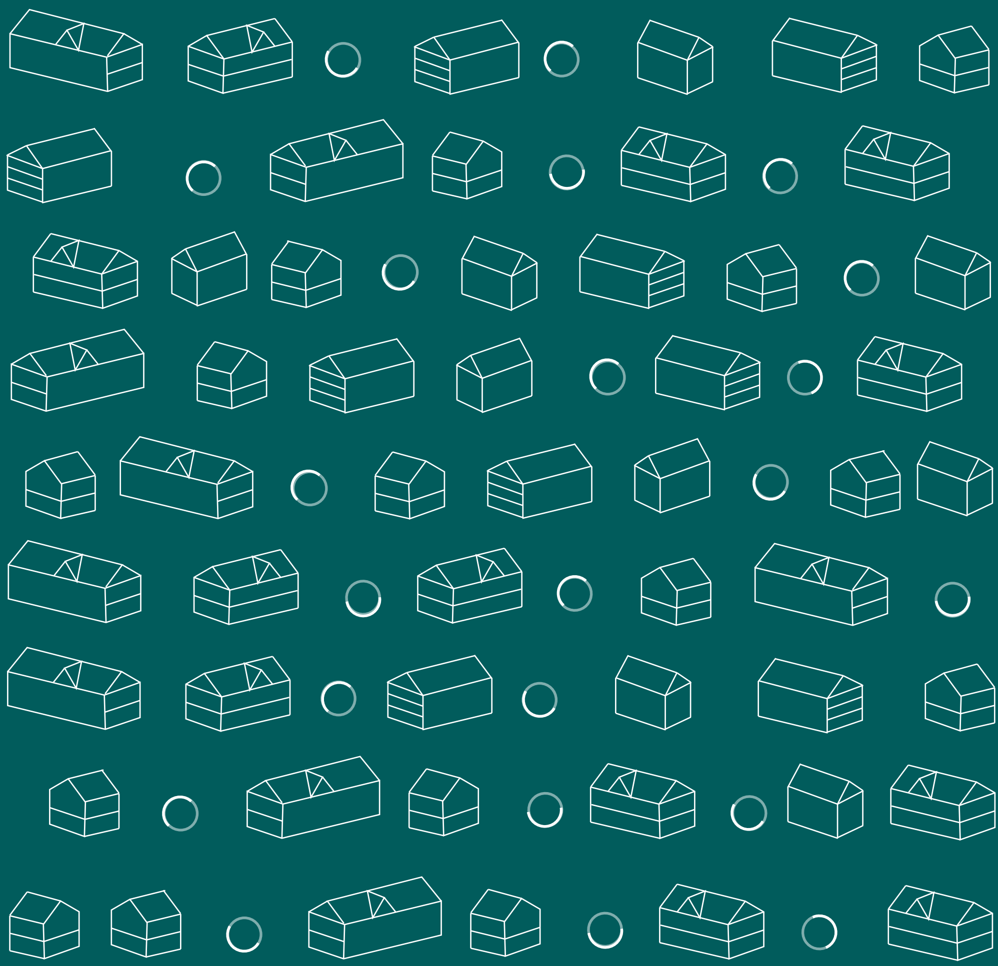

Parametric design and ecological awareness
The making of a tool for planning decisions

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Doctoral Dissertation
Doctoral Program in Architettura. Storia e Progetto
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The making of a tool for planning decisions.

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I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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Sara Giaveno

Turin, April, 2022

Abstract

In our era, a new ecological awareness has been developing with the search for an environmental and planetary balance by dragging architectural design and urban planning into the debate (Gregory, 2013). The ecological issue gradually became, in the last decades, a design matter. Ecology, in the fold of architecture, wants to take a step beyond consolidated sustainable practices and promote a new balanced alliance between nature and humans, new ways of inhabiting the earth, and a new dialectic between natural and artificial (Causarano, 2017). In these terms, architecture is invested with the role of expressing a new philosophical and aesthetic vision by embodying ecological awareness and innovation in the fold of the information revolution (Wines, 2000).

The study grounds its roots in the context described and adopts a research-based approach to address the ***purpose of enquiring about the intersection between ecological awareness and information revolution related technologies in contributing to the foundation of a new philosophical vision of architecture and in triggering innovation and transformation in consolidated design practice***. How does it is possible to reach the purpose? The study tries to contribute to the debate on the theoretical and practical sides.

The purpose is addressed by different reading and enquiry plans developed in the dissertation in the following three parts: *Theoretical background and implications, The laboratory experience, Observatory on the experiment*.

The first part contextualizes the work's theoretical background and the starting research implications. It clarifies the background in its concepts, contributions, and terminology. It illustrates the theoretical recognition of ecology and digital technologies intersection supported by the elaboration of critical thought. It describes the wave of environmental, social and technological implications and the Academy-Industry collaboration model's influence on research development. The last part of the section is dedicated to introducing the research proposal definition.

The second part is the operative plan developed in the fold of a laboratory experience. It is dedicated to illustrating and discussing the original contribution of the thesis consisting of a digital tool planning decisions at a micro-scale to

create dynamic Embodied Carbon and Embodied Energy scenarios. In that context, the research employs the previous premises as a background and moves toward the practical exploration of digital dynamic methodologies. The procedure of creation and validation consists of building the perimeter of a real and working playground (made of roles, responsibilities, constraints, objectives and implications). Later, assemble the digital tool (by setting architectural and environmental impact variables) and putting it into play on a real action context to observe its performative power. The section documents the process and unfolds the digital tool's model/data responsiveness, its potential in hybrid configurations and decision-making scenarios creation.

The third part is dedicated to tracing the critical discussion and observations of the process and results in their theoretical and practical challenges. Its task consists in outlining a knowledge account founded on the observative and practical involvement in the research process. In particular, it builds a theoretical reflection by employing the laboratory experience process as a means of interpretation. It unpacks the research path stages and highlights its performative characteristics to trace the innovations that parametric practice can trigger in the design discipline. Besides, the observatory illustrates the performative characteristics of the tool in itself and comparison with traditional methods, its transformative power in the design process and its influence on the designer's role and the creative process. It links back to the outcomes with the initial research questions and interests and outlines the potential of the research's theoretical and practical output in contributing to ecological debate in the fold of the information revolution.

Acknowledgement

I want to acknowledge the *Drawing to the Future* laboratory at Politecnico di Torino for supporting my research work and doctoral path. A special thanks go to *CRH Innovation Centre for Sustainable Construction,* for having believed in the research project and for the tireless support of its development. I want to thank professors, PhD colleagues, loved ones and friends for the feedback on the ongoing study.

Da un haiku giapponese

L'alunno mostra al maestro una sua poesia:
Una farfalla,
le strappo le ali,
e guarda, un peperoncino.

La risposta del meastro non si fece attendere,
e disse:
Un peperoncino,
gli metto le ali
e guarda, una farfalla.

L'atto poetico deve sempre essere positivo,
cercare la costruzione, non la distruzione.
Costruire trasformando qualcosa di ordinario
in straordinario, e nobile.

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Introduction

PART 0

Introduction to the research activity

0.1 Premise and motivations

In our era, a new ecological awareness has been developing with the search for an environmental and planetary balance by dragging architectural design and urban planning into the debate (Gregory, 2013). The ecological issue gradually became, in the last decades, a design matter.

Ecology, in current times, has developed widely both as a science and as a practice. It touches on problems of great importance for all countries and in particular for those densely populated, industrialized ones and those in the process of massive industrialization: the exploitation of natural resources, the protection of nature, the protection of the landscape, the fight against water pollution, the control of human settlements and so on[1]. The conception of ecological thinking, as we know it, arose between the late sixties and early seventies (P. Gregory, 2013), which were years of complete redefinition of human awareness in terms of consciousness toward its existence and the resources necessary for its survival. The ecological awareness unveils the unconscious (Morton, 2021) and puts into light the chain of human actions responsible for the ecological crisis. In these terms, it pushes humanity beyond anthropocentrism by re-dimensioning its position in the biosphere.

At different scales of intervention, design is called to respond to these growing needs. Ecology, in the fold of architecture, wants to take a step beyond consolidated sustainable practices and promote a new balanced alliance between Nature and Humans, new ways of inhabiting the earth, and a new dialectic between natural and artificial (Causarano, 2017). In these terms, architecture is invested with the role of expressing ***a new philosophical and aesthetic vision by embodying ecological awareness and innovation in the fold of the information revolution*** (Wines, 2000).

How can architecture express the new vision, and with which means?

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[1]"Ecologia" in Treccani vocabulary, https://www.treccani.it/vocabolario/ecologia/.

The methods to reach the new vision in architectural design are various and diversified[2] , but all are united by the use of advanced technological and digital systems able to manage the flow of information and communication. The revolution in the architectural paradigm and its ontology goes hand in hand with the information and digital revolution. Digital procedures, such as parametric design and computation, amplify the potentiality of the design project to store, manage and elaborate flux of information in the form of data.

Architctercure, therefore, is now invested in complex tasks. In the first instance, it reverberates the evolutionary changes of nature and the flows of electronic communications. Secondly, it has to embody the role of a medium to amplify our senses and perception ability, to extend ourselves (McLuhan, 2015)[3].

The current research grounds its roots in the context described, which consists in enquiring about the intersection between ecological awareness and information revolution related technologies. ***The interest is exploring the intersection between ecological awareness and information revolution and its contribution to founding a new philosophical vision on architecture and triggering innovation and transformation in consolidated design practice.*** *How does it is possible to reach the purpose?* The study tries to contribute to the debate on the theoretical and practical sides.

In the first instance, ***from the theoretical side***, the study attempts to clarify the ecological and parametric background of their concepts, contributions, and terminology. Secondly, it explores and defines the multidisciplinary set of contemporary issues related to the ecological challenge that architecture is called to consider. Once identified the "problems" and the implications to take into account, the investigation proceeds by illustrating the contribution that information revolution-related technologies can provide to the debate. The dissertation opens toward a wide and comparative enquiry on problems and tools to define an operative proposal able to contribute to the debate.

In the second instance, ***from the practical side,*** the study proposal defined the boundaries of a laboratory experiment that consisted of assembling and testing a digital tool and tracing a transformative power in action compared to traditional procedures. In particular, the research employs the theoretical premises as a background and moves toward the practical exploration of digital dynamic methodologies to devise a parametric tool for planning decisions at the service of designers to anticipate design choices. The procedure consists of building the perimeter of a real and working playground (made of roles, responsibilities,

[2] See *Chapter 1 Parametric design and the ecological challenge* for further details.
[3] Particularly suggestive is the McLuhan original title "The medium is the message".

constraints, objectives and implications). Later, assemble the digital tool (by setting architectural and environmental impact variables) and putting it into play on a real action context to observe its performative power. The section documents the process and unfolds the digital tool's model/data responsiveness, its potential in hybrid configurations and decision-making scenarios creation.

The dissertation, in conclusion, ***reconnects to the theoretical side***. The study builds an observatory on the experiment that is dedicated to tracing the critical discussion and observations of the process and results in their theoretical and practical challenges. Its commitment consists of outlining a knowledge account funded on the observative and practical involvement in the research process to highlight the potential of the digital tool in responding to the ecological challenge and in embodying a transformational power in consolidated design practice.

The dissertation, in particular, is structured in four sections and six chapters. Part 0, the current section, is dedicated to introducing the research activity in its statements, questions, methodological notes and detailed structure. Part I illustrates the theoretical background and the implications that influenced the thesis development in its process and results. Part II, the operative section, is dedicated to narrating the laboratory experience in its boundaries, actors involved, resources at disposition and the toolkit. The narration aims to clarify the conditions that led to the tool devising, testing and validation. Part III coincides with a critical observatory focused on interpreting path and results founded on the personal observative and practical involvement in the research process[4].

At this point, it is necessary to introduce a critical reflection on the motivations and approaches selected to address the proposal. The personal motivation for the research lies in my curiosity about exploring architecture as a means to interpret contemporary dynamics. My personal interest in the research focuses on unfolding hidden potential in digital tools and methodologies in responding to contemporary debate beyond formalism. The employment of parametric and digital procedures is focused on exploring their potential of embodying issues and restituting an interpretation through architecture. Architecture, in this way, can adopt a needed shift from object-oriented[5] to relational ontology founded on societal purposes by thinking in terms of correlations, networks, transformational series, and working via generative scripts (Schumacher, 2012). In other words, I intend architecture as a matter of relations and, consequently, communication. By considering this concept, parametric and computational methodologies can provide a useful means to amplify human perception and manage, store, and manipulate the complex flux of information

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[4] The paragraph *0.4 Structure of the thesis* describes in details the dissertation structure.
[5] Parametricism took distances from formalism and image-driven architectural design outputs.

typical of the contemporary city. The study is positioned in this fold and aims to test the digital tools' effectiveness when put into proof of a contemporary target related to the city's dynamics. The decision to focus on an ecological target was oriented by both personal interest in the topic and various and complex dynamics inextricably related to the contemporary city[6]. However, the research proposal in its definition, had to deal with implications beyond personal interest. The main factor that affected the proposal choice in its specificity and development was addressing the research in the context of an **Academy-Industry** collaboration model. In particular, the relationship was built between Politecnico di Torino and CRH[7], a building material provider based in Amsterdam, which entirely financed the research project. Together with CRH, at the beginning of the doctoral path, it was fixed the necessity of reaching the practical definition and assembly of a tool with some defined prerequisites. The tool, therefore, had to acquire a strong specificity to function and effectively respond to the proposal and reach the mature form previously cited. The collaboration model contributed to expanding the limits of the research beyond academia and letting filtrate into the research path implications that are usually far from fundamental research. The current thesis is an example of what happens when the academic world opens toward a research-based approach, including aspects of applied science[8].

The following paragraphs of the *Introduction* are fundamental in clarifying to the reader the common ground before diving into the thesis reading.

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[6] Read carefully *Chapter 2. Interpreting implications as a design matter* for the full and complete narration of the research implications.

[7] See paragraph *2.1.3 The "machine": Academy-Industry collaboration model.*

[8] The *Methodological notes* section and the paragraph *2.1.3 The "machine": Academy-Industry collaboration model* will explain in detail what consisted of the model and which were the implications and achievements that brought in the research development.

0.2 Research statements and questions

The research questions ground their roots in a wider research purpose consisting in enquiring about ***the intersection between ecological awareness and information revolution related technologies***. The research proposal, in particular, explores ***the intersection contribution to founding a new philosophical vision of architecture and triggering innovation and transformation in consolidated design practice***.

The research questions definition is based on the research proposal and focuses on some punctual aspects to address in the dissertation from the theoretical and practical side:

- How can a designer investigate the potentiality of parametric design in contributing to the ecological debate and produce knowledge about it?

- How can be devised a parametric design tool for planning decisions at a micro-scale?

- In which terms does the parametric tool employment trigger innovation in the design process and gain transformative power over communication procedures, the creative process, and the designer’s role?

0.3 Methodological notes

The thesis is developed in the doctoral path of *Architecture. History and Project* at Politecnico di Torino. The research was entirely financed by the CRH[9] Innovation Center for Sustainable Construction based in Amsterdam. The project thesis started from the beginning with the support of a collaboration model established between Academia and Industry[10] that counted a long path for its definition but provided a fruitful methodology of action. This kind of collaboration, funded on balance made of benefits, constraints and expectations between two parties, influenced the research path development and target definition in many aspects. The collaboration model established some "fixed" and "variables" implications influencing the thesis target and pushed for external validations and tests of the methodology and tool[11]. Combining these two factors contributed to expanding the limits of the research beyond academia and letting filtrate into the research path implications that are usually far from fundamental research. The current thesis is an example of what happens when the academic world opens toward a research-based approach, including aspects of applied science. The advantages are for both parties, particularly the opportunity of knowledge and technology transfer, melting holistic methodologies and pure science with applied ones, expanding the scale toward multidisciplinary topics and collaborations, and working on a real-world target. Moreover, the added value for an academic researcher lies in the chance to interface with dynamics usually far outside his world, like immersing yourself in a real context of action made by multidisciplinary actors and roles, interests related to market dynamics, profitable goals and return on investment logic. However, characteristics that seem challenging, at first sight, hide some tough sides because the necessity for the industry to obtain a tangible result perfectly inserted into a market logic is far from the consolidated academic research purpose. Establishing and keeping this balance is a difficult task but is currently necessary to ensure the academy the role of elaboration and transmission of critical knowledge and engine capable of triggering social innovation.

Between the academic collaborations built up during the research path, the *PhD visiting* at KTH Stockholm in February-March 2020 with the support of Professor Kjartan Gudmundsson provided an essential contribution to the tool development and bibliography recognition. Unfortunately, due to the starting of the pandemic, I lost the chance to fulfil the Erasmus in September 2020 at

[9] See *Chapter 2.* for further and detailed description.
[10] See *Chapter 2.* Paragraph *2.1.3 The "machine"* for further details.
[11] See paragraph 2.1 The research implications and paragraph *4.1.4 Validation phase*.

Carnegie Mellon University Pittsburgh at Code Lab with the supervision of Professor Daniel Cardoso, aimed at the creation of the tool interface. Anyway, even if the pandemic stopped the research field and the exchange with many actors involved in the research process for several months, the parametric tool creation and requirements validation were completed in all core parts. The last section of the thesis suggests how to employ the current work as background, hopefully, for future development.

The parametric tool for planning decisions process of creation was the object of a publication in Sustainability 2021, 13 with the title *Embodied Carbon and Embodied Energy Scenarios in the Built Environment. Computational Design Meets EPDs*[12].

0.3.1 The role that I embodied

Shaping and defining the personal position assumed in the process was one of the thoughtest tasks of the research. Reaching a balanced position in a complex network of multidisciplinary actors, opposing goals and interests, complex mediations, and negotiation requires an effort in terms of management but, especially, in terms of traduction. As **a researcher**, I found myself at the core of a centripetal movement of actors and entities, and I embodied the role of a translator of communication and intents. For all intents and purposes, I assumed the role of mediator of a complex communication system in charge of transmitting and processing information and later traducing it to make it understandable to all parties. Hence, the task was conducted by building a system of traduction that included two declensions, once related to the objects and the other to the people involved (Armando & Durbiano, 2017).

Moreover, my personal involvement in the process was also in the shoes of an **actor with full power** and, especially, with the responsibility of having trigged the process. I personally moulded the premises at the base of the process in terms of objectives, tools, and main actors involved. Then I put these entities and elements into action in a laboratory experiment to assemble a tool for planning decisions in a real context of action. Once triggered, the design process developed with a large degree of autonomy by including new actors, tools, objectives, etc., during time according to new needs. Still, during the unfolding of the process, I kept the threads of the mechanism over time. To what purpose? It can be said that I assembled a real and working **playground** in which to put parametric procedures into play on a real design target to observe their performative power into action and, later, build over critical observations on their effectiveness.

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[12] Sustainability 2021, 13, 11974. https://doi.org/10.3390/su132111974.

The **observatory on experiment** aims to create an account of knowledge through practical and observative involvement in the process. It explores the relationship that occurs between producing and thinking and the particular way of creating knowledge through producing[13]. I positioned both the object of study and myself at the centre of experimentation and evolved together by letting us contaminate each other. In this way, the researcher abandons her authoritative position towards the object studied and, on the contrary, **learns *with* and *from* it**. The researcher passes from a linear to an *integrated* process of knowledge by going beyond the mere information transmission. This approach not only consists of providing facts and data *about* the world, but it allows us **to be taught *by* it** (B. Gregory, 1972).

The approach cited is strategic in addressing the task of outlining knowledge concerning parametric design, which is currently under definition in a complex process of legitimacy and comprehension achievement. Toward parametric design and digital-related technologies in general, the need is increasingly felt to define cornerstones of knowledge and translation systems that make their complex tools understandable. The fact that parametric tools are both complex in terms of their articulation and use and their design results seem unpredictable causes a lot of mistrust. However, it can be overcome and understood by making use of an efficient translation system and repositioning the author with respect to the object.

The position described draws its principles from the anthropological approach to the research grounded on fieldwork and empirical investigation, participant observation, and a holistic view of contents and their relationship. However, the position found **in the middle between** anthropology, intended as the study *with* and learning *from* in which fieldwork is a masterclass where novice learns to see and hear things in the way the mentors do; and ethnography is a study *of* and learning *about* which products are account with documentary purposes (Ingold, 2019). By analyzing the definitions, the research approach embodies the binomial: **a study *with*** (typical of anthropology, in which I am observer, an actor that trigged the process with full powers); **a learn *from*** (usual of anthropology, characterized by iterative sharing) **but also *about*** (typical of ethnography) certain practices that are an object of observation and documentation. Moreover, the research embodies two desires, both **transformational and documentary**, balancing them. The study does not incorporate the ideas of describing the things in their specificity by focusing on vigorous data collection to interpret. However, it employs the documentary purpose, grounded on descriptive fidelity, to support the narration about how the fieldwork was moulded and the relationship between actors and entities evolved. Here the participant observation is identified as

[13] See *Chapter 5* for complete description.

creating knowledge from "within" by a practical and direct engagement during an integrated process of sharing to build a critical investigation over current conditions and propose open questions of debate around future possibilities. The digression suggests that the comparison between the two different approaches is thin and fleeting. Consequently, the approach toward the research activity is not strictly collocated into one category with respect to the other.

In conclusion, the position toward the research activity is not strictly. However, a punctual definition of the ambition, limits, and intents was needed to clarify the research's reading and interpretation plan.

0.3.2 The purposes

The thesis purpose is ***to enquiry the intersection between ecological awareness and information revolution related technologies in contributing to the foundation of a new philosophical vision on architecture and in triggering innovation and transformation in consolidated design practice.***

From the frame of the purposes, three detailed research questions were shaped to identify some punctual points to develop:

- How can a designer investigate the potentiality of parametric design in contributing to the ecological debate and produce knowledge about it?
- How can be devised a parametric design tool for planning decisions at a micro-scale?
- In which terms does the parametric tool employment trigger innovation in the design process and gain transformative power over communication procedures, the creative process, and the designer's role?

The research purpose is addressed by different reading plans developed in the dissertation in the following three sections: *Theoretical background and implications, The laboratory experience, Observatory on the experiment*.

The first one concerns a theoretical recognition of the intersection between ecology and digital technologies intersection supported by the elaboration of critical thought. It illustrates a possible new kind of philosophical and aesthetical vision in architecture able to be the interpreter, and the medium, of the changes in nature and the flow of communication by employing advanced technological and digital systems.

The second is an operative plan developed in the fold of a laboratory experience. In that context, the research employs the previous premises as a background and moves toward the practical exploration of digital dynamic methodologies to devise a parametric tool for planning decisions. In particular, the scope is devising a digital decision-making tool at the service of designers to anticipate design choices. The procedure of creation and validation consists of building the perimeter of a real and working playground (made of roles, responsibilities, constraints, objectives and implications). Later, assemble the digital tool (by setting architectural and environmental impact variables) and putting it into play on a real action context to observe its performative power. The section documents the process and unfolds the digital tool's model/data responsiveness, its potential in hybrid configurations and decision-making scenarios creation.

The third section corresponds with an observatory on the laboratory experience and the experiment results. It aims to create an account of knowledge through personal practical and observative involvement in the process. The observatory illustrates the performative characteristics of the tool in itself and comparison with traditional methods, its transformative power in the design process and its influence on the designer’s role and the creative process. The narration is correlated with critical reflections on the research's theoretical and practical output in contributing to ecological debate in the fold of the information revolution.

0.3.3 The object and the original contribution

The object is ***a digital decision-making tool*** at the service of designers to anticipate design choices. The digital tool employs the theoretical premises of the research as a background and moves toward the practical exploration of digital dynamic methodologies. The result is an attempt to merge ecological awareness and information revolution technologies to obtain a tool tailor-made on several implications and test its performance into action within a real design process and toward an environmental target. The tool was devised and assembled in the context of a laboratory experiment and tested in its performance and requirements during several validation phases until its mature form. The laboratory experiment defined the perimeter of action of the tool, the implications and constraints to take into account, the objectives definition, the workflow of the activities and regulated the role and the responsibilities during the creation and validation steps. The result was not pre-established at the beginning but was the outcome of a long and iterative test process with different variables and exchanges between various multidisciplinary actors[14]. At the end of the iterative process made of tests, steps back and achievements, the mature form of the tool became:

[14] *Chapter 3* and *Chapter 4* narrates the phases of tool creation and validation in details.

a parametric tool for planning decisions at a micro-scale in the conceptual design stage that generates dynamic environmental impact scenarios to create awareness of embodied carbon and embodied energy emissions related to the artefact.

By comparing the initial general proposal and the effective tool definition, it is possible to highlight how much is precise the final output. The tool was tailor-made to respond to precise “fixed” and “variable” implications, respectively, the prerequisites established at the beginning of the research path from the Academy-Industry collaboration model and that one selected during the process to better reach the scope[15]. The tool had to acquire a strong specificity to function and effectively respond to the proposal and reach the mature form previously cited. The tool was assembled using a precise methodology[16] that combines software, input and outputs to obtain the outcome in the form of digital scenarios. Which is the hidden procedure and kit to obtain the tool's final configuration?

1. The tool merges *parametric and computational design potential* to combine the digital model with several data aimed at calculating the Embodied Carbon and Embodied Energy related to the artefact;
2. Data are filled in the script in the form of *variables,* that are three*:*
   a. shape
   b. materials
   c. environmental impact indicators
3. The script provides output *dynamics design scenarios* expressed in terms of Embodied Carbon and Embodied Energy. The scenarios are digital responsive models that dynamically modify their **spatial configuration** and **environmental impact results** when subjected to a different input.

In particular, the dynamic scenarios work with a ***double and mutual*** plan of action: the two variables associated with materials and impact indicators can be combined in a fixed and single artefact to generate an impact scenario; if the artefact is modified in its form (with the consequent change of the shape variable) it influences the quantities associated to materials and impact indicators variables with the resultant modification of the impact scenarios. Therefore, ***the combination of variables affects the impact scenarios and the generative mechanism of form in multiple possibilities.***

[15] *Chapter 2* narrates the entire systems of the research implications.
[16] Read *Chapter 4* paragraph *4.1.2 The methodological proposal* for further details.

Combining shape, materials, and environmental impact in a mutual and iterative relationship governed by a parametric and computational procedure could represent an attempt to explore the intersection between digital design technologies and ecological awareness. The proposed attempt is consciously perfectible[17], but it could represent ***a working prototype of action*** in that direction.

The tool, and the laboratory experiment at the base, try to take a step beyond consolidated design procedures to obtain not only a new technological mean but also investigate in a broad view the implications that new means could produce on consolidated design practice, the creative process and designer's role. The question is, how does it change the practice with a new tool? And which is the consistency of the design output compared with the traditional means? The dissertation tries to respond to these questions by outlining a critical observatory on the experiment to interpret the performative process features and the transformative tool power.

In the final instance, some considerations about using a prototype have to be outlined. The parametric prototype employed for testing and manipulating the tool assembling consists of a residential model provided by Heijmans[18] that is part of a more extensive complex of houses designed for a neighbourhood in Amsterdam. The residential prototype was used as the fieldwork for the tool application, requirements definition and validation phases finalized to the mature tool configuration. The tool needed a manipulable and simple object to calibrate its requirements and functioning. The perspective is to open its employment from neighbourhood to the city scale in the future[19] by including variables related to the localisation and *genius loci*. Moreover, at the moment, the tool combines three types of variables consisting of form, materials and environmental impact indicators. The outlook considers additional variables such as dynamic environmental input and links their values with automatic form manipulation potentiality[20].

[17] Refers to the *Conceptual background* and *Concluding remarks* for the deepest reflections.
[18] Heijmans is the construction industry involved in the tool validation phase.
[19] The perspective of employment and next development are narrated in the *Concluding remarks* section.
[20] See *Concluding remarks* section.

0.3.4. The investigation methodology

The investigation methodology is tailor-made for addressing the purposes and the devising of the research object cited. The investigation embodies a double scope: ***documentary and transformative***. The ***duality*** cited is motivated by personal involvement as an ***observer*** that narrates facts and as an ***actor*** with full power in the process. The documentary purpose is accomplished by employing a narration that illustrates the chronological development of thoughts, implications, and controversies addressed in the research path. The result is a ***diachronic plan of narration*** that describes the research complex of changes evolving over time. The transformative purpose is addressed, instead, by adopting an ***experiment-based approach*** consisting of creating the conditions for an experiment to the practical exploration of digital procedures in the fold of ecological purposes. In particular, for devising and testing a digital tool for planning decisions and validating its performances into action in comparison with traditional procedures.

The double contribution is analysed under the lens of an ***observatory*** of the process and the experiment to outline an account of knowledge through practical and observative involvement. The position adopted is the ***participant observation*** (Dei, 2012) which implies a modality of ***knowledge from "within"***[21] with direct, practical and sensorial participation with the object of study. The participant observation perspective allows the researcher to abandon an authoritative position and, on the contrary, to **learn *with*** the object **and *from/about* it**[22]. The researcher, therefore, adopts toward the object an ***integrated process of knowledge*** founded on iterative process exchange during the object ***study*** and, in this case, ***production***. The term *"making of",* which is related to the tool devising, includes the double meaning of "construct" and "interpret". Therefore, it evokes the iterative process between producing and creating knowledge and ***learning by doing***. By embodying this binomial as the key reading, the *observatory* investigates the methods to build a theoretical reflection on process and results when it is grounded in the context of a practical experience.

The diachronic plan of narration and the *observatory's* reflections encourage an investigation method grounded on relationship ***thinking through observation*** and a ***problem seeking*** approach. Engaging the problematization approach, at this juncture, helps in questioning beliefs considered commonly true by posing that knowledge as a problem, enabling new viewpoints, reflection, and especially, ***action to emerge***[23].

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[21] From T. Ingold, *Making*, Raffaello Cortina Editore, 2019.
[22] *Ibid.* The approach to the research merges the anthropology and etnography principle.
[23] In reference to Focault's studies (2011). *Storia della follia nell'età classica* [1962]. BUR.

0.3.5 Chapters development and use of the sources

The section intends to illustrate how the research parts and related chapters make use of sources and materials[24].

Part I is composed of the first and the second chapters that define the ***theoretical background and implications.*** *Chapter 1. Parametric design and the ecological challenge* is developed on a wide book and magazine papers literature review on ecology, parametric and computational design and their intersection. *Chapter 2. Interpreting implications as a design matter* is founded on the multidisciplinary reading of sources, mostly scientific articles and reports, UN and European guidelines, and institutional websites. The sources comprehend various topics and their intersections, particularly contemporary environmental and social issues influencing the research proposal, parametric design and its power in prototyping, Building Information methodologies and the Academy-Industry collaboration model. The scope is merging theoretical background and implications to highlight the motivation at the base of the research proposal. The section dedicated to the *Conceptual background* represents the indispensable premise to address the topics.

Part II corresponds with ***the laboratory experience***. It illustrates the original contribution of the thesis consisting of a digital tool planning decisions at a micro-scale able to create dynamic Embodied Carbon and Embodied Energy scenarios. The section narrates the tool creation and its positioning toward existing methodologies. It is constituted by *Chapter 3. Building the playground*, dedicated to illustrating and settling the boundaries of the experiment. *Chapter 4. Devising the tool for planning decisions* narrates the methodological proposal and its steps toward the tool assembly and validation. As the description suggests, both the chapters employ an experimental approach and deepen the specific literature on Building Information Modelling, Life Cycle Assessment, computational procedures and their intersection mostly by selecting scientific articles on the topics. The sources are here employed as literary reviews and as materials for settling methodologies comparisons and creating benchmarks useful to calibrate the tool requirements. *Chapter 4* makes use of the case study, consisting of a residential dutch house, to calibrate the tool assembly and test its requirements and scenarios results.

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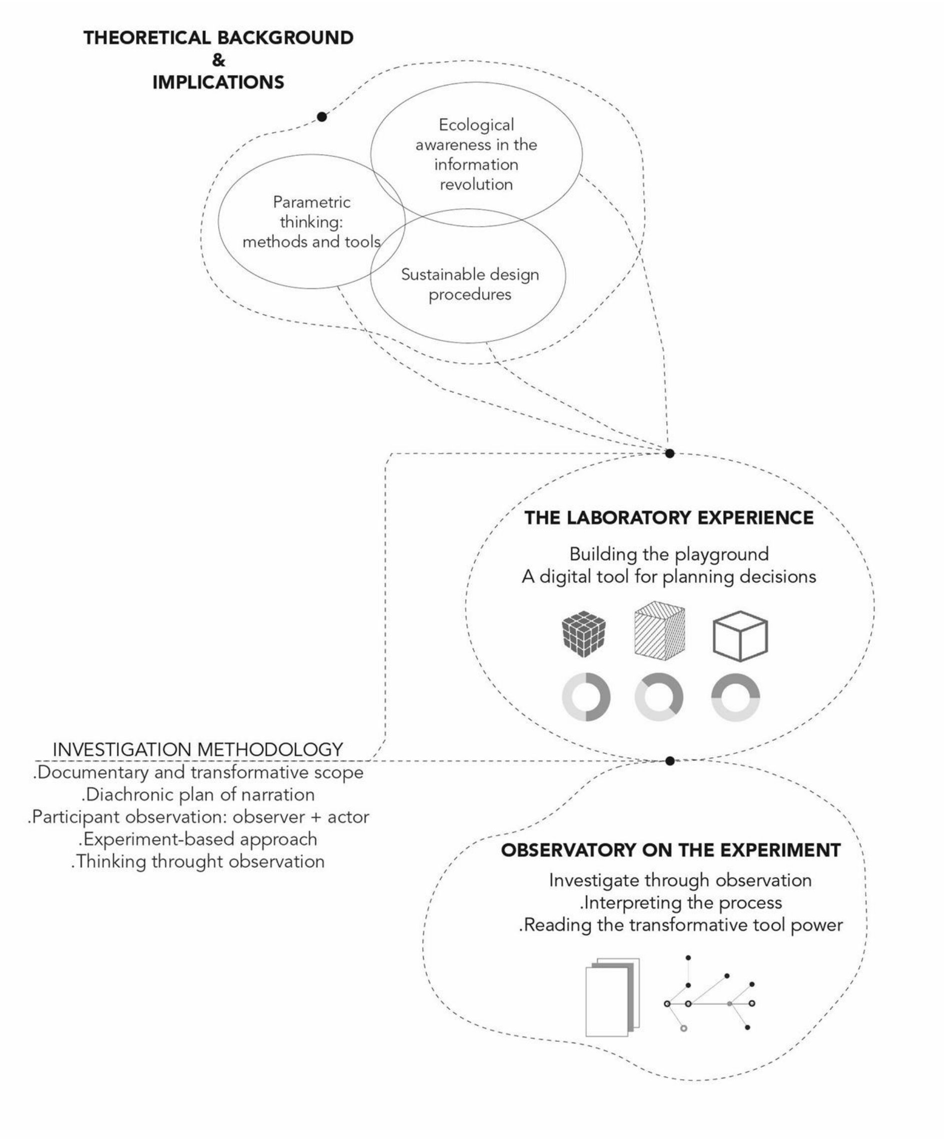
[24] The section outline the part dedicated to the sources typology and employment and introduces some aspects that will be deepened during the thesis dissertation.

Part III is dedicated to the ***observatory on the experiment***. Its task consists in outlining a knowledge account founded on the observative and practical involvement in the research process. *Chapter 5. Investigate through observation* consists of a theoretical reflection built on the weave between practical activities interpretation and theoretical recognition of literature resources on the topic, book and magazine papers for the most. The chapter also outlines the positioning of the tool and the new methodology in comparison with traditional ones by using scientific articles as a source for creating final benchmarks and assessments. In conclusion, *Chapter 6. Concluding remarks* employed a literary book review to highlight the potential next applications of the tool and future enhancement to improve the transformative power of the tool and the process.

0.3.6 Graphical abstract



0.4 Structure of the thesis

The thesis is organized into four sections and divided into an introduction and six chapters. The first and the second chapters define the implications and the theoretical background of the research. The third and fourth chapters discuss the innovative contribution of the study and narrate the development of the thesis and the experiment. The fifth is dedicated to the critical discussion of the results, and the sixth is to illustrate concluding remarks and future challenges.

PART 0: **Introduction**

0. Introduction to the research activity

Part 0 introduces the research activity's premises, consisting of a detailed narration involving the working hypothesis, problems, questions, and methodology adoption. It illustrates the thesis's structure in its parts and chapters and narrates methodological notes and contributions.

PART 1: **Theoretical background & implications**

1. Parametric design and the ecological challenge
2. Interpreting implications as a design matter

Part 1 contextualizes the work's background and the starting research implications. The first chapter clarifies the theoretical background in its concepts, contributions, and terminology. The second chapter illustrates the wave of environmental, social and technological motivations and the Academy-Industry collaboration model's influence on research development. The last part of the section is dedicated to introducing the research proposal definition.

PART 2: **The laboratory experience**

3. Building the playground
4. Devising a tool for planning decisions

Part 2 is dedicated to illustrating and discussing the original contribution of the thesis consisting of a digital tool planning decisions at a micro-scale able to create dynamic Embodied Carbon and Embodied Energy scenarios. The section narrates the tool creation and its positioning toward existing methodologies.
The section makes use of the discussed notions and implications to narrate the stages that led to elaborate a digital tool addressing the research proposal. At this

point, the laboratory experience is instrumental in setting up the socio-technical context where the tool can be assembled and tested.
The first chapter recounts the stages of the laboratory experiment built up to tailor-made the tool. It illustrates the experiment preparation phases and defines its consistency in terms of roles and responsibilities, the workflow of the activities and the toolkit. The second chapter unfolds the detailed phases of the tool assembly work, the methodology set up for its realization and the chronological validations. It illustrates the outcome, consisting of a digital tool for planning decisions that merges parametric and computational procedures to create environmental impact scenarios, in the form of dynamic diagrams, at a micro-scale in the conceptual design stage.

PART 3: **Observatory on the experiment**

5. Investigate through observation
6. Concluding remarks

Part 3 is dedicated to tracing the critical discussion and observations of the process and results in their theoretical and practical challenges. Its commitment consists in outlining a knowledge account founded on the observative and practical involvement in the research process. The first chapter builds a theoretical reflection by employing the laboratory experience process as a means of interpretation. It unpacks the research path stages and highlights its performative characteristics to trace the innovations that parametric practice can trigger in the design discipline. The aim is not to provide an exhaustive enquiry on the parametric in the fold of design but to extract some reflective observations grounded on a practical experience and put them in dialogue with a bibliographic background. The second chapter shifts the critical focus on the tool and opens thoughtful considerations toward its transformative power over collaboration procedures and activities workflow. It reflects on the potential implementation of the digital tool and its applicability to enrich its scale of employment. It links back to the outcomes with the initial research questions and interests and outlines the potential of the parametric procedures to contribute to the ecological debate and provide means for planning decisions.

0.5 Conceptual background

The current section is dedicated to clarifying the crucial themes addressed in the thesis and defining my position on them. In particular, due to their wide and fleeting discipline boundaries, the ecological and parametric matters require a clear description concerning their employment in the dissertation. The section proposes introducing the definitions and describing my positioning toward them in the current research thesis[25].

The first theme to introduce is Ecology. Ecology, as commonly known, is *a discipline dedicated to studying the relationships between organisms and the natural world*[26]. Ecology, in its definition, puts organism and nature in relationships, that is, a relationship of democratic balance between the two entities. The quality of the relationship is measured for their balance, not for their dependence or mutual exploitation dimension. Ecology exalts the reciprocal relationship between ***nature and "living organisms"***, a definition that encloses natural and human organisms with the same grade of importance and legitimacy in the planetary balance. Ecology, in current times, has developed widely both as a science and as a practice. It touches on problems of great importance for all countries and in particular for those densely populated, industrialized ones and those in the process of massive industrialization: the exploitation of natural resources, the protection of nature, the protection of the landscape, the fight against water pollution, the control of human settlements and so on[27].

The conception of ecological thinking, as we know it, arose between the late sixties and early seventies (P. Gregory, 2013), which were years of complete redefinition of human awareness in terms of consciousness toward its existence and the resources necessary for its survival. The ecological awareness unveils the unconscious (Morton, 2021) and puts into light the chain of human actions responsible for the ecological crisis. In these terms, it pushes humanity beyond anthropocentrism by re-dimensioning its position in the biosphere.

The current ecological awareness pushes for clarifying some crucial aspects. First of all, ecological awareness ***unveils*** the concatenation of actions and ways responsible for the ecological crisis and, consequently, provides proof that we "are something among others" (Morton, 2021). Therefore, ecology considers

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[25] The historical use of the terms, the termology employment, the evolution of thoughts is addressed and described in details in *Chapter 1* dedicated to Parametric design and the ecological challenge.
[26] "Ecologia" in Treccani vocabulary, https://www.treccani.it/vocabolario/ecologia/.
[27] *Ibid.*

humans and non-humans at the same level, and thus it ***disarms*** the human instincts of domination and consumption applied to natural entities.

Secondly, Ecology pushes ***to get rid of the common notion*** of Nature intended as "everything" but also "other respect to us" or "the absolute other" (Morton, 2021). In other words, to give up on considering Nature as a separate entity, as something to protect by keeping distance from it. This kind of conception nourishes a confused and indeterminate idea of Nature that is simultaneously an untouchable *simulacrum* and resource enslaved by humans. This fallacious conception forbids humans from establishing an authentic and direct relationship with Nature, embodying an "attitude of paternalistic care"[28] that hides dominatrix and possesses trends with degenerative consequences. On the contrary, Nature must be admired with ***an aesthetic appreciation attitude***, something by which we are fascinated or enchanted by respecting and feeling part of its inner integrity and alterity.

This conception visibly takes a step beyond standard environmentalism and consolidated sustainability principles. From the beginning, the urgent necessity to find a new planetary and environmental balance dragged into the environmental debate of both architecture and urban planning at different scales that have been gradually oriented toward sustainable development purposes. However, the "sustainable development" definition proposed by the Bruntland Report[29] (1987) as "a process by which resources exploitation, the direction of investments, the orientation of technological development, and institutional changes are coherent with future and current needs" implied, also if maybe involuntary, a hierarchical relationship between human and natural resources. The latter is considered a substance to satisfy the human's future needs if exploited consciously. Ecology, in the fold of architecture, wants to overturn this concept and take a step toward a ***new balanced alliance*** between Nature and Humans, new ways of inhabiting the earth, and a ***new dialectic between natural and artificial*** (P. Gregory, 2013).

J. Wines, in *Green Architecture*[30], employs the term *connectedness* to express the idea that Nature is not a resource to be exploited but an extension of ourselves.

What does it entail?

A new bond between ethics and architecture that, understood as art, has to express a new philosophical and aesthetic vision related to ecological awareness and the information revolution[31].

[28] Term employed by Morton in *Ecologia Oscura*, Luiss, 2021, p. 9.

[29] In 1987, Gro Harlem Brundtland, president of the World Commission on Environment and Development (WCED) established in 1983, presented the report *Our common future*, formulating a guideline for sustainable development still valid today.

[30] J, Wines, *Green Architecture*, Taschen, Koln, 2000. The term *connectedness* is related to the concept "being connected".

[31] *Ibid.*

Architctercure, therefore, is now invested in complex tasks. In the first instance, it reverberates the evolutionary ***changes of nature*** and the ***flows of electronic communications***. Secondly, it has to embody the role of a ***medium*** to amplify our senses and perception ability, to extend ourselves (McLuhan, 2015)[32]. By the contribution of these two characteristics, architecture is exalted in its dialogic and interactive ability with the environment and users. It occurred, therefore, a shift of the architectural aesthetics from sculptural object to a mediator able to absorb and ***transmit messages***. The artefact, no longer isolated, became the place for transition, connection and communication. It gradually transforms into an ***interface*** that is a permeable and mediating entity between different logic[33], subjected to continuous exchanges capable of profoundly modifying its essence.

The lines of research on ecological-relational models and the attempts to address the new philosophical and aesthetic vision related to ecological awareness and the information revolution are the object of Chapter 1; indeed, their narration will not be anticipated. However, a further clarification must be made, namely the role that digital technologies have in the achievement of ecological objectives.

Reaching a new kind of philosophical and aesthetical vision in architecture able to be the interpreter and the medium of the changes in nature and the flow of communication requires the use of advanced technological and digital systems. The revolution in the architectural paradigm and its ontology goes hand in hand with the informatics and digital revolution. Digital procedures, such as parametric design and computation, amplify the potentiality of the design project to store, manage and elaborate flux of information in the form of data. The parametric and computational design merges to provide *a process based on algorithmic thinking that enables the expression of parameters and rules that define, encode, and clarify the relationship between design intent and design response* (Jabi, 2013). The parametric model stores information in the form of data and is empowered by algorithm calculation potential that allows data combination and manipulation[34]. In this way, they can simulate the dynamics similar to a living organism, a process of genesis characterized by dynamism and evolution[35].

With this in mind, the research moves toward ***dynamic investigation methodologies and models*** to explore, first all, the temporal and spatial modalities

[32] Particularly suggestive is the McLuhan original title “The medium is the message”.
[33] Term “Interfaccia” from Treccani vocabulary. https://www.treccani.it/vocabolario/interfaccia/.
[34] Further details will be illustrated in *Chapter 1* and *Chapter 4*.
[35] They can be supported by several and multiple digital technologies like crowd modelling, agent-based modelling. See *Chapter 1* for further details.

of the design process. Secondly, to test data manipulation of multiple variables[36] and investigate the dynamism of results and responsiveness of the models. Thirdly, to experiment with the computational and parametric methods of form generation and hybrid configurations. Fourth, their potential contribution to planning decisions and providing scenarios configurations framed into the ecological debate.

The research attempts in its experimentation to reach the objectives described, but even if it represents a primordial and perfectible attempt to merge ecological awareness and informatics revolution technology, it can represent a ***working prototypal of action*** toward that direction. ***The tool*** merges parametric and computational design potential to combine several different data in the form of variables (form, material, environmental impact indicators) to obtain dynamics design scenarios. The scenarios are represented by digital responsive models able to modify their spatial configuration and environmental impact results in a dynamic way when subjected to a different input.

The tool for planning decisions required an articulated and tailor-made process constituted of roles balance, responsibilities, multidisciplinary contribution, attempts, practical obstacles and long validation phases until its definition in its mature form[37]. Moreover, in its formulation, it was enclosed into fixed implications and necessities imposed by the playing parties that strongly directed its development[38]. Even if consciously perfectible, the research in its experimentation aimed at taking a step beyond consolidated design procedures[39]. It framed its experiment in a wider philosophical and aesthetical debate to inquire about design solutions for a new balance between artefact and environment. The leading thought was that the ecological awareness transition in design should not be only grounded on the use of renewable energy and new material. Still, it must be established on the foundation of a new binomial relationship between humans/nature with information technologies' mature and ethical support.

The dissertation will narrate and illustrate the evolution of thoughts, collaboration procedures establishment, the methodology composition, the phases of the tool assembly and narrations related to a critical observatory of the research process and the experiment. The thesis closes with suggestions that lay the ground for next research and development.

[36] Variables like: form, materials and environmental impact indicators.
[37] The detailed process of creation is described in *Chapter 3* and *Chapter 4*.
[38] Read *Chapter 2* for the complete panorama of implications.
[39] It refers to energy efficiency, compatible and high-tech technologies, recycled materials and so on, illustrated by P.Gregory, *Teorie di Architettura Contemporanea*, Carocci editore, 2013.

Theoretical background & implications

PART I

Chapter 1.

Parametric design and ecological awareness

The current chapter belongs to the *Theoretical background and implications part* that contextualizes the work's background and the starting research implications. The chapter clarifies the ***background in its concepts, contributions, and terminology.*** It illustrates the theoretical recognition of ecology and digital technologies intersection supported by the elaboration of critical thought. The current chapter, together with the next one dedicated to illustrating the wave of environmental, social and technological motivations and the Academy-Industry collaboration model's influence on research development, is instrumental in introducing the research proposal definition.

The research suggests in its premises its aspiration in influencing the cognitive and critical debate on the environmental topic and, in particular, in affecting its operative strategies with a tool[40] that embodies *transformative power*[41] over consolidated procedures.

Ecology, currently, is a wide and ambiguous box that converges multiple matters with undefined perimeters. The chapter tries to trace the boundaries and identify its principles for taking a position. Two levels of in-depth analysis address the ecological matter: narrate current tendencies about ecology definitions and principles and explain their chronological evolution; provide an overview of parametric and algorithmic thinking in the fold of their application for environmental targets. *What consists of today the ecological matter, and how can it be interpreted? Why and how parametric design can contribute to the debate around it?*

Responding to and tracing the relationships between these questions are finalized, in conclusion, to framing the proposal into the ecological discourse.

[40] The digital tool is tailor-made to drive decision-making process, read the *paragraph 0.3.3 The object for its introduction.*

[41] The aim is to generate an effect on the world (Dei, 2012).

1.1 Introduction to ecological awareness in the information revolution

The conception of ecological thinking, as we know it, arose between the late sixties and early seventies (P. Gregory, 2013). Even though the effects of the first and second industrial revolutions (1784 and 1870) were yet tangible, and it was the moment to enter the third (1970), we had to wait until the early seventies for a certain kind of ecological awareness. Not by chance, ecology was born in the decade when we saw the Earth from space for the first time (1969) and considered the planet as a whole. In those years, although it was well-established the thought that we were no more at the centre of the Universe (Copernican revolution, 1543[42]) and the animal kingdom (according to the evolution theory by Charles Darwin, 1859[43]), we thought we were still masters of our mental contents (Floridi, 2014). After Sigmund Freud (1859-1938) and his psychoanalytic work, the conscience concept was also put into crisis and will never be the same.

The late sixties were years of complete redefinition of human awareness in terms of consciousness not only toward its existence but also with respect to the resources necessary for its survival. The oil crisis (1973) pushed in creating insecurity in our production system and spread awarenesses about the planet's scarcity in terms of resources and the necessity of alternative energy sources (P. Gregory, 2013). The ecological awareness grew, therefore, with the anthropocentrism crisis.

The ecological awareness unveils the unconscious (Morton, 2021) and puts into light the chain of human actions responsible for the ecological crisis. In these terms, it pushes humanity beyond anthropocentrism by re-dimensioning its position in the biosphere. Ecology establishes a balanced relationship between living organisms (humans, animals and plants) and their natural environment. Ecology, therefore, currently goes beyond the concept of sustainability. By taking a step back, the first attempts in ecological thinking during the early seventies powerful invested the architecture, urban planning debate and design theories at various scales aimed at a "sustainable development" (P. Gregory, 2013). Surely, it embodied the essential intent to found a new human/nature alliance. However, its definition still incorporated a position of domination over the natural world by humans. Sustainable development was defined by the Bruntland Report[44] (1987)

[42] *De revolutionibus orbium coelestium* publication in 1543.
[43] *The origin of species* publication in 1859.
[44] In 1987, Gro Harlem Brundtland, president of the World Commission on Environment and Development (WCED) established in 1983, presented the report *Our common future*, formulating a guideline for sustainable development still valid today.

as a process by which resources exploitation, the direction of investments, the orientation of technological development, and institutional changes are coherent with future and current needs. The definition itself highlight the hierarchical relationship that human establishes with natural resources. Resources are exploited (but consciously) to ensure needs satisfaction for current and next generations (of humans). Indeed, "sustainable development" represents a virtuous and indispensable guideline to regulate human growth still valid. Anyway, the concept sounds old-fashioned today. The environmentalism of the seventies failed, for contemporary thought, in tracing a division line between the human and natural world; between human and a "Nature", which was intended as a separate place, wild, distant, to preserve by staying far from her. A Nature imagined as *Everything* e and as the *Other* (Morton, 2021). Our imaginary charged with a simulacrum of Nature as a powerful and venerable entity but, at the same time, a resource subjected to guarantee man's growth and development. On the one hand, intact and untouchable; on the other, trade goods.

"Nature was a kind of private property without an owner, exhibited in an ad hoc built art gallery. Wilderness areas are giant abstract versions of products hanging in shopping mall windows." (Morton, 2019)

The human "invention" over the natural world nourished confusion and impeded to the creation of an authentic relationship with it. Humans imposed a fallacious dominion and paternalistic care over it by carrying, as an effect, the ruins of the environmental balance. According to Morton, humanity should substitute the benevolent protection and condescension attitude with a feeling of fascination toward nature and realize the inner and authentic belonging to the natural world[45].

In other words, humans must quit perceiving themselves as "other" than nature. Ecology takes a step forward and pushes to embrace a new existential modality[46] founded on coexistence between humans, not humans and the world. Ecology is a way of existing and thinking; it is a profound new approach to interpreting our relationship with the natural world. What if the ecological discourse permeates habits, life, society, and artistic production? It could be time for a new global environmental culture, not framed into specialists' perimeters but pervasive in living aspects and human products.

Just as ecological thinking is evolving, its products are under changing and charging new meaning. At the beginning of the seventies, the attempts pushed from ecological science carried toward Land Art and Environmental art, which

[45] Morton explains in *Dark Ecology* (2016) the importance of experience beauty and fascination.
[46] Ecology intended as a pervasive way of exist, in *Dark Ecology* (2016).

produced mainly formal outcomes still linked to the traditional concept of safeguarding. Today, the architectural and artistic research aims at reaching an eco-compatible aesthetic able to transpose on the technological and epistemological level the union between nature and humans (Wines, 2000). Since the beginning of the century, Wines pushed for abandoning the idea of correspondence between nature/resources and conceived the term ***connectedness*** to express the vision of nature as the extension of the human self and vice-versa. The concept directly implies a new association between architecture and ethics that should express the current ***philosophical and aesthetic vision correlate with ecological awareness and informatics revolution***[47]**.**

The role of architecture

"Architecture must reverberate the variable and evolutive changes that manifest in nature and the flowing interactive flux of data that stream through electronic communication." (Wines, 2000)

An architecture that privileges the dialogue and interaction skills with the environment and humans (Gregory, 2013) and, therefore, that pushes the traditional conception of architectural aesthetic from the sculptural object to its ability to absorb and transmit information[48]. In other words, from a sculpture to an ***interface*** (see Figure 1).

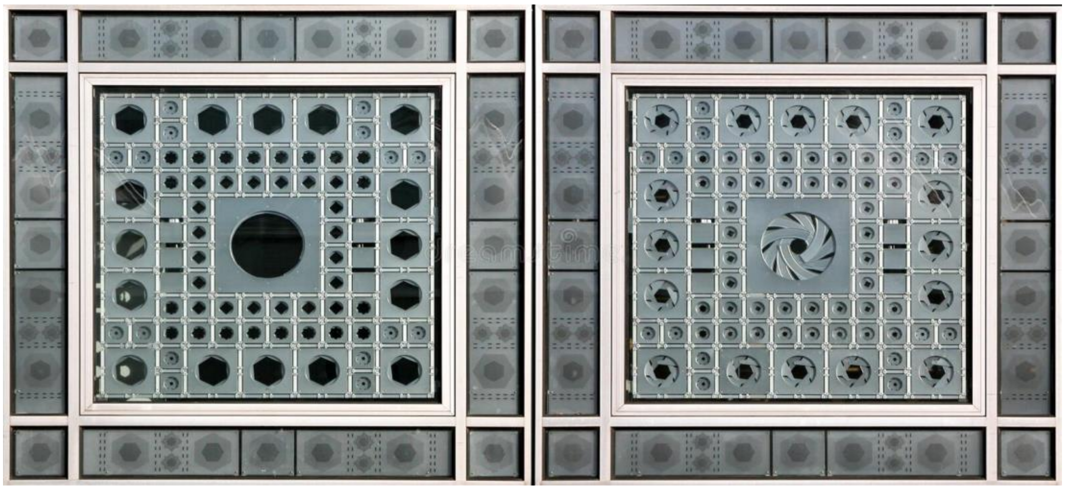

Figure 1. Institute du Monde Arab, Paris, 1987. Detail of the facade.

[47] Wines, for first, in *Green Architecture* (2000) suggests the strategic power of infomatics revolution in contributing to ecological awareness.
[48] One of the first attemps is the Institute du Monde Arab, Paris (1987). The facade regulates sunlight like a camera shutter when exposed to different light stimulus.

The interface concept is crucial for the new thriving eco-relational models finalized to transform the artefact into a transition, connection and communication space with dialogic ability. The interface expresses ***a porous and mediating entity*** between several logics that work differently[49], a connection and adaptation entity that generates constant exchange and interaction with another system (for example, the environment) to allow itself to be changed by this (see Figure 2).

Space dematerializes to permit the implicit communication between subject-artefact-context connected by mutual relation and permutation in matter, energy and information. The binomial architecture-nature imposes as the unifier factor of the communications system, the **medium** that expands ourselves, our senses and our ability of perception[50].

Figure 2. Diller+Scofidio, Blur Building, swiss Expo 2002, Yverdon-les-Bains[51].

How could architecture embody this purpose? The architecture discipline should recognize the centrality of the ecological matter and provide a new philosophical foundation to a design approach grounded on technological innovation and models inspired by nature. In other words, it should integrate the information technology contribution (even if risky) and embody the artefact

[49] Concept extrapolated and interpreted from Enciclopedia Treccani, *"Interface"*.
[50] The concept of *medium* is inspired by the McLuhan study in *Understanding media: the extension of men* (1964). The analysis is not reducted to mass-media, McLuhan intented as a medium everything able to trigger a change; according with this meaning even a clock can be defined as a medium because it has trasformted the way we perceive time.
[51] The Diller+Scofidio cloud doesn't have form and dimensions, it is a dynamic interface obtained from nebulizers that draw water from the lake and vaporize it at high pressure.

ecology and information (Gregory, 2013). An architecture, therefore, that is able to ***go beyond the concept of sustainability***-focused on technical energy efficiency and perspective of regenerative resources (see Figure 3).

New paradigms, founded on eco-models, are multiple and diversified. It can be a matter of “eco-digital” architecture, promoted by Wines, which is capable of taking root in places with material and immaterial consistency like a “sponge of information” that receives and communicate data with the context[52]; or the Kengo Kuma’s “digital gardening” able to produce the architecture disappearance in favour of manifesting the place consistency[53]; or by the “naturalistic camouflage” with the naturalization of the artefact[54]; and, in the end, the “technological naturalism” inspired by the organic world[55].

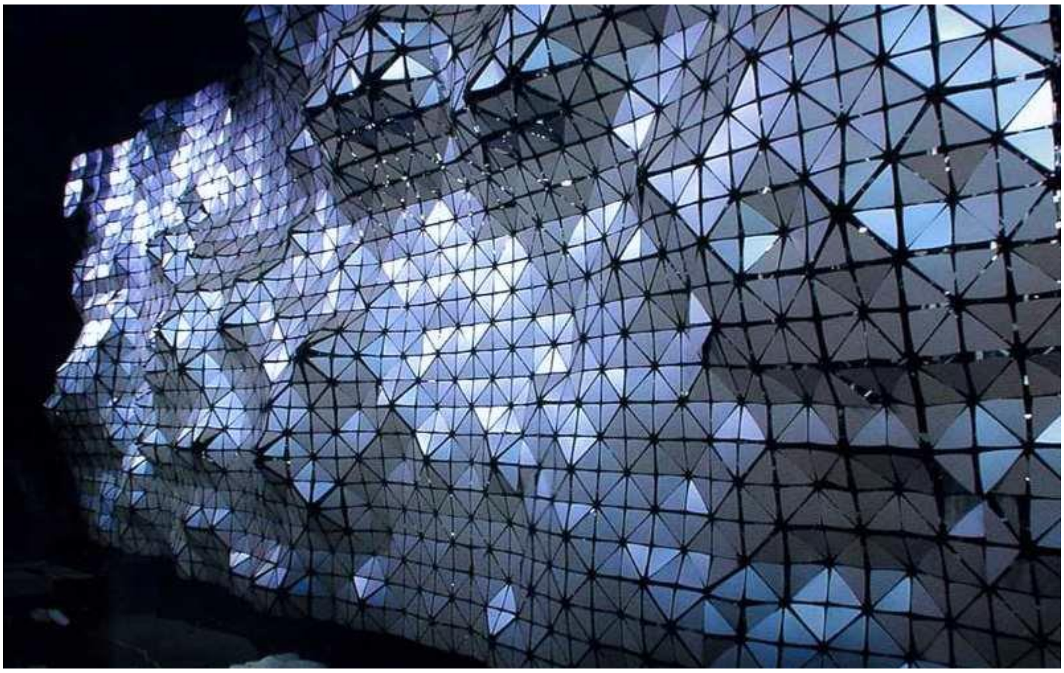

Figure 3. dECOi, Aegis Hyposurface, 2000[56].

[52] From J.Wines, *Jewel in the balance* in A. Marras (ed.), *Eco-tec. Architecture of the In-Between*, Princeton Architectural Press, New York, 1999, pp. 109-116.
[53] From K. Kuma, *Digital Gardening*, in “Space Design”, November 1997, in L.Alini (a cura di) *Kengo Kuma. Opere e Progetti*, Mondadori Electa, Milano, 2005.
[54] F. Repshiti, *Green Architecture*, beyond metaphor, in “Lotus Architecure”, 135, 2008.
[55] Toward abstraction and lightness inspired by R.Piano and Shigeru Ban.
[56] ‘Aegis’ is a metallic surface that has the potential to deform physically as a real-time response to electronic stimuli from the environment (movement, sound, light, etc.). Driven by a bed of 896 pneumatic pistons, the dynamic ‘terrains’ are generated as real-time calculations.

Architecture became no longer connoted for its formal characteristics but for its ability to transform into an environmental filter, sensitive and reactive, until it becomes (in extreme experimentation) an *immaterial body* understood as the pure flow of energy stream, in analogy with informative flux (Purini, 2008)[57]. Architecture is the place of interaction, transition, and communication, where *generative reproduction* occurs[58], which means the mutual co-evolution generated by the interactive process. This tendency is embodied in several experimentations like *bio-mimetic systems* where natural materials, with the aid of energy sources and mechanic and informatics systems, put into action behaviours inspired by nature. The artefact can embody the biological principle of shape-changing when subjected to external variation, such as in the case of the hygroscopic change conducted for the Faz Pavilion (see Figure 4).

Figure 4. Studies for responsive surfaces, Achim Menges[59].

[57] F. Purini, *Architettura Virale. Infezioni della scrittura architettonica* in “Lotus International”, 133, 2008, pp. 82-87.

[58] R. F. Malina, *The beginning of a new art form*, 1990, in P.L. Cappucci *Realtà del virtuale. Rappresentazioni technologiche, comunicazione e arte*, Clueb, 1993.

[59] Studies on conifers behaviour by Prof. Achim Menges for Faz Pavilion, from Achimmenges.net.

The experimentation on ecological visions with generative process registered a great precursor in the figure of F. Roche, that was one of the first at testing evolutive systems at the beginning of the 1990s in his laboratory *New-Territories*. Roche's works are positioned halfway between architecture and an art installation where the extreme conceptualization became a tangible artefact. Even though high jump toward concept and ephemeral finds the obstacle in being applied to larger-scale and practical applications, Roche deserves to have introduced in the consolidated design processes concepts like evolution, dematerialization and entropy[60]. He takes the attempt of the bio-mimetic system and bio-morphism at the highest (*Camouflage* project, 1993) until the artefact disappearance into the surrounding environment (*Transfert* project, 1993, see Figure 5).

Figure 5. F. Roche, Transfert, Foret de Compiègne, 1993[61].

[60] From Wines, Green Architecture, Taschen, 2000.
[61] Roche positioned two identical huts covered by moss in two different microclimate area (sud, surrounded by beech trees and north by conifers). Each huts will embody a different appearance in

Concepts that characterized Roche's activity in recent times are enriched and contaminated with disciplines also apparently distant from architecture (visual art, cinema, biology, digital fabrication) and with digital tools that allow extending the linking between architecture and environment. Humans and their products are part of an overall and out of reach complexity that connects the universe and the body cells in a direct relationship, as Charles and Ray Eames suggest in the video *Power of Ten*[62]. It is clear that a new sensitivity is growing no more than only a matter of reducing human construction impact on the planet but a new paradigm[63]. A "paradigm of the living" (Causarano, 2017) that is able to push forward a hybridization between human and architecture, architecture and animals and the natural world. A paradigm to surpass the consolidated way in which we act, think and create knowledge. Current eco-models are pushing to rethink concepts, methods, and architecture problems and invite to find solutions in nature. They are inverting the tendency of a design object made from assemblage to an object that grows and evolves with generative rules. Since the industrial revolution, design has been dominated by manufacturing and mass production that dictated a world "made of parts". In our imagination, objects are made by discrete parts and distinct functions. The eco contro-tendency is a system that gradually varies its functionality and evolves and grows. An architecture that is at all effects organic, at the intersection between biology and technology[64] (see Figure 6).

The current paragraph is strategic to highlight the premises at the base of the ecology and information revolution relationship. At this moment, raise some crucial questions.

How can architecture manage the electronic and informatic flux to become a medium, and how does it can interpret the phenomenologic space and related interactions. In conclusion, why now? Why this not was possible decades ago? The next paragraph tries to explore the implication that made this possible.

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response to the environment they are subjected. Image from *New-Territories* website. https://www.new-territories.com/Defaut2.htm

[62] In 1999 F. Roches intervenes at ANY Paris with the video Power of Ten by C. and R. Eames that showed a continuous zoom from intergalactic cosmos until the human cells and stops on a picnic scene in Chicago.,

[63] The term want to express the meaning of paradigm associated to T. Kuhn's theory in "The structure of scientific revolution". A new paradigm should be a set of principles, universally recognized cultural and scientific concepts, methodological procedures, methods of communication and transmission of theories, which inspire the work of the "scientific community" of a given epoch.

[64] The defintion is related to Neri Oxman (MIT) studies narrated in Ted Talks (2015). See the complete interview at https://www.youtube.com/watch?v=CVa_IZVzUoc&t=2s.

Figure 6. Neri Oxman, Aguahoja III Pavillion, 2019[65].

[65] The Aguahoja pavilion by N. Oxman and his research group The Mediated Matter is a five meter tall biocompatible structure composed by cellulose, pectin and chitosan. In particular, it is made from shrimp shells, insect exoskeletons and dead leaves, 3D printed by a robot, modeled from water and colored natural pigments. The result is a matter-organism made of biopolymeric compounds that captures carbon dioxide, improves pollination, increases soil microorganisms and provides nutrients. Derived from organic matter, printed by a robot. Full description at https://www.media.mit.edu/projects/aguahoja/overview/.

1.2 The contemporary challenge of technique

Admitting that architecture should express a new human/nature alliance, ***how*** does it possible to establish it? And ***why now***?

Rethinking the dialectic natural and artificial pushes to revise the binomial artefact and environment and the essence of their relationship. Architectural research aims at an eco-compatible aesthetic that can transpose a new concept of union between nature and man, of breaking down barriers on a technological and epistemological level. The attempts are multiple and various. It may occur, has been described in the previous paragraph, about *bio-mimetism* and *bio-morphism*, through a design that embodies the biological rules, codes and principles of nature; or through *eco-sustainable systems* that the artificial mechanism can establish an exchange with the context in terms of information and energy (P. Gregory, 2013). In both cases, it is not only a matter of a new aesthetic representation but rather favours transition and exchange of information flux between artefact and the context. It occurs in the architectural aesthetic transition ***from sculptural object to medium***. At this point, ecological awareness and informatic revolution find their counterpoint.

The challenge of technology

By considering the necessity of employing technology to reach the highest objective of ecology, humans, in current times, should ***perform two tasks***: rebuild the human perception and consciousness about technical objects; identify the role and potentiality of technology in expanding architecture dominion by considering the ethical consequences.

Let's start from the first point, ***rebuild the technology perception***. The scepticism liked to technology has profound and ambiguous roots in our cultural perspective. On the one hand, concerning technology are exalted the achievements (in terms of progress); on the other are disapproved the consequences (on environment and civilization). The result is an ambivalent debate that carries to what is called the "paradox of technique"[66]. The paradox splits thinkers between those who associate technique with the decay of the West and those who believe in the enhancement of technique as operative means.

Culture has set up a system of defence against technique[67]. A defence based on scepticism, false beliefs and fear provoked by the fallacious premise that technical objects do not embody human reality. The opposition between

[66] P. Chiodi, Esistenzialismo e filosofia contemporanea, Edizioni della Normale, Pisa, 2007, p. 53.
[67] Technique intended as the set of practical activities based on empirically acquired norms, or on tradition, or on the application of scientific knowledge, which are or were typical of a given social and productive situation, of a given epoch, of a given geographical area. Treccani, see https://www.treccani.it/vocabolario/tecnica/

culture/technique and human/machine is without foundation and leans on a sort of ancient xenophobia, intended as the fear of what is unknown, even though such a foreign being is still a human creation. The human feels so close to its powerful creation but at the same time perceives the fear of losing control over it, a suggestion pushed forward by literature, such as Mary Shelley[68], in which book we feel empathy and repulsion toward the monster. Not by chance, the alternative for the celeb Shelley's book was *The Modern Prometheus*. Prometheus is the titan friend of humanity and progress, the inventor of writing, medicine and architecture, the inspirer of metallurgical art and the domestication of animals through which gift directs men on the path to civilization[69]. The titan incarnates the fear toward technological development and forges, for the first time, the binomial *sublime*[70] and *progress*.

The story and its interpretation suggest that the most significant cause of alienation in the contemporary world lies in the lack of understanding of the machine. It is not the machine that causes alienation but our misunderstanding (or incomprehension) of its nature and essence (Simondon, 2021). According to Simondon, culture unbalances the relationship by admitting the legitimacy of aesthetic objects in their power of embodying significance and repulsing technical objects to a world that doesn't possess value and significance but only "use" or "useful function". This perception doesn't allow us to find a proper location for technical objects in our imagination, something that is worsened by the fact that machine is consistently different from humans, but at the same time, it is the "double" of men. The increasing sophistication of machines, in fact, is capable of dreaming, reacting, collaborating and, moreover, not feeling pain or regret and capable of having its willing nourish the idea of a "robot" as the twin of the men but devoid of interiority. The outcome is an ambivalent cultural behaviour that interprets technical objects in two ways: a mere material assemblage with a lack of significance that possesses only utilities[71]; a robot animated with hostile intention toward our culture and civilization. It is clear that the contradiction, which is intrinsic in our culture, comes from ambiguity in our thoughts. The machine is not a living being, any more than a statue or other human production. No product can be considered real, endowed with a true interiority, a good or bad

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[68] Mary Shelley, *Frankestein: or the modern Prometheus*, 1818.
[69] Treccani,see: https://www.treccani.it/enciclopedia/prometeo_%28Enciclopedia-dei-ragazzi%29/
[70] In the Philosophical inquiry into the origin of our ideas of the sublime and beautiful (1757) E. Burke considers a source of s. in art everything that can arouse the idea of pain and danger, and indicates the reasons for the pleasure one feels in front of the self. The triumph of the instinct of conservation in the face of a destructiveness that does not press too closely. From Treccani see: https://www.treccani.it/enciclopedia/sublime/
[71] See Simondon G., *Del modo di esistenza degli oggetti tecnici*, Orthotes, 2021.

willing; everything else is the product of our imagination and illusions. The direction, in conclusion, is to give back to technique the legitimacy of an object dense of significance with equal dignity compared to other human products and inextricably waved with them.

At this point, it can be introduced the second point of debate consists in identifying ***the potential of technological progress*** in expanding architecture dominion beyond representation. The technique has always been double-stranded with human progress, in a broad view, since men appear in the world. The paragraph will not deepen the stages of men's development (in terms of ability, intellect and perception of the word) that occurred simultaneously with technique progression; this reflection is taken for granted. The discussion is going to focus on the strict link that manifests between the creative process and technique and, by consequence, between the introduction of new technology and the way we perceive and create artworks. The importance of the informatic revolution in architecture lies not in the mere technical creation and adoption of new tools but in the way they allow a new interpretation of reality, a new vision of the world. By citing Sacchi and Unali[72], digitalization has changed our ways of representing and radically changed our way of thinking and shaping the architectural project. Technique and science have introduced new sophisticated modalities of artefact conception and realization and new tools to indagate and discover more closely reality, a phenomenon that provoked the succession of new paradigms[73] in history (Causarano, 2017). The progression of techniques ***amplifies our effects and perception of reality*** and discloses worlds unknown. Let's think, for example, how much increased our interpretation of the world the invention of the lens and mirrors for Galileo's studies or the perspective and the use of the framework for Reinacessence painting or the contemporary digital platforms to share ideas in a globalized world; the list could last infinitely. What nourishes ambiguity toward technology perspective is its association with the decline of our century, like pollution or resources exploitation. In response to this, it is necessary to re-dimension technology at the scale of "means"; secondly, to assume a meditative[74] attitude toward science to comprehend its essence and lay a new foundation for an ***ethic grounded on the principle of responsibility and awareness of limits***. Heidegger pushed for highlighting the matter of limits because science alone can't interpret the fullness of living beings and, therefore, can't be the only form of knowledge of reality. The challenge of technology in the contemporary world can be then addressed, therefore, by assuming meditative thought able to listen and

[72] Sacchi L., Unali M., *Architettura e cultura digitale,* Skira, 2003.
[73] The term paradigm refers to Kuhn's conception in The structure of scientific revolutions, 1962.
[74] Heidegger, in Science and Medidation (1953) talked about the necessity of an alternative thinking to the scientific one and suggested "meditation" as the means trought which reaching the essence of the things.

interpret reality, an awareness of limits and ethical principle of responsibility an expansion of speculative thoughts beyond science toward social and environmental dimensions. The outcome would be a technology as a technical tool to mitigate the effects of humans on the ecosystem and a means to establish a new balance in the binomial artefact and natural world. *How to practically reach this objective?*

You are probably asking yourself ***why now*** and why it was not possible ten or even twenty years ago? Because we are in the rare moment of our history where the ***simultaneous confluence of four fields is giving us access to tools never experimented with before***[75]. The first one is computational design allowing us to design complex forms with simple code; the second one is additive manufacturing letting us produce parts by adding materials; the third is materials engineering which permits us to simulate the design behaviour of materials; and the last is synthetic biology, letting us design new biological functionality by editing DNA. At the intersection of these spheres, there is the "formula" to perform ***a new kind of architectural production*** that expresses the current philosophical and aesthetic vision correlated with ecological awareness and informatics revolution.

The "formula" to reach the merging of ecological awareness and informatic revolution comprehend both the tools cited and their intersection and a new methodological approach. The increasingly massive presence of information technology and the affirmation of new modes of production involve a profound rethinking and new types of approaches that take account of these changes by exploring an idea of architecture based exchange and complexity (Saggio, 2010). The approach avoids the Cartesian dualism of intellect/matter and human/nature to overcome the top-down design logic (typical of the deterministic machine approach) in favour of a bottom-up procedure inspired by natural processes (that start from simple relational systems between elements to create complex reality). ***Technology, in this way, can become "means[76]" that make possible the transition*** from the static conception of architecture as a static object, closed and autonomous, to an entity that favours interchange and dynamic connections. In other words, architecture must adopt a shift from an object-oriented[77] to ***a***

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[75] Reflections from Neri Oxman, Ted Talks: Design at the Intersection of Technology and Biology, see at https://www.youtube.com/watch?v=CVa_IZVzUoc&t=167s. The Mediated Matter Lab team conducts research at the intersection of computational design, digital fabrication, materials science and synthetic biology and applies that knowledge to design across disciplines, media and scales from the micro scale to the building scale.

[76] "Means" intended as something that **amplifies the cognitive and perceptive potentialities**, something that prolongs our strengths according with A. Koyré. A. Saggio, *Architettura e modernità. Dal Bauhaus alla rivoluzione informatica*, Carocci, Roma, 2010, p. 402.

[77] Avoid formalism and image-driven outputs. The matter about the foundation of a new ontology will be deepened in the next paragraphs.

relational ontology founded on societal purposes by thinking in terms of correlation, network, transformational series and working via generative scripts (Schumacher, 2011).

In performing this kind of task, scripting became not only strategic but also indispensable. Scripting massively expands traditional processes' creative and intellective potentiality by allowing the growth of much more complex relationships between form, materials, and performance in addition to favouring the integration between the activity of design and realization[78]. The computational design logic permits the employment of the matter's properties as shape generators, allowing the simulation of growing models and reproduction of the living mechanism. According to Menges, the challenge that informatic revolution poses to architecture does not lie in learning computational design techniques but in "acculturating a mode of computational design thinking" (Menges & Ahlquist, 2011). Menges expresses the concept with the term *Computation Design Thinking* to describe a design thought whose foundations are found in the confluence of various disciplines (math, philosophy, biology, informatics) to allow the radical rethought of the design process according to recent scientific progress (morphogenesis, cybernetics, systems theory and moreover). Therefore, computation is not only conceived as a toolkit but as ***a methodology that opens up to the unexpected interdisciplinary relationship between far matters and the re-foundation of the discipline on a relational ontology.***

The current paragraph has introduced some concepts and definitions related to informatics revolution and computation that were strategic in describing how they can be employed to integrate technology and ecology purposes. However, the story of parametric and computational thinking had a long and troubled path until their definition and the recognition of their legitimacy in the design debate. Hence, the next paragraph addresses a necessary degression of the parametric history to describe the stages of the design approach development and clarify its terminology.

[78] The moment of realization is integral part of the design process, for example with numerical control machines.

1.3 Thinking parametrically: the evolution of thought and applications

Technique and technology have been the crucial protagonists of the debate around informatics innovation and its integration with ecological purposes until now in the thesis narration. Instead, the current paragraph aims to clarify to the reader ***terminologies and concepts*** linked to the informatics revolution and unveil the history of its tools. The section narrates the chronological history of parametric tools in their evolving ontology, scope and design outputs. The intent is to illustrate that the parametric and computational design is the condition *sine qua non*-reaching the philosophical and aesthetic vision correlated with ecological awareness and informatics revolution.

The paragraph intends to trace the parametric thought history in the fold of architectural debate by touching on several crucial stages aimed at the parametric design formulation and its empowerment with computation. In conclusion, the section introduces the matter of parametricism as a new architectural style by questioning its legitimacy as a movement and ***addressing the debate around the emergence of a new paradigm.*** The aim is to narrate a degression concerning the evolution of parametric design in its form and definitions to describe it at its epistemological level.

Today, the parametric design seems to be the architecture's answer to contemporary, technologically empowered civilization. It is configuring, at all effects, with the dignity of a "style" that takes advantage of informatics and computational revolution. The parametric design seems to have superiority in terms of the technical functionality of the built environment much more than other architectural approaches (Schumacher, 2016). In other words, it can efficiently address the challenges imposed by the society of the Information Age. Nowadays, already it takes care of complex urban tasks at various scales, including infrastructures, such as airports and railways stations. However, the parametric design formulation passed through a long and troubled path before its complete formulation. The section describes the history of computation within architecture, starting from the pioneers that first made involuntary use of generative rules, passing by crucial precursors of modernity and, finally, approaching contemporary experimentation. It opens the door to a wide reflection on the use of parametric notation as part of the ancient architectural lineage rather than a recent phenomenon associated with digital design, as generally regarded.

1.3.1 The Parametric Design formulation

The term "parametric" seems to be coined by the architect Luigi Moretti in the **1940s** when he used the words **"Architettura Parametrica"** for the first time in design history. However, at that moment, the invention of the term and its conceptualization predated the actual use of the computational process as we currently mean it. At that time, around 1942, Moretti's research on Parametric Architecture was focused on investigating the relationship between architectural design and parametric formulas without the aid of computers (see Figure 7, Figure 8). Only about twenty years later, in **1960**, during the XII Triennale in Milan, thanks to the use of a 610 IBM computer, he exhibited the models of the parametrically designed stadium. He was the first that creates a three-dimensional architecture model using a set of parametric relationships controlled by digital computation.

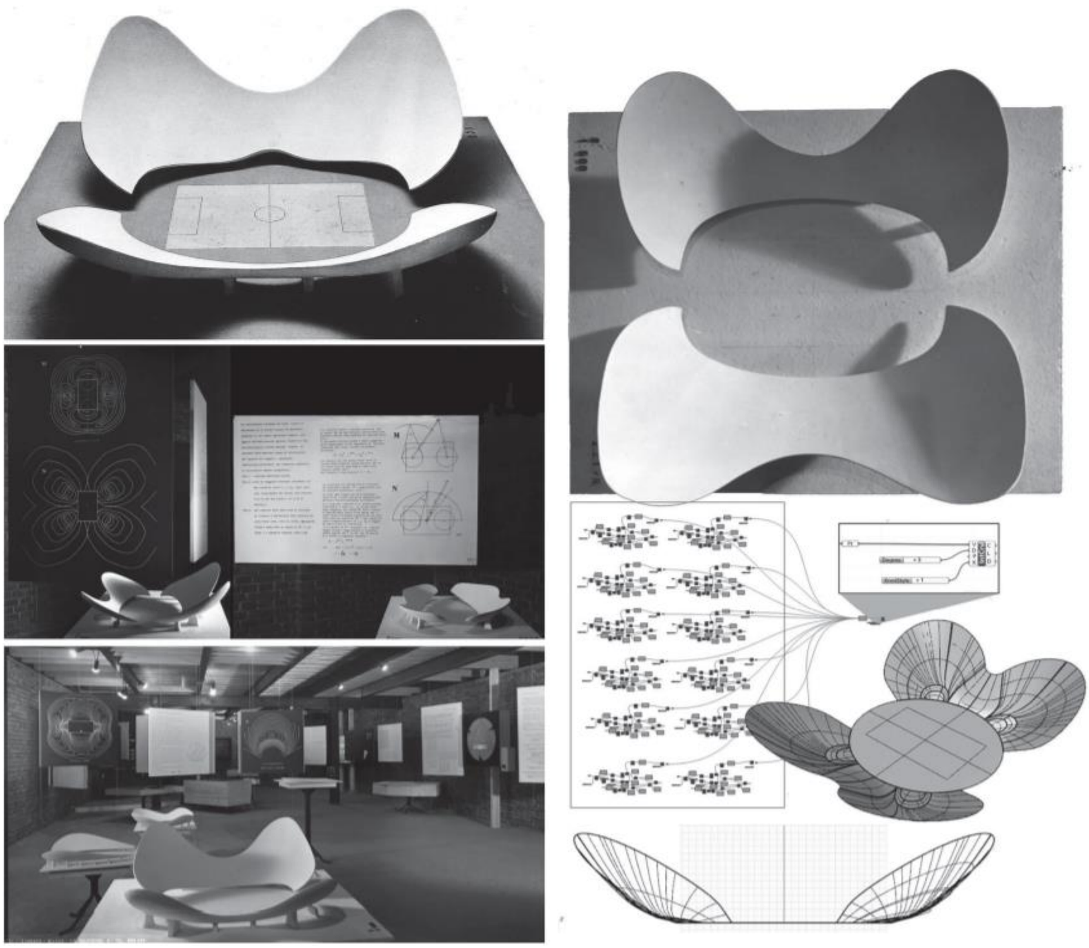

Figure 7. Luigi Moretti's model for a parametrically designed stadium. Exhibition XII Triennale di Milano, 1960. (Bianconi et al., 2019)
Figure 8. Parametric transcription of Luigi Moretti's stadium formula with visual programming technologies. (Bianconi et al., 2019)

Parametric design, as now conceived, is not fundamentally different from Moretti interpretation also if, in the 1940s, the terminology has changed. First of all, it is necessary to provide a clear explanation of what ***Parametric Design*** represents today:

"A process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response."(Jabi, 2013)

The parametric design process is an activity aimed at parametric model creation and management. Patrik Janssen tried to explain it as follows:

"an algorithm that generates models consisting of geometry and attributes and uses functions and variables, including both dependent and independent variables." (Frazer, 2016)

The definition evokes that a parametric model is a set of data organized by parameters controlled in turns by rules. Every element of the model is composed of data (e.g. diameter, height, base etc.), each organized by specific parameters or variables. Those parameters are put in a relationship by a rule. A rule can be, for example, the proportional relationships between elements. Therefore, if a parameter changes, the other parameters linked to those one change automatically by the rule. For example, considering a classical column has parameters that control the dimensions of the single elements, which are managed in turns by a proportional relationship (see Figure 9). It means that a dimension, such as a diameter, is a dependent variable, and therefore it changes automatically by the proportional rule if it is changed the variable of the height. This means that by shifting the parameters of proportional rules, we could manage the style of the elements and maybe pass from a Doric column to an Ionic or, in general, the style of a building (Frazer, 2016). By reassuming, parametric design is characterized by two key points according to Frazer description:

1. Parameters that control the relationship between geometrical elements;
2. The use of generative procedures to control the variables.

Not necessarily the use of parametric procedure has to lead toward the definition of a "style". It could be only a means by which to elaborate complex and new geometries or manipulate datasets. It was, for first, Patrik Schumacher who at the beginning of the 2000th, expressed the stylistic intentionality to found a movement grounded on parametric procedures for design. He named it "Parametricism".

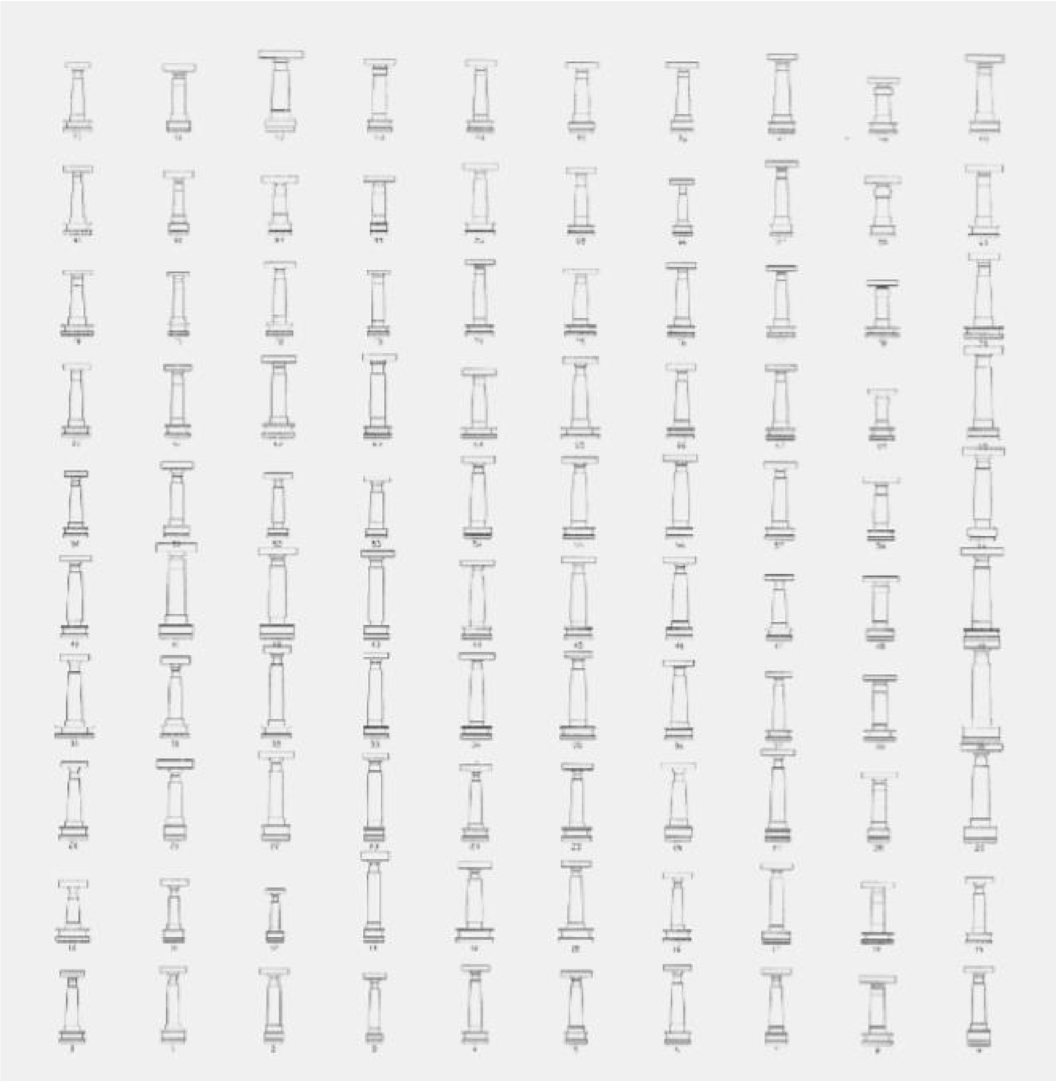

Figure 9. John Frazer and Peter Graham, the evolution of a Tuscan column using the parametric rules of James Gibbs to control the proportion and a genetic algorithm to manage the variations. Ulster University Belfast, 1990. (Frazer, 2016)

According to Mario Carpo, Digital Parametricism, as it is intended today, was introduced with the book *The Fold* in **1988** by Gilles Deleuze (Carpo, 2016). In the book, Deleuze illustrated Leibniz's differential calculus and highlighted its relationship with the parametric discourse. Deleuze explained that calculus consists of mathematical functions using:

1) variables (X, Y);
2) and parameters (a, b, c).

Using the parameters permits writing the script of a function that represents a generic geometry, for example, a generic family of curves. The equation $y= ax^2+bx+c$ represents a generic parabola. By substituting numbers for the parameters, the script notates a specific geometry. Thus, the equation $y= 2x^2+3x+4$ represents a specific parabola. He first discovered the potentiality of parametric notation: its power in generalization.

Deleuze was fascinated by the ***generality linked to parametric notation*** and experimented with the use of a general script to define a series of objects (see Figure 10). The script[79], in fact, permits the generation of a great number of variables within fixed limits. After setting a rule (for example, a mathematical function), the user should only vary parameters to obtain a great variety of objects. Deleuze's student, Bernard Cache, proceeded with his master's research and later affirmed that parametric notation suites the logic of computer-based design and fabrication. Parametric notation became the basis for creating the new non-standard technical object typical of the digital age (Carpo, 2012).

However, generalization incorporates also some hidden risks. Carpo addressed the concept of generalization[80] and its implications by highlighting the risk of describing the world through mathematical formulas. Over time, we have learned how to extrapolate generalized problems into a formal scheme, and we began to transmit reassumed and condensed interpretations of the facts observed. Theories tend to be shorter than the description (Carpo, 2017). A short script is nowadays employed to deduct many future events of the same kind. However, the extrapolation of the formulas belonging to the script is created on the basis of past experiences, not the future. Therefore, the power of prediction, and in other words, simulation, often associated with the parametric notation, is put under a critical lens in these terms.

[79] In computer science, a program or sequence of instructions that is interpreted or carried out by another program. (Treccani, 2021b)

[80] Carpo addressed the topic in the book *The second digital turn*(Carpo, 2017) in relation to the crisi of Modern science.

Figure 10. P. Jansenn and J. Frazer, A generative evolutionary design method, 2004. A set of generative rules defines a parametric space that includes a wide variety of feasible designs (Frazer, 2016).

1.3.2 From 3D model to information model

The parametric design seemed to be the suitable solution in response to contemporary civilization. It seemed to incorporate solutions for world society's momentous technological and socioeconomic empowerment. However, in the early 2000s, society was invested by the great recession provoked by a world economic crisis that implied a stagnation in investments, especially in the building sector. This event provoked hostility toward the mere **formalism** associated with parametric design because of its considerable lack of societal purposes[81]. In other words, the crisis of its legitimacy was grounded on the critical of its purely image-driven architecture (Schumacher, 2016). At that moment, the parametric design was not able to incorporate the current necessity associated with a contemporary society that was gradually moving toward Information Age. ***The parametric design had to rethink the design discipline's problems, methods, and concepts.***

Gradually the matter of formalism took a step back in favour of a matter of information. From 1970, the progress in electronic technologies, automation processes and human-computer interaction brought society directly into the Third Industrial Revolution. Mainly, this decisive step was marked by the invention and the development of ICT (Information and Communication Technologies) able to register, accumulate and transmit information for future consumption (Floridi, 2014). Managing the quantity of data produced every day gradually became strategic to ensure and promote social welfare, individual growth and social development.

At that time, architectural discourse should therefore ***incorporate the informational matter.*** That means that CAD technologies were not completely suitable for the task. They offered a spatial and geometrical representation of the design object, but the result was purely formal. Around the early **2000s**, experimentation with information incorporation led to the definition of a family of technologies known as **BIM** (Building Information Modeling). BIM technologies progressively offered a documental perspective of the design output by considering the 3D spatial dimensions and the time and financial[82] dimensions (Ferraris, 2018). In addition to the spacetime relationship, BIM can perform simulations[83] in a wide range thanks to its empowerment in information storage and manipulation.

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[81] The issue of the societal purposes related to Parametricism is going to be fully described in the next chapter *Parametricism as a style*.

[82] Today, BIM technologies offer 7 dimensions of analysis, in particular: modelling (3D), scheduling (4D); costs (5D); sustainability (6D); Facility Management (7D).

[83] Light, thermal, structural analysis and moreover.

"BIM is the term used to define the digital representation of physical and functional characteristics of an object which facilitates the exchange and interoperability of information." (BIM Open Innovation)

Specifically, the definition suggests that BIM goes beyond formal representation to include physical information (graphic and alphanumeric) related to the objects. BIM is, in fact, parametric-driven modelling that integrates a wide range of information in addition to geometrical. BIM is not software but a digital methodology that uses multiple technologies to perform analysis and simulations thanks to interoperability exchange. However, if BIM has the merit to have incorporated the information matter efficiently, the weakness of the methodology is the dangerous reduction of the building to a bundle of properties (Ferraris, 2018). BIM offers a rethink in terms of methods and problems, but there is a deficiency in the theoretical system and concepts. The risk is proposing a technical solution to a complex system of problems. BIM well interprets and solves the information management task, the redefinition of the team collaboration process, the organization of data, and the communication of results by manifesting its ability to interpret the current society needed. However, the methodological achievement should currently incorporate a new ontology grounded on societal purposes, which is the effort that parametricism sets out to address (see Figure 11).

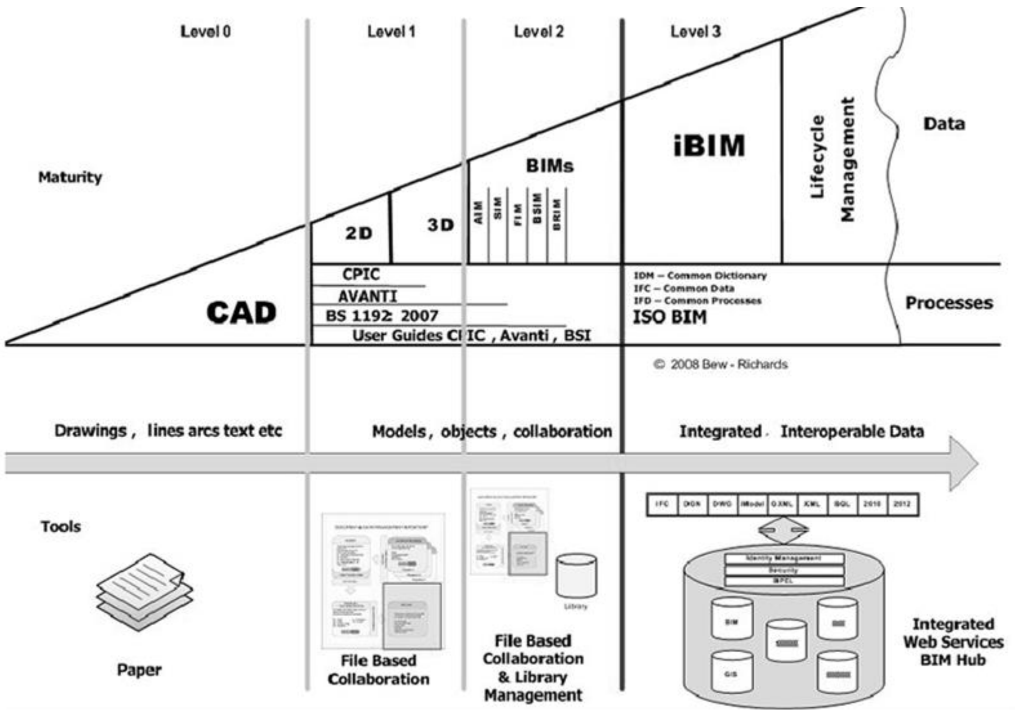

Figure 11. From CAD to BIM information maturity levels. (Tekla campus, BIM maturity levels, 2021, https://campus.tekla.com/bim-maturity-levels)

1.3.3 Empowering parametric design through computation

The interest in a kind of parametric modelling able to host information beyond geometrical input is strategic in introducing the discourse about Parametricism. That's because Parametricism formulation borrows some aspects from parametric design, such as methodological procedures and technical processes, but it added to the sum of issues related to social and environmental discourse. Parametricism, in fact, took a step beyond formalism related to parametric design to incorporate a broader range of information. To do that, it has to use great power in computation to manage a mass of big data and transform the data analysis into graphical outputs.

Therefore, more and more sophisticated parametric information modelling systems have been developed over time. That software can accurately manage 3D information for the entire project life cycle, from conceptual design, visualization and analysis to fabrication and construction. The main examples for the architectural field could be Autodesk Revit, Allplan by Nemetschek, Tekla by Trimble, Archicad by Graphisoft and Rhinoceros. That software, mainly known as **design authoring** software, has been gradually supported by **visual programming language (VPL)**, in other words, algorithmic modelling software for two main tasks:

a) The generation and control of simple and complex shapes;
b) Big data management and control.

VPL, in fact, build with parametric software a strict correlation in terms of exchange of information. Usually, VPL works as computational power and parametric software as database and visual representation. A common process could be reassumed as follow:

1) Building the 3D information model with a BIM authoring software;
2) Creating a script by VPL software to perform a certain task. For example, the creation of a complex shield;
3) Connect the VPL software to the BIM software. Automatically the script will read the data connected to the model and will perform the analysis;
4) The result in terms of graphical output or information calculation will be visible and readable directly into the BIM model.

Visual programming software essentially merges the potentiality of traditional programming with visualization. An excellent example is Dynamo[84], a plug-in for

[84] Dynamo is a VP software tailor-made for Autodesk Revit.

Revit and Grasshopper[85] for Rhino. Visual programming is any programming language that allows users to create programs by manipulating graphical elements rather than textual. VPL uses expressions, texts, symbols and elements of syntax to perform certain kinds of tasks. For example, instead of typing text bound by syntax, we connect pre-packaged nodes that contain alphanumeric parameters and formulas to create a specific geometry. The structure of VPL is built on the connection between "boxes" that control the entities and "arrows" that represent the relations (see Figure 12). In this way, ***as well as the sentence of a text,*** we build a chain of entities and relations that express a specific task. Perhaps without knowing it, we are working algorithmically - defining a step-by-step set of actions that follow a basic logic of input, processing, and output (Dynamo Primer, Guide, Autodesk 2021). In mathematical logic, an ***algorithm*** is, in fact:

"A procedure that allows, with a finite number of steps performed according to a finite set of explicit rules, to obtain the value of the function for a given argument."(Treccani, 2021a)

It is curious in this definition to focus on the similarity between text and algorithms in their structure. Both are procedures built with the logical relationship between entities and ***performed with a finite number of consequential steps controlled by rules***.

The increase in collaboration in terms of various software and various disciplines became essential for managing contemporary complex projects based on collaborative procedures. The gradual rising of collaboration and co-authorship was made possible by sharing empowered technologies. Computational tools, algorithms, and modelling software became the essential tools across the design process for architects, engineers and manufacturers. At this moment, parametric discourse is developing into "Parametricism" (Schumacher, 2009)**.** Parametricism is gradually keeping a distance from deterministic and image-driven results. It is not a software or an informatic procedure, but it is achieving the legitimacy of an architectural movement. It is based on multidisciplinarity, broad collaborative procedures and projects, and a new ontology grounded on social and environmental purposes. It is opening the doors to a new discourse on digital, as we have never heard before.

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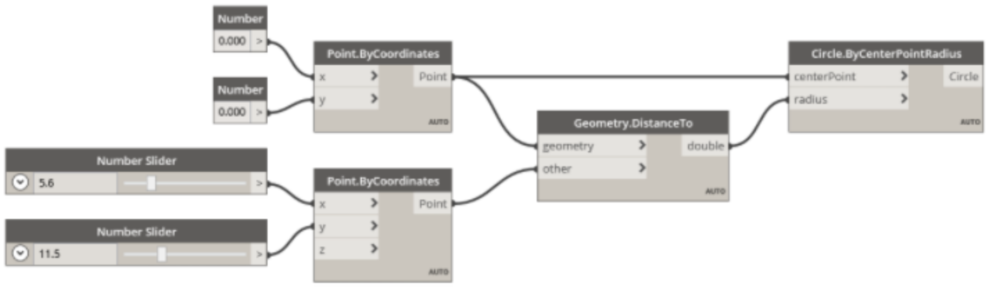
[85] Grasshopper is a VP platform developed by McNeel Associates.

Visual Program:



Textual Program:

```
myPoint = Point.ByCoordinates(0.0,0.0,0.0);
x = 5.6;
y = 11.5;
attractorPoint = Point.ByCoordinates(x,y,0.0);
dist = myPoint.DistanceTo(attractorPoint);
myCircle = Circle.ByCenterPointRadius(myPoint,dist);
```

The results of our algorithm:

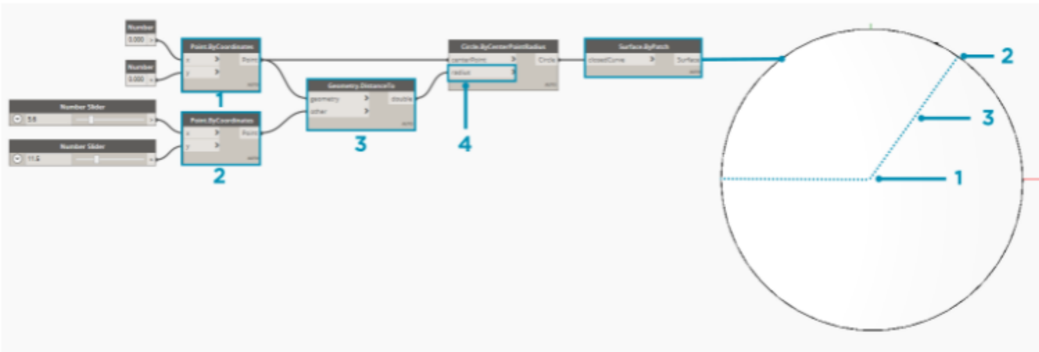


Figure 12. A comparison of the same algorithm - "draw a circle through a point" - programmed with nodes versus code from the Dynamo Prime Guide. (Autodesk, 2021).

1.3.4 Parametricism as an architectural movement

"Digitalization has not only changed our ways of representing but also radically changed our way of ***thinking*** *and* ***shaping*** *the architectural project."*(Sacchi & Unali, 2003)

The suggestive side of the citation lies in binomial thinking and shaping. On the one hand, considering "shaping", they highlight the influence of digital over the methodological approach to give form to the architectural project; on the other, with "thinking", they suggest that the change is not only in tools but is in mind. This means that digital changed the systems of values and thoughts through which we think about architecture. Consequently, digital in architecture is being won the legitimacy of a "movement" rather than a method, as commonly thought. This is happening because digital, particularly current digital parametric notation, is bringing a necessary re-theorization of the architectural discipline, a redefinition of concepts, methods and problems, and a foundation of a new ontology. The chapter intends to face the complex forces and dynamics that led to the rise of the parametric paradigm and the consequent foundation of Parametricism as a style.

The formulation of the term is very controversial and requires a deepening into contemporary society's political and social dynamics to be clarified. Since the launch of Parametricism at the 2008 Venice Architecture Biennale and further consolidation in 2009 with the article "Parametricism: A New Global Style for Architecture and Urban Design" (Schumacher, 2009), the term has gained increasing resonance in the architectural debate. Over the last thirteen years, Parametricism has been critical theorized and experimented with thanks to the activity of the main protagonist Patrik Schumacher, Partner at Zaha Hadid Architects[86] (ZHA) and the Architectural Association's Design Research Lab[87] (AADRL). The chapter intends to critically interpret the stages that led to the rising of the parametric method and show the main points that constitute the fundamental pillars of the stylistic movement. The reflection on Parametricism requires, in fact, going beyond the latest technical achievements to focus on the constituent's traits of what is turning out to be an architectural movement in all respects. Tracing the ***characteristics of a movement*** requires facing a series of constituent parts such as a *corpus* of theories and paradigms, an ontological system, a set of functions, and, eventually, a retooling of the discipline. By taking into account these premises, the chapter intends to face the dissertation by following some key stages: the transition from parametric design to

[86] https://www.zaha-hadid.com/.
[87] https://drl.aaschool.ac.uk/schumacher-studio.

Parametricism; the foundation of a tailor-made theoretical *corpus* and the passage from an object-oriented ontology to a relational one; the societal function of architecture as a frame for communication; the re-foundation of an architectural semiology; the autopoiesis concept and retooling of the discipline.

With the addition of the suffix **"ism"**, Parametricism claimed the stylistic intentionality of a movement. This means a necessary re-foundation of theories, concepts and ontology. The term formulation was a laborious task during the time due to the difficulty in defining the exact nature and perimeter of Parametricism. It has an ambivalence in its meaning since it describes(Schumacher, 2012b):

a) A recognizable **style in a visual sense**. Schumacher affirmed in 2012 that "*Parametricism is the great new style after Modernism*", it succeeds Modernism in changing the aspect of the built environment. It adopted characteristic visual factors such as *"complex and dynamic curvilinearity accentuated by a swarm-like proliferation of continuously differentiated components."* (Schumacher, 2012b)
b) A **process-driven architecture in terms of method**. Parametricism depend on the use of computational techniques and new digital tools, which plays a crucial role in building a new design methodology and process. However, Parametricism is not only a matter of techniques. It incorporates values and sensibility toward social and environmental issues that emerged even before the sophisticated computational methods available today.

Parametricism is configuring with the legitimacy of an architecture movement, distinguished from the others by its own ontology, methodology and values. Finally, Parametricism incorporates what defines **an architectural style**:

"…a coherent and comprehensive (research) programme, complete with both a functional and a formal heuristic." (Schumacher, 2012b)

The functional heuristic refers to the fact that Parametricism is defining itself as a process not only embracing technical achievements but also, and especially, incorporating environmental, political, social, cultural, practical economic, theoretical, philosophical and behavioural parameters (Burry, 2016). In this sense, we talk about **Parametricism 2.0** when we move to apply computational techniques to handle social and environmental issues.

How to manage this complexity? By employing a generative engine, selection procedure, learning algorithm and a complete design system from inception to development, optimization and resolution (see Figure 13). Architecture has lived exploratory phases, manifesting new possibilities coming to the invention and employment of computer software and computing.

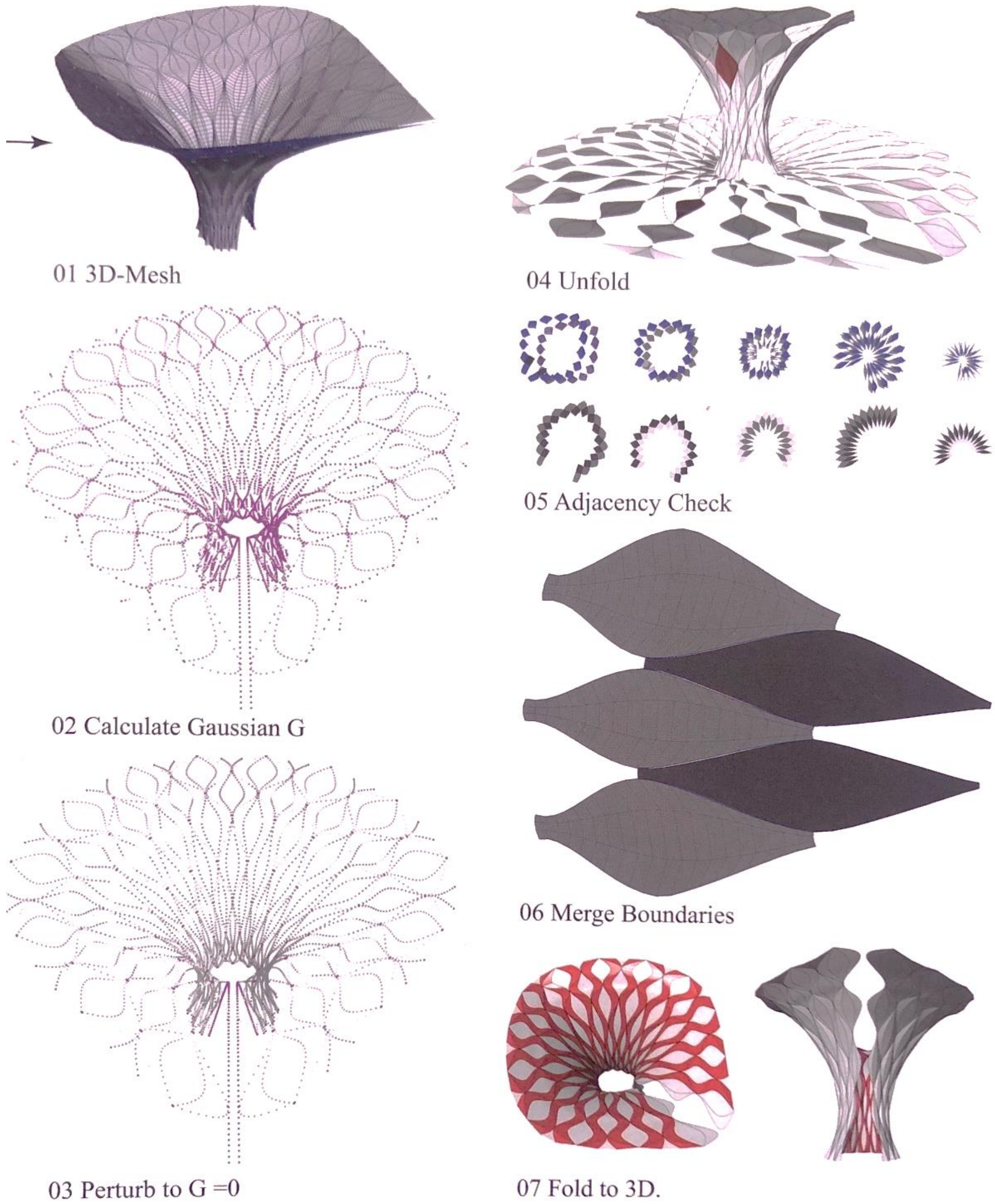


Figure 13. Zaha Hadid, Arum digital workflow, Venice Architecture Biennale, 2012.

1.3.5 The foundation of a new paradigm and the ontological innovation

Parametricism founded its fortune when architecture was finding itself in a moment of innovation due to the necessary adaptation to the socio-economic era of post-Fordism (Schumacher, 2008). Parametricism responded to the gradual rising of complexity and dynamism typical of the post-Fordist network society. In this context, the single consumption standard of the mass society evolved into a heterogeneous multiplicity. Therefore, contemporary avant-garde design finds itself in organizing the increasing complexity and layering of a society that is constantly differentiating. This tendency gradually led the architecture discipline to ***retool*** its methods on the basis of the parametric paradigm. This was made possible mainly thanks to the possibilities provided by the microelectronic components and their embedding into devices and, later, architectural parts and fabrics. Moreover, parallel to the technology progress, increased the interest in complex systems, data manipulation, self-generation, dynamic analysis and transformation scenarios that indeed inspired Parametricism. However, Parametricism faced controversial phases during its formulation. It is grounded on the concept of **"Parametric Design"**: the design process that employs variable parameters or algorithms to generate geometries or objects (Schumacher, 2016). The parametric design seems, in its definition, strictly related to methodological issues and technical processes. It is a matter of tools and methods and avoids aesthetic discourse. With the addition of the suffix "ism", parametric becomes **"Parametricism"** and consequently gains stylistic intentionality of a movement. Recognizing a new stylistics movement means though building a critical reflection on architecture, a corpus of theories, and a new ontology. Parametricism aspires to be single and recognized as the style successor of Modernism in the current era of many tendencies.

The avant-garde styles and their continuous evolution and substitution with new ones could be interpreted in ***analogy to the scientific paradigm***.

First of all, it is necessary to clarify the concept of paradigm: *it indicates universally recognized scientific achievements, which, for a time, provides a model of problems and solutions that are acceptable to those who practice a specific field of research* (Kuhn, 2009). Therefore, Kuhn's paradigm concept connects people in the scientific community that, for a certain period, possess and share a set of scientific and ethical values, criteria of judgment, problems and models to interpret issues of contemporary time. The acceptance of a paradigm by a scientific community determines what Kuhn calls "normal science", a period during which the community shares and consolidates the common values to interpret the world. However, unexpected phenomena could provoke an anomaly in the systems of values. Scientists realize that the established value system is no longer capable of responding to the current dynamic, and therefore, they find themselves having to replace the old paradigm with another. This represents the moment when a scientific revolution occurs. The world change, and consequently, the paradigms change with it. At that moment, it is needed to rethink basic concepts, methods and problems.

Such as in the scientific field, the innovation in the architecture field proceeds via the progression of the world and the systems to interpret it. In particular, styles in architecture represents cycles of innovation (Schumacher, 2008). In current times, Parametricism seems to be architecture's answer to the momentous technological and socio-economic transformation of world society brought about by the Information Age(Schumacher, 2016).

Considering architecture in the middle of a cycle of innovation characterized by adopting a new paradigm involves rethinking the problems, methods, and concepts of the design discipline. The ***adoption of a new paradigm*** is more than employing new methodologies and tools. It involves a complex process of learning, interpretation, critical analysis, and the building of new theories. It is more than changing verbs and prepositions. It involves the essence of the thing. This is the reason why the debate about Parametricism shifted from methodological issues to ontological discourse. The adoption of a new ontology means rethinking the essence of things. It means rethinking the knowledge of being, reality, and the object itself (Treccani, 2021c).

We assist with Parametricism to a necessary shift from the object-oriented ontology, typical of the first period of parametric experimentation, to a relational ontology. It was a needed redefinition because the parametric discourse lived a crisis of legitimacy at the beginning of the Century because it was often associated with the profligacy of the boom years (Schumacher, 2016). In 2008, the economic crisis and the consequent great recession led to an investment break at various levels. Therefore, in a time of economic difficulties, investing resources in formal complexity was considered outrageous. Parametric methodologies then began to attract resentment. The loss of legitimacy happened because parametric discourse was grounded on formalism, specifically on an object-oriented ontology characterized by image-driven solutions and formal principles.

To succeed, Parametricism has to keep the distance from the idea of architecture design as a juxtaposition of forms and elements that lead to a sculptural object. It must adopt a needed shift from object-oriented[88] to **relational ontology** founded on societal purposes by thinking in terms of correlations, networks, transformational series, and working via generative scripts (Schumacher, 2012a). Architecture is a matter of relations, and in other words, of communication. What architecture concretely does for us? If a building fulfils functions, mainly providing a shelter, architecture is grounded on theory-based

[88] Parametricism took distances from formalism and image-driven architectural design outputs.

academic engagement and innovative practice with future orientation (Schumacher, 2011).

The engagement of architecture lies in what Schumacher calls **the societal function.** Schumacher addresses the topic by deepening two key issues:

a) The correspondence between spatial and social evolution;
b) The framing task belongs to the built environment.

Schumacher, for first, traces the historical parallel between the spatial organization and social order. He states that the evolution of society proceeds progressively parallel with the evolution of the space where the social file takes part. The built environment shapes the social interactions and works as a frame by ordering fluxes, regulating situations, establishing positions, and more. Think, for example, of primitive societies. Let's analyze the structure of the spatial organization. We understand that the space is accurately thought to regulate interactions, help define situations, and favour or disadvantage various kinds of sharing. Consequently, the built environment shapes social and political life.

"Social order requires spatial order. […] The evolution of society goes hand in hand with the evolution of its habitat, understood as ordering frame."(Schumacher, 2012b)

By reassuming, the societal function of architecture consists of the main task: ***framing communicative interactions***. The built environment incorporates the task of framing and, in other words, organizing and facilitating social activities, communications and situations (see Figure 14, Figure 15). Architectural settings become the frame of the communicative action and establish between people and environment a stable ***broadcast.*** Architecture is, therefore, conceived as a physical ordering apparatus that separates and connects social actors and their activities(Schumacher, 2011b). In particular, the architecture incorporates two kinds of competencies:

1) Organization, aimed at regulating spatial distribution and patterns;
2) Articulation focused on comprehension and perception of the pattern and distribution cited.

In other words, the first term is related to the communication relationship between the human and space in terms of body and physical movement; the second one is in terms of sensitive experience by the human being intended as a perceiving subject. In this way, architecture's competence acquires both a phenomenological and a semiological dimension:

"The spatial order of the human habitat is both an immediate physical ordering apparatus that separates and connects social actors and their activities, and a *mnemotechnic substrate for the inscriptions of social memory."*(Schumacher, 2012b)

The built environment moves from the traditional conception of a place made by the mere assemblage of elements to embrace a much more complex definition that includes relations between people and the environment, information broadcast, data flows and permanent sharing. The built environment becomes **"semantically charged"** thanks to communicative action (Schumacher for Iris Ceramica Group, 2020) and, consequently, starts to incorporate a significant amount of embedded, accumulated information and knowledge. Schumacher describes it as follows:

"Thus emerges a semantically charged built environment that provides a differentiated system of settings that help social actors to orient themselves with respect to the different communicative situations […] So the system of social settings, as a system of distinctions and relations, uses both, the positional identification of places, that means spatial position and a morphological identification of places (ornamental marking) as props for the social communication process."(Schumacher, 2012)

In other words, the built environment became a communication interface that was navigable and information-rich (see Figure 15). Architecture acquires the task of regulating information flows and, thus, their inscription and the social memory. The outcome is a gradual configuration of a spatial-morphological system of signification (Schumacher, 2013).

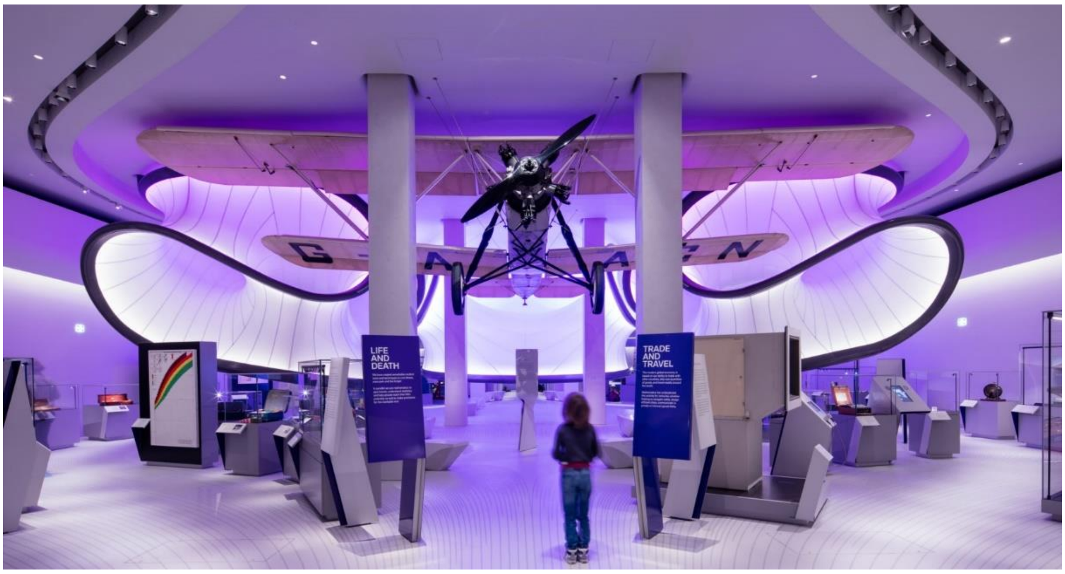


Figure 14. Zaha Hadid Architects, Mathematics: The Winton Gallery, London, 2016. The spaces were created using algorithms and design technologies. (zaha-hadid.com)

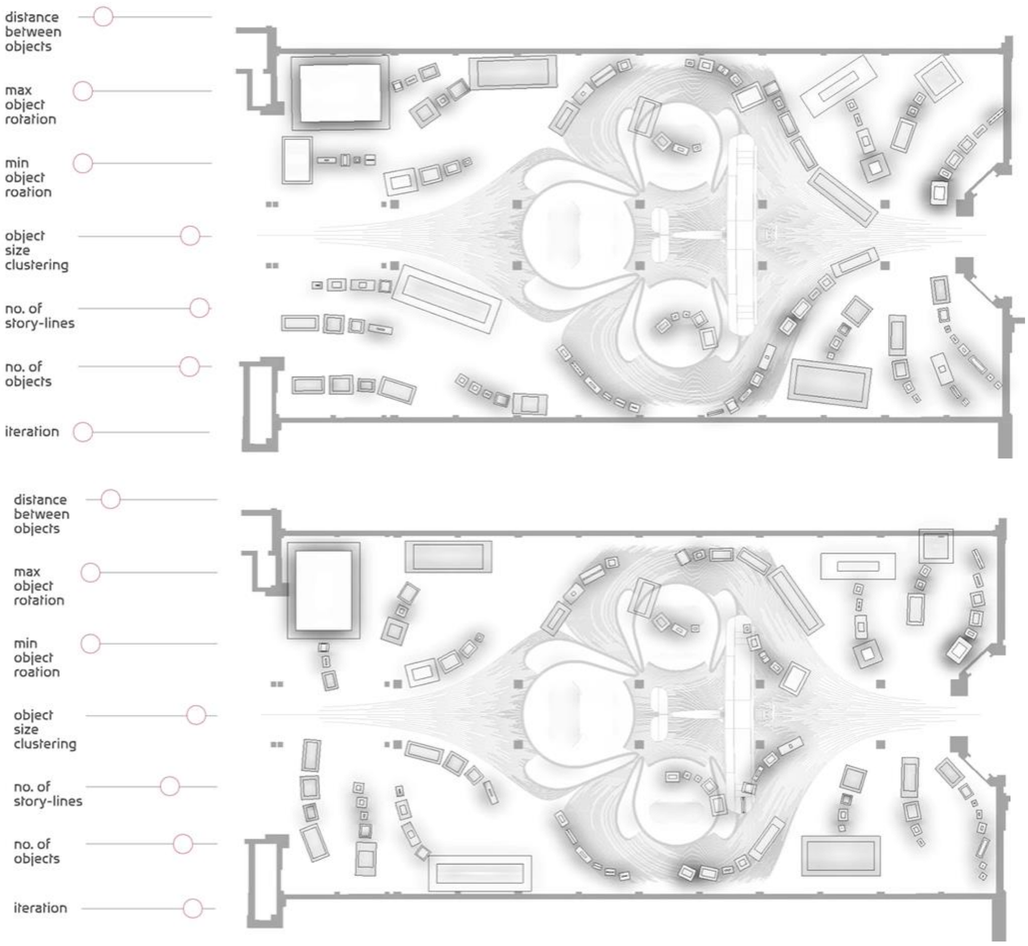


Figure 15. Zaha Hadid Architects, The Winton Gallery configuration. The images show the layout of various built environments modelled by varying parameters settings positioned at the left. (zaha-hadid.com)

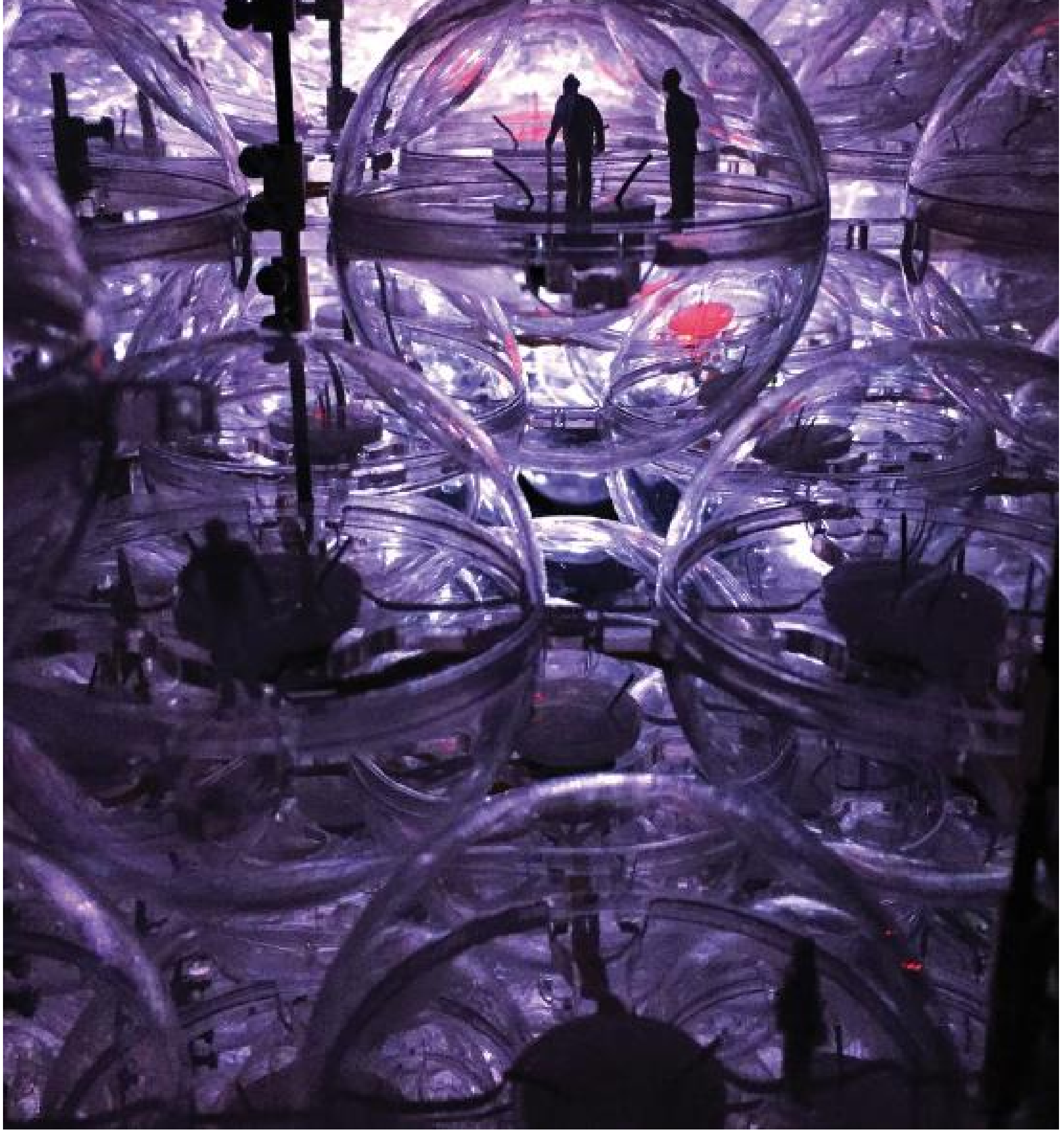


Figure 16. Minimaforms, Emotive City, 2015. The emotive city is a speculative model of a contemporary city where the fabric of the cells composing of sensitive material. The model enables emotive interactions of social scenarios to influence how the city is built. (https://exhhale.com/2016/05/23/minimaforms-emotive-city)

1.3.6 The re-tooling of the discipline

The city is gradually configuring as a complex permanent broadcast and becoming a giant information-rich communication platform constituted by unprecedented complexity. The level of complexity that the built environment has to deal with is provoked by the increasing relations, information exchange, simultaneous events, and more that characterize contemporary social life. The built environment regulates and frames communications but its also responsible for its transcription and, therefore, guardian of society's memory. Consequently, there is a broad **"embedded knowledge"**[89] accumulated within spatial frames that must be read, managed, stored, and generally navigated. The built environment to adequately respond must configure itself as an **interface of multi-modal communication** (Schumacher, 2012). In other words, as an interface for information exchange with multiple modes to perform interactions, such as the interaction between humans and computers (see Figure 17). Specifically, the reference to the multi-modal approach refers to flexible systems of interaction that allow users to interact through various input modalities, such as touching, speaking, writing, gesturing, and to receiving from the system output modalities, such as movement, graphics and more.

How is it possible to practically configure the built environment according to these premises? It is made possible by employing crowd modelling techniques via agent-based models (Schumacher, 2013). First of all, it is necessary to clarify the terms:

a. **Agent-based modelling** (ABM)[90] is a computational model to simulate the interaction of autonomous decision-making entities, called agents, to understand the **behaviour** of a system (see Figure 18). Each agent individually assesses their situation and makes decisions based on rules. Agents may execute various behaviours appropriate for the system they represent. It combines elements of gaming, sociology, evolutionary programs and moreover. In conclusion, a micro-scale model attempts to simulate and predict a certain kind of phenomenon. In these terms, we could introduce the concept of behavioural modelling.

b. Crowd modelling[91] is the process of simulating the dynamics of a large number of agents usually employed to create virtual scenes. For example, it is helpful in modelling crowd social behaviours evolve over time upon some events.

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[89] In P.Schumacher, The societal function of architecture, IOA Silver lecture, Vienna, 2011.
[90] National Academy of Science, 09/2021. https://www.pnas.org/content/99/suppl_3/7280
[91] The definition is included in the article (Zhou et al., 2010).

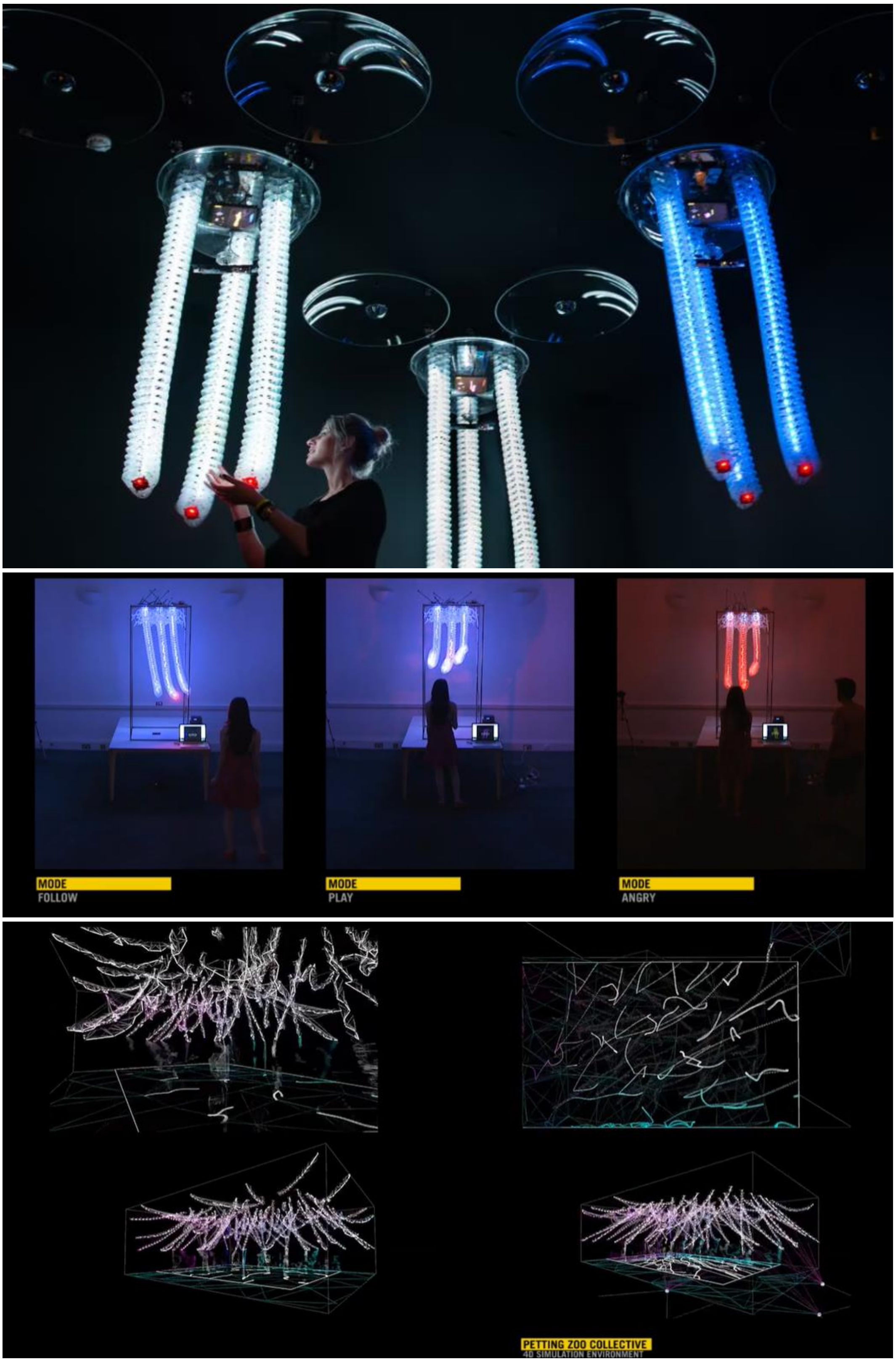

Figure 17. Minimaforms, Petting Zoo, FRAC Centre, Orléans, France 2013. Real-time augmented behavioural complexity. AI creatures learn and explore behaviours through interaction. (Spyropoulos, 2016) (https://vimeo.com/74377028)

By employing the integration of those two modelling techniques can be operationalized an agent-based crowd modelling:

"The scripting of the agents' specific behavioural dispositions, in relation to specific spatial and/or morphological features of the designed environment, allows designers to model and work on the signification relation." (Schumacher, 2013)

In some way, it represents a sort of life-process modelling that today, for the first time, can be integrated into the design speculation. The agent-based crowd modelling modulates the agent's behavioural rules depending on the morphological environment designed following a semiological code. Morphological features (colours, for example) combined with ambient conditions (lighting or temperature, for example) constitute a certain kind of ambient that can influence the behaviour of the agents (see Figure 18). At this point lies the critical factor, for the fact that an agent's behaviour can be scripted and correlated to the morphological features of the designed environment. Therefore, can be scripted the agent's answer to a specific environment clue with the intention to obtain **dynamic action-artefact networks**. The dynamic networks allow two kinds of analysis(Schumacher, 2013):

a) Simulating the social agent answer when it is subject to environmental clues due to action and interaction human/context;
b) Anticipating individual disposition and reaction into patterns of social interaction.

This approach to architectural speculation profoundly influence the discourse of semiology linked to design discourse. Schumacher affirms, in fact, that these new tools allow for the re-foundation of architectural semiology as agent-based parametric semiology[92]. However, the concept is not clearly understandable until we clarify the use of the term semiology in this context. By considering the F. de Saussure's (1857-1913) definition, semiology is:

"The study of signs in the framework of social life, as part of social and general psychology [...] It is mainly focused on the discourse about the functioning of intentional and artificial sign systems (natural-historical languages, road signs, maritime signals, the Morse alphabet, etc.), including in

[92] See P. Schumacher, *Parametric Semiology – The design of information rich environments*, published in *Architecture in Formation*, Taylor and Francis, New York, 2013.

the context of social life (e.g., object systems of use, such as fashion, cars, etc.).”(Treccani, 2021)

Figure 18. Theverymany, Labrys Frisae, Art Basel, Miami, 2011. Studio for Art, Architecture and Computation. Parallel computing and multi-agents based systems allow an understanding of the surface. (https://theverymany.com/constructs/11-art-basel-miami)

The semiology definition suggests that signs constitute a system of signification that regulates social life. We are completely immersed in a system of coding to which we assign meaning and signification. In this context, we will not focus on the various assumptions of semiology, but it is enough to consider it in relation to the architectural discourse. The design project has the scope to systematize all the environmental correlations, concerning form/function, into a coherent and recognizable system of signification (see Figure 19, Figure 20). In other words, a design project has the aim to create a semiological project. However, what about this semiological project assembled via programmed social agents and coded morphological clues? The answer is a parametric semiological project. Schumacher describes it as follows:

"This system of signification works if the programmed social agents consistently respond [...] to the articulated environmental configuration. However, rather than modelling scenarios frame by frame, agent-based modelling works by defining the agents' behavioural dispositions and biases relative to environmental features. The event itself then becomes an emergent global pattern resulting from the local interactions of agents with each other inside the environment."(Schumacher, 2013)

If this succeeds, architecture firmly maintains its social function by framing social events and scenarios. Under this lens, parametric design can be employed given articulating increasing complexity in social processes. The task of Parametricism can be achieved only through techniques like:

a) **Scripting**, with *Phyton*;
b) **Digital fabrication** for large scale physical assemblage;
c) **Advanced 3D parametric modelling**, for example, combining information modelling with visual programming such as *Revit* with *Dynamo* and *Rhinoceros* with *Grasshopper*;
d) **Behavioural modelling**, for example, with software such *as Processing or MiArmy* and *AI.implant* (plugins for Maya), and *Massive*.
e) **Rendering and image-making.**

To achieve a design solution that responds to the necessities expressed by Parametricism is necessary to open the practice to multidisciplinary. It is intended regarding both the tools cited that must be combined over the entire design process and concerning various subjects. The design project is, in fact, gradually configuring as a wave of relational knowledge at a crossroads between architecture, ecology, material science, information technologies and more.

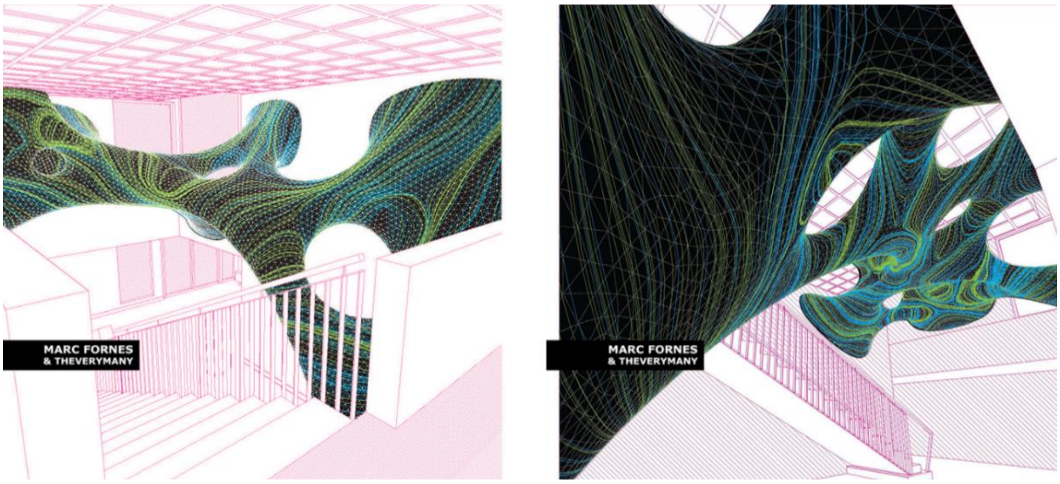

Figure 19. Theverymany, Under Stress, Inra Institute, Rennes, 2014. A simulation model with advanced 3D modelling and parametric computation.

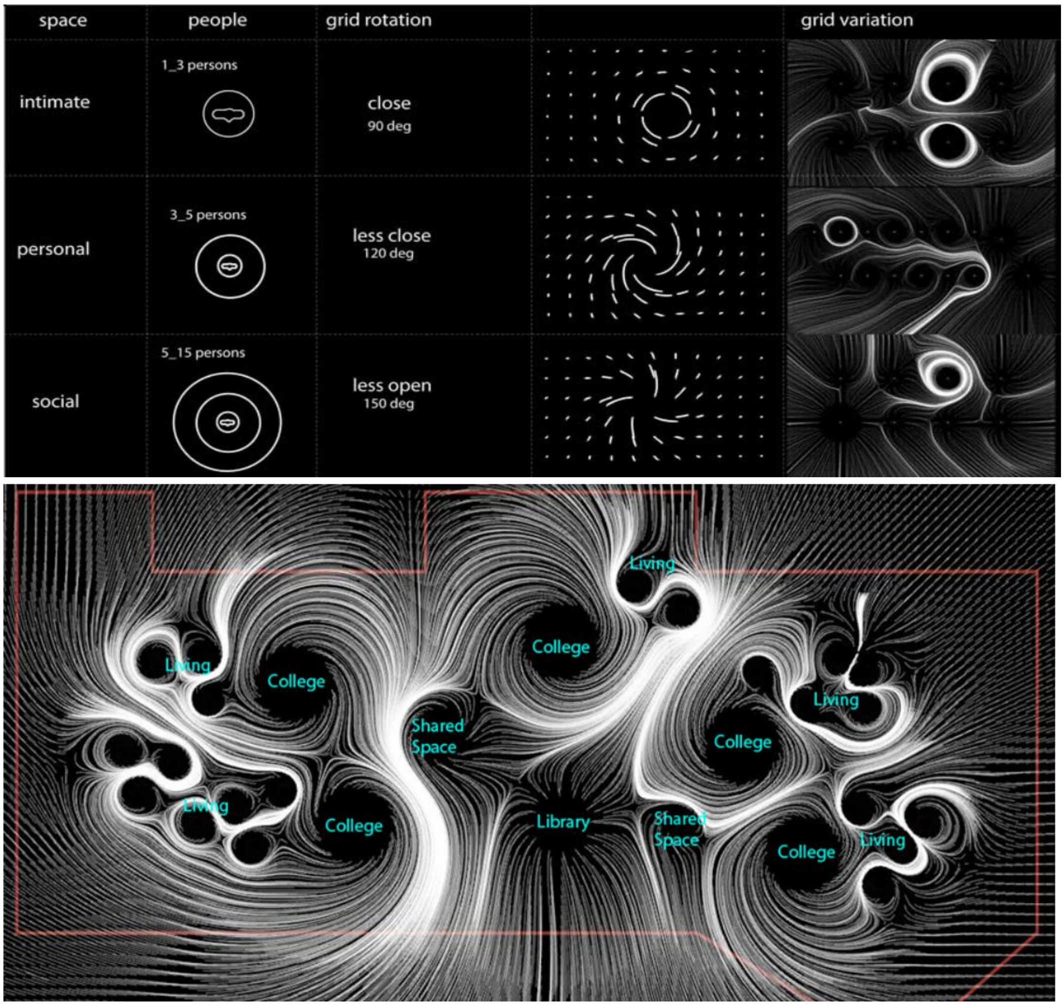

Figure 20. P. Schumacher, *Semio-field*. Differentiation of public vs private as parametric range and masterplan with program distribution. (Schumacher, 2013)

The chapter narration was useful to clarify to the reader terminologies and concepts linked to the informatics revolution and unveil the history of its tools. The section narrated the chronological history of parametric tools in their evolving ontology, scope and design outputs. The intent is to illustrate that the parametric and computational design is the condition *sine qua non*-reaching the philosophical and aesthetic vision correlated with ecological awareness and informatics revolution.

Reaching a new kind of philosophical and aesthetical vision in architecture able to be the interpreter and the medium of the changes in nature and the flow of communication requires the use of advanced technological and digital systems. The revolution in the architectural paradigm and its ontology goes hand in hand with the informatics and digital revolution. Digital procedures, such as parametric design and computation, amplify the potentiality of the design project to store, manage and elaborate flux of information in the form of data. The parametric and computational design merges to provide *a process based on algorithmic thinking that enables the expression of parameters and rules that define, encode, and clarify the relationship between design intent and design response* (Jabi, 2013). The parametric model stores information in the form of data and is empowered by algorithm calculation potential that allows data combination and manipulation[93]. In this way, they can simulate the dynamics similar to a living organism, a process of genesis characterized by dynamism and evolution[94].

With this in mind, the research moves toward ***dynamic investigation methodologies and models able to merge parametric and computational design potential***. Paragraph *2.2 Introducing the proposa*l will merge the theoretical background and implications described in *Chapter 1* and *Chapter 2* to illustrate the object of the proposal.

[93] Further details will be illustrated in *Chapter 1* and *Chapter 4*.
[94] They can be supported by several and multiple digital technologies like crowd modelling, agent-based modelling. See *Chapter 1* for further details.

Chapter 2.

Interpreting implications as a design matter

The chapter belongs to the *Theoretical background and implications part* that contextualizes the work's background and the starting research implications. The current chapter, together with the previous one dedicated to the theoretical recognition of ecology and digital technologies intersection, is instrumental in introducing the research proposal definition. The two chapters' combination constitutes the background where the research proposal is grounded and shaped by its objectives and operative strategy.

The current chapter represents the ***bridge*** connecting theoretical recognition to the operative side. In fact, it adopts a leap of scale and embodies a complementary task with respect to the previous one. It shifts from a theoretical and bibliographical recognition to jumping into the determined ***set of research implications*** underlying the thesis proposal in its practical contribution: devising a tool for planning decisions to test the effectiveness of information related-tech in contributing to the ecological debate.

Addressing this task implies moving from theoretical premises toward practical exploration. However, the tool requisites, limits of actions, input and output required a detailed study and wide deepening in the net of multidisciplinary issues related to the contemporary city dynamics. The tool shaping was not casual but determined by ***particular and precise forces*** that guided the operative design choices' in terms of motivations, tools, and data to consider.

In the first instance, the chapter identifies the ***fixed prerequisite*** of the research path, which were the constraints imposed at the beginning of the research activity. It later illustrates the ***multidisciplinary net of variable implications*** that have to be addressed to reach the tool definition in its purpose.

In conclusion, the chapter describes the research operative proposal as the result of the converges between multidisciplinary driving forces and digital technology choices.

2.1 The research implications: matters and tools

By taking into account the previous chapter, it is possible to assume that an ecological matter is not only enclosure in the environmental debate, but it is part of a net of implications widely expanded over its domain of interest. Working on an ecological target implies considering a wave of multidisciplinary relationships. *How to practically investigate the devising of a tool aimed at testing information-related technologies in the fold of ecological awareness?* The current chapter tries to exemplify the implications considered in the thesis and narrate the path that led to the operative proposal.

Working and deepening some topics was absolutely not a case, but every matter taken into consideration was part of a broader set of implications. Some of the implications could be defined as "fixed" because they were prerequisites established at the beginning of the research path; others were "variable", meaning they were selected and chosen during the research path to fix the scope better.

"Fixed" The thesis had some prerequisites. It has to be developed in the fold of an ***Academy-Industry collaboration model***[95]. The Industry selected two main UNSDg, especially 11 (sustainable communities) and 13 (climate action), underlying the research proposal. The prerequisite was employing:

a. ***BIM*** methodologies
b. focusing on construction ***materials*** and related ***carbon emissions***.

"Variable" The variable implications resulted from the definition of the research **gap**[96] and the toolkit to address it. They were shaped during the research path meetings and validations sessions between Academia and Industry:

1. Employing integration between ***parametric and computational design***
2. Including ***Embodied Carbon*** and ***Embodied Energy impact scenarios***
3. Focusing on the ***conceptual design stage***
4. Run a ***micro-scale*** simulation for a residential case study

From the integration between theoretical background with fixed implications and the variable ones came out the purpose of employing a ***research-based approach*** to develop a ***digital tool*** and test its performance in action.

[95] Read *Introduction* for preliminary information.
[96] The research gap will be described in *Chapter 3. Building the playground.*

2.1.1 A wave of environmental and social issues

Moving from the theoretical plan to the operative one implies considering specific problems and implications that are inextricably connected in a net of relationships. The paragraph intends to justify the strict and hidden connection between the implications taken into consideration to provide a clear overview of the choices made for the tool devising. The list of implications counts some punctual problems and their relationship with unexpected factors to be highlighted and considered. That's why parametric design, computation, and BIM procedures find a better place for application here. The thesis tries to keep together a complex net of ramifications and provide a tool to trigger a transformation in traditional procedures. The list of the main implications underlying the research operative proposal is here presented:

- $C0_2$, why it matters
- Why consider Embodied Carbon
- Increasing in demography
- The strategic focus on materials
- UN actions: the UNSDg

CO_2, why it matters

The discourse around implications is here addressed by considering the most influencing factor in the climate change challenge: CO_2 emissions. According to United Nations Development Goals (UNSDg)[97], 2010-2019 was the warmest decade ever recorded. It was the theatre of wildfires, droughts, hurricanes, floods and other climate disasters across continents (ONU, 2015). However, climate change consequences are not limited to environmental issues but influences lives, human development and national economies. To restrict global warming to 1.5 C, as called for in the Paris Agreement[98] (adopted in 2015), greenhouse gas emissions must begin falling by 7.6 % each year starting in 2020. In particular, the Agreement aims to strengthen the global response by keeping a global temperature rise below 2 degrees Celsius above pre-industrial levels. The interesting point is that to reach this target, the Agreement suggests some practical actions:

1. appropriate financial flows;
2. a new **technology framework**;
3. an enhanced capacity-building framework.

[97] In particular, Goal 13: Take urgent actions to combat climate change and its impacts. https://www.un.org/sustainabledevelopment/climate-change/
[98] Paris Agreement 2015 https://www.un.org/en/climatechange/paris-agreement

At this point, it is interesting to highlight that technology plays a crucial role in advantaging the reaching of carbon emissions reduction.

The UNSDg urgent actions are grounded on the environmental data collection in the last decades. Over the past century and a half, global temperatures have risen by almost one and a half degrees (see Figure 21). The graph shows the trend of global temperatures over the last 140 years, where the vertical axis (degrees centigrade) is centred on the average value of the time series. According to the graph, ten warmest years have occurred since 2005, with the six warmest years being the six most recent years.

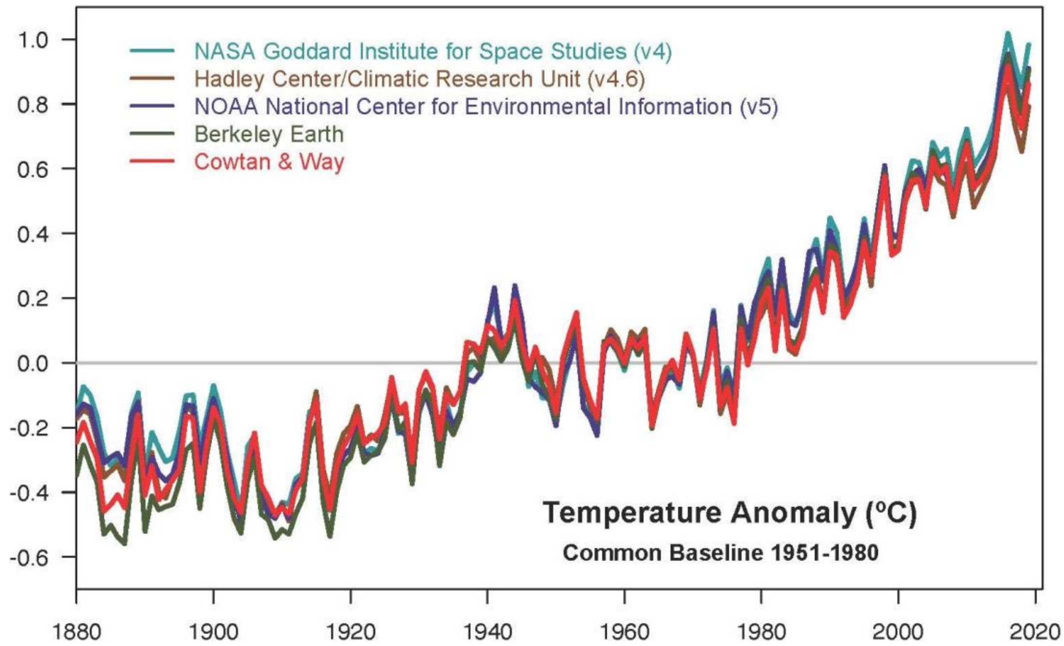

Figure 21. Increasing in temperature by NASA[99].

If the above graph is compared with the one related to the concentration of CO_2 in the atmosphere (see Figure 22), measured in parts per million (ppt), it is possible to notice the same increase in the last decades. The graph shows the atmospheric carbon concentration (registered from burning fossil fuels and cement production) that since the Industrial Revolution started to grow constantly, peaking nowadays. The data collected are enough evidence to prove that carbon rising is strictly connected to human activity.

[99] Charts from NASA Goddard Institute for Space Studies. Courtesy of Dr. Berardino D'Amico, Edinburgh Napier.

Suppose scientists calculated that 2050 is the time horizon beyond which global emissions must reach zero (see the red line in Figure 22) to avoid overheating above 1.5C. In that case, it is not difficult to understand how ambitious this task is.

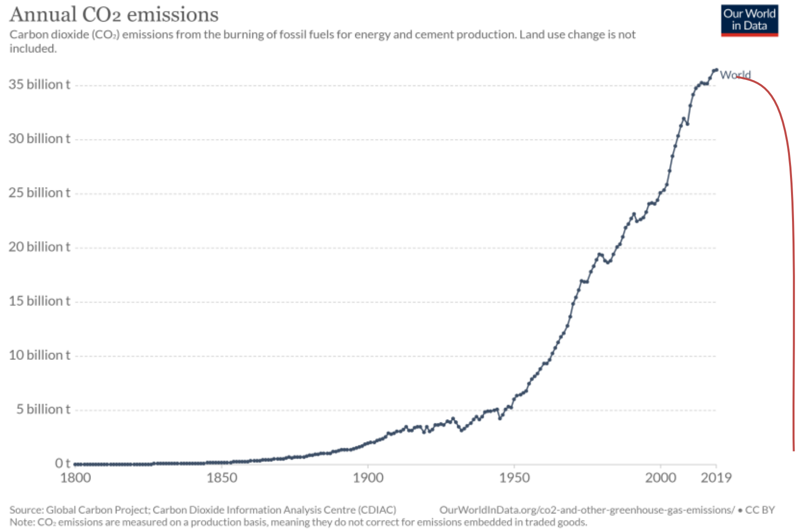

Figure 22. Annual carbon emission, Global Carbon Project[100].

By taking different sources into account, it is a data collection from the Mauna Loi Observatory concerning CO2 (see Figure 23).

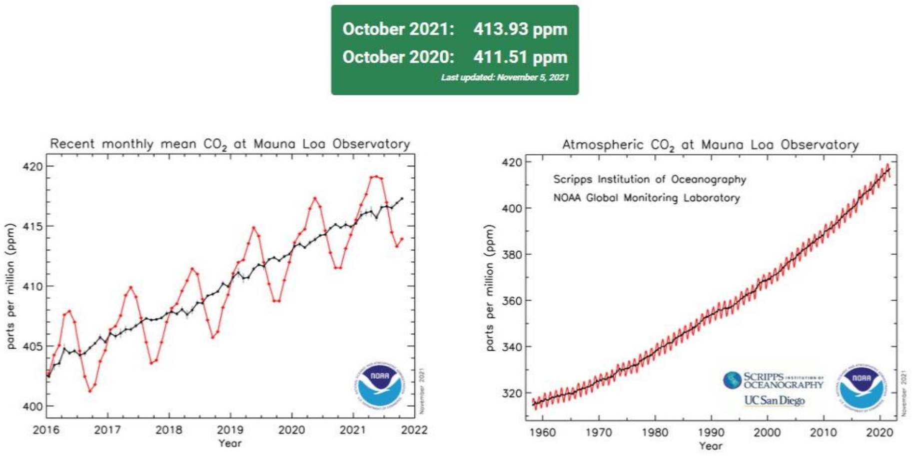

Figure 23. Mauna Loi Observatory, monthly average CO2.

By analyzing the table on the right, it is possible to notice the increasing carbon line defined as "the baseball bat". The data report the same trend as the

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[100] Source: Global Carbon Project. Courtesy of Dr. Berardino D'Amico, Edinburgh Napier.

previous graph by focusing on 1960 to nowadays. The chart strengthens the idea that:

a. The mitigation measures that were undertaken until today did not show significant effectiveness in reducing CO2 amount in the atmosphere.
b. It is necessary to employ the most robust solution to reach the 2050 target of zero-emission target.

The European Commission adopted several legislative proposals in 2000 to achieve greenhouse gas emissions. The recommendations intend to reach climate neutrality in the EU by 2050, including a 55% net reduction in emissions by 2030[101]. Among the various actions, one of the most important is represented by the **European Emission Trading System** (ETS Directive 2003/87), which imposes a greenhouse gas emissions authorization on the emitting plants. Each authorized plant must annually offset its emissions with quotas that can be bought and sold by the individual operators[102]. The chart[103] (see Figure 24) shows the historical emissions (tons CO_2 eq) from 2005 to 2020 for all of the countries. It is clear that the system is efficient because it has to be employed the most robust actions to achieve the near carbon neutrality target.

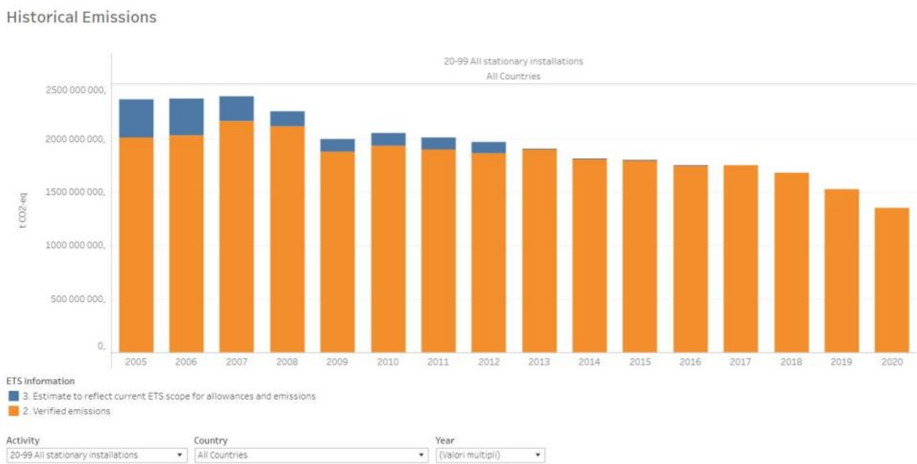

Figure 24. Historical emissions from 2005-2020 (EEA, 2022).

[101] European Commission: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/emissions-cap-and-allowances_it
[102] EU ETS: https://www.mise.gov.it/index.php/it/energia/sostenibilita/gas-effetto-serra/sistema-europeo-per-lo-scambio-di-emissioni-eu-ets
[103] EEA, 2022: https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1

Why consider Embodied Carbon

Embodied Carbon

Considering these premises raises a question, what is the problem with buildings? In which grade do buildings influence these statistics?

Building environment strongly contributes to the global energy demand for an amount that is almost 30%[104] and to the emission linked to the use of that energy (for example, heating, cooling, lighting etc.). The charts show that **30%** of global energy demand for running buildings is responsible for **28%** of global GHG emissions (consider light blue portions, see Figure 25):

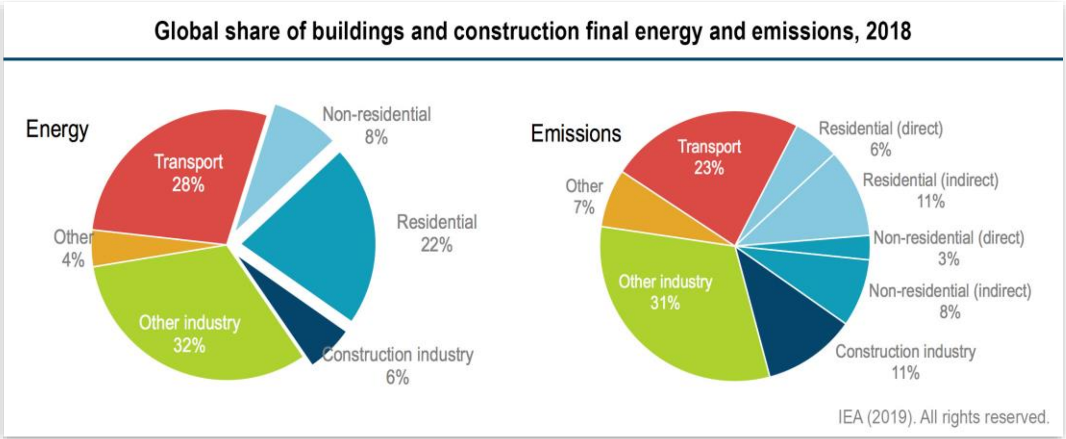

Figure 25. Global energy and emissions for buildings. (EIA, 2019)

In terms of global energy demand and related emissions of the buildings (light blue portions), the calculation reported above does not take into account the emissions related to Embodied Carbon contribution. The portion related to EC is that one in dark blue, precisely the **6%** of the global energy demand of the construction industry is responsible for **11%** of global emissions (see Figure 25). These data suggest that EC energy and related emissions are among the most influencing factors in the global carbon balance.

First of all, it is necessary to define what EC is and its contribution to the Whole Life Carbon (WLC). In this context, the studies conducted by London Energy Transformation Initiative (*LETI, Embodied Carbon Primer, 2021*) represent a great contribution to the debate.

Whole Life Carbon emissions are the sum total of all asset-related GHG emissions and removals, both operational and embodied over the life cycle of an asset, including its disposal[105] (A1- A5; B1-B7; C1-C4) (see Figure 26).

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[104] EIA, 2019, Annual Energy outlook, https://www.eia.gov/outlooks/aeo/

[105] London Energy Transformation Initiative (LETI), 2021. https://www.leti.london/ec-workstream

Overall Whole Life Carbon asset performance includes separately reporting the potential benefit from future energy recovery, reuse, and recycling (D) (see Figure 26):

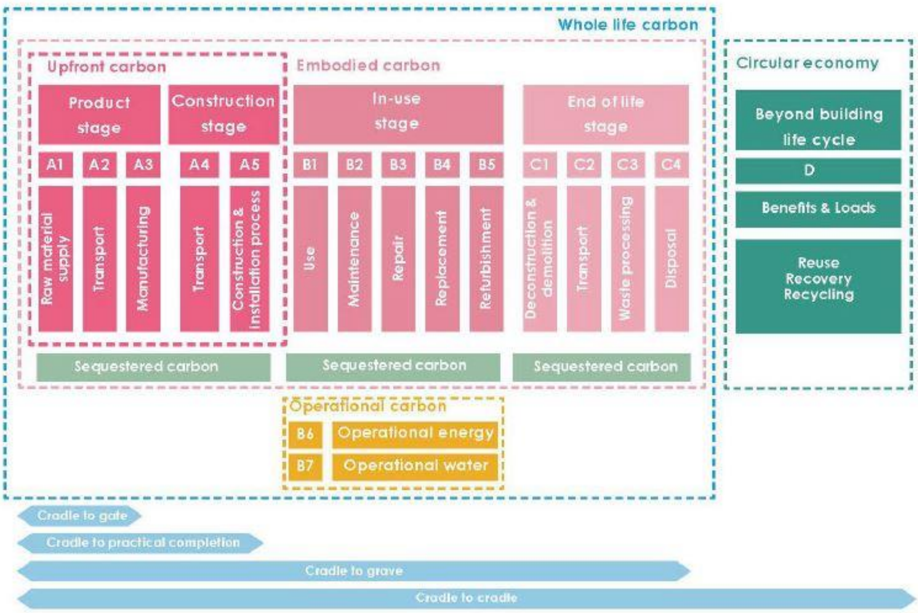

Figure 26. Life cycle stages are defined by BS EN 15978:2011.

Therefore, the whole life carbon of a building is formed by two main components, the Operational Carbon and the Embodied Carbon (see Figure 27):

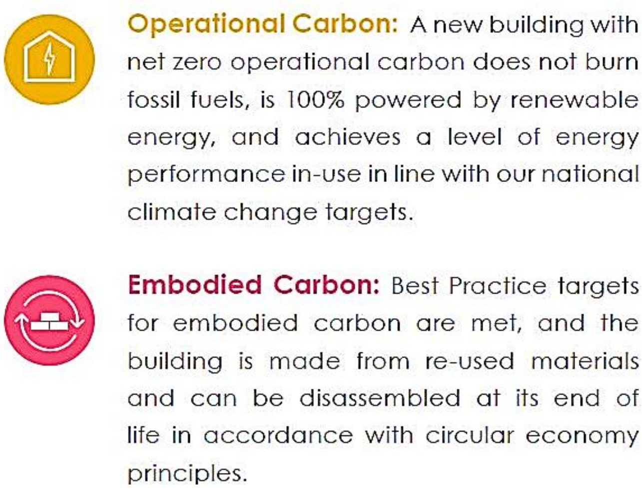

Figure 27. Operational vs Embodied (LETI, 2021).

In particular, the Embodied Carbon emissions are the GHG emissions and removals associated with materials and construction processes throughout the whole life cycle of an asset (Modules A1-A5, B1-B5, C1-C4) (see Figure 26). In other words, it is related to the phases listed below (see Figure 28):

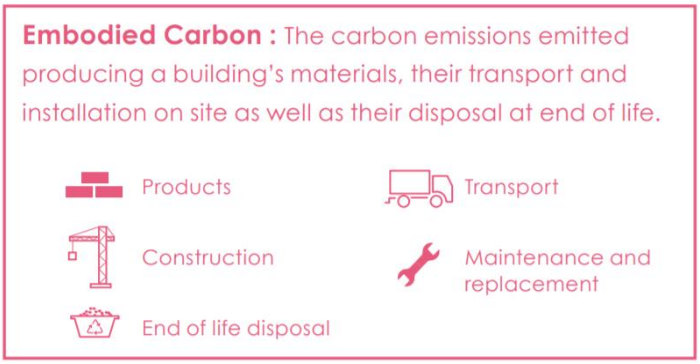

Figure 28. Embodied Carbon phases (LETI, 2021).

The circular diagram reported below, which is structured by the BS EN 15978 life cycle stages, aims to emphasize (see Figure 29):

a) The integration between the predesign period (light grey) with the other phases;
b) the opportunities available to reduce the upfront carbon emissions associated with Life Cycle Stages A1-A5.

The diagram underlines that the pre-design phase (light grey) is strategic, not only in "closing the circle" in terms of materials used but also in becoming the main strategic phase in which adopting sustainable solutions.

Today, sustainable analysis is made in the late design stage, like the development phase, where the influence on design changes is low, and the costs for changes are very high. A change in consolidated processes has to be carried out and anticipate choices and solutions in the decision-making phase (see Figure 30).

The figure below integrates LETI suggestions with RIBA (*RIBA, Plan of Work, 2020*, s.d.) to show the efficient integration of EC analysis in the early design stages. The diagram suggests anticipating decisions and target choices together with the actor of the process (designer, client, etc.) since the strategic definition of the project is to maximize opportunities in terms of low carbon design. The peculiarity is that this guide is thought for designers, not for specialists, and therefore it pushes for bottom-up initiatives in carrying out sustainable procedures.

In the next paragraph, we will deepen other aspects that consider EC as strategic for contemporaneity.

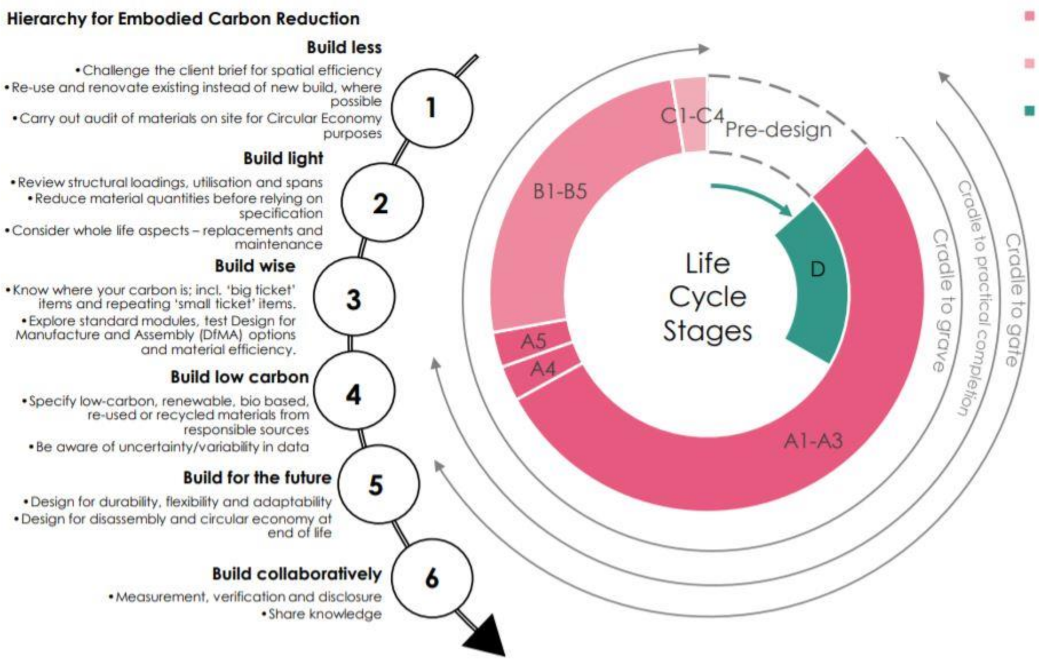

Figure 29. Life Cycle Embodied Carbon emissions (LETI, 2021).

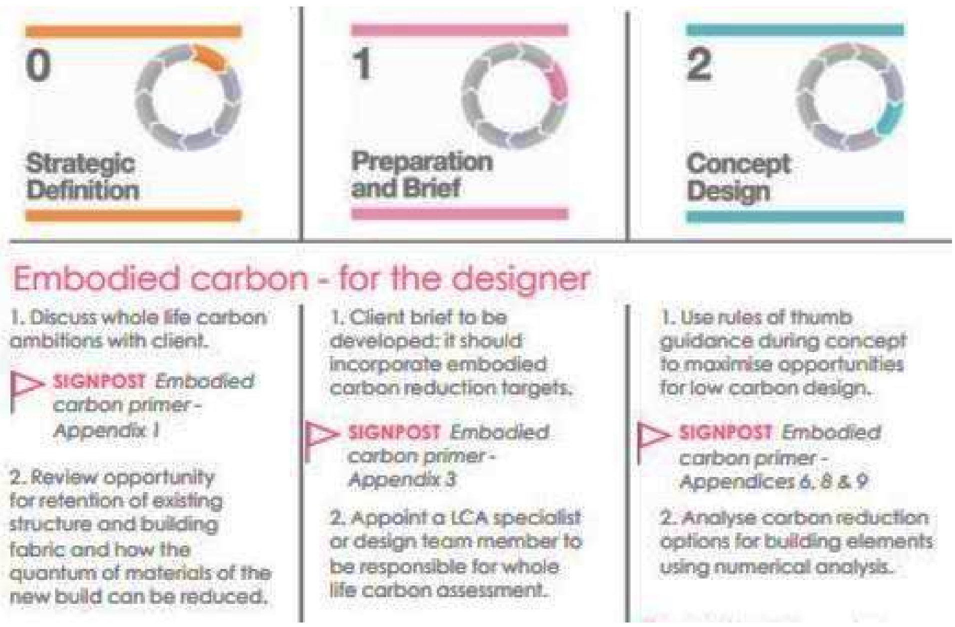

Figure 30. EC integration in the early stage of design (LETI, 2021).

Increasing in demography

The increase in demography is one of the most influential factors to keep into account when we talk about future investments in the building sector. From UN prospect[106] (see Figure 31), it is estimated that the growth in population will be around 8.2 billion people in 2025 and approximately 10 billion in 2050.

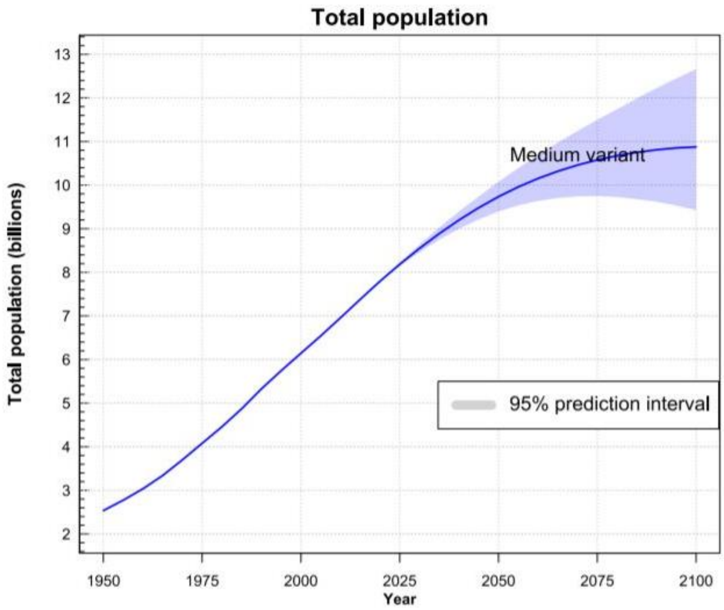

Figure 31. World population prospect.

Reaching such an exponential increase in demography means responding to a housing demand without precedents. In the following decades, it is going to be necessary to welcome the request for habitation with the consequent increase of new floor area. The refurbishment tendency for buildings will be insufficient to respond to the increasing housing demand. The new floor area parameter is strategic in considering the building sector energy use and global emissions because it goes hand in hand with the increase in population, around 2.5% per year since 2010[107] (see Figure 32).

[106] UN Department of Economic and Social Affairs, polulation dynamics https://population.un.org/wpp/Graphs/DemographicProfiles/Line/900

[107] IEA, World Energy Statistics Balances, 2019, www.iea.org/statistics, www.iea.org/buildings.

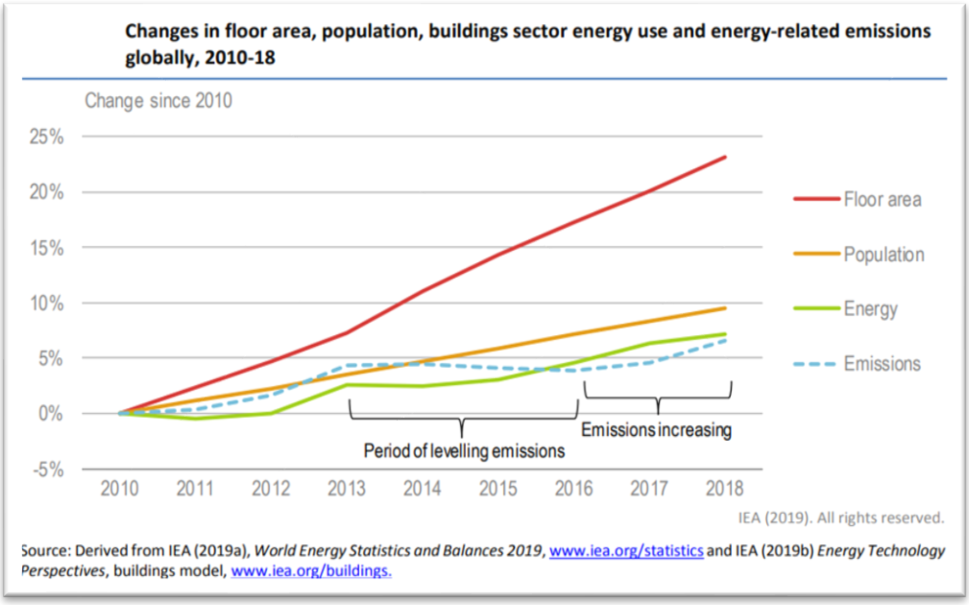

Figure 32. Changes in the floor are and population (IEA, 2019).

The other parameters, such as the energy demand (light green) and emissions (light blue) (see Figure 32), are provoked by the rise in floor area. In other words, the increase in buildings number is mainly due to the growth in population and improved living standards.

Moreover, the increasing trend in new construction justifies an early calculation of Embodied Carbon and Embodied Energy and pushes for sustainable scenarios during the preliminary design phases (see Figure 30).

The strategic focus on materials

By taking into account the premises narrated in the previous paragraphs, the issue of achieving net-zero emission by 2050 suggested by the Paris Agreement (UN, 2015) is almost impossible by only considering the improvement in the energy efficiency of buildings. The emissions also related to EC have to be eliminated or drastically reduced due to their influence on 11% of the global emissions (see Figure 25). *How to reach that?*

Working on materials decision-making processes could be an efficient possibility. As is suggested by the graphic, the most challenging emissions to eliminate comprehend the ones related to cement (4%) and iron and steel (5%), in total the 9% of the global emissions (see Figure 33)[108]. This high rate is provoked by the direct result of chemical reactions that take place during the transformation phase of raw materials for such materials.

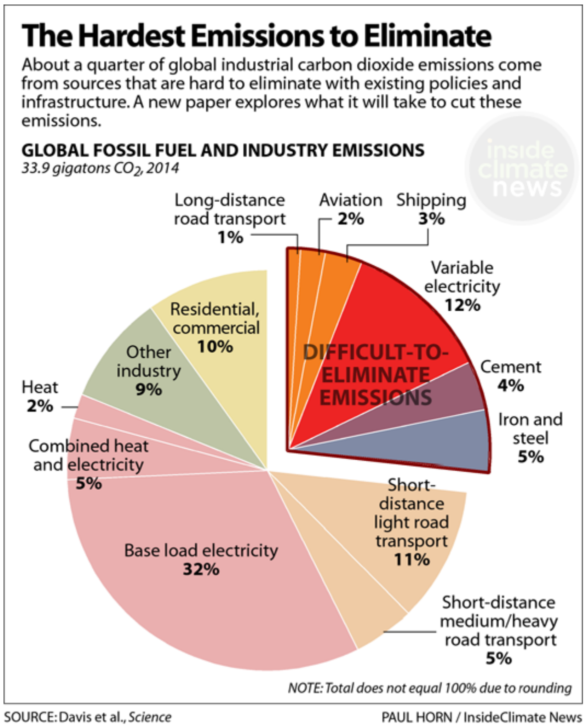

Figure 33. The most complex emissions to eliminate.

Assuming that the global energy production will be converted in future by "green" solutions (such as solar, aeolian etc.), the emissions related to building materials production would still be challenging to reduce. The hypothesis could be employing **tools for decision-making in the concept stage** able to configure suitable solutions for emissions reduction.

Materials choice, in fact, plays a crucial phase in contributing to sustainable scenarios. The strategy could be to replace the high-carbon materials with **low-carbon** ones. Here is attached a diagram (see Figure 34) from the Inventory of Carbon and Energy Database (ICE)[109] that reports the impacts of several materials in terms of $KgCO_2$ per unit. The figure suggests that a sharp material choice from the strategic to the concept design stage can make a considerable difference for our planet.

[108] Courtesy of Courtesy of Dr. Berardino D'Amico, Edinburgh Napier.
[109] The ICE Database https://circularecology.com/embodied-carbon-footprint-database.html

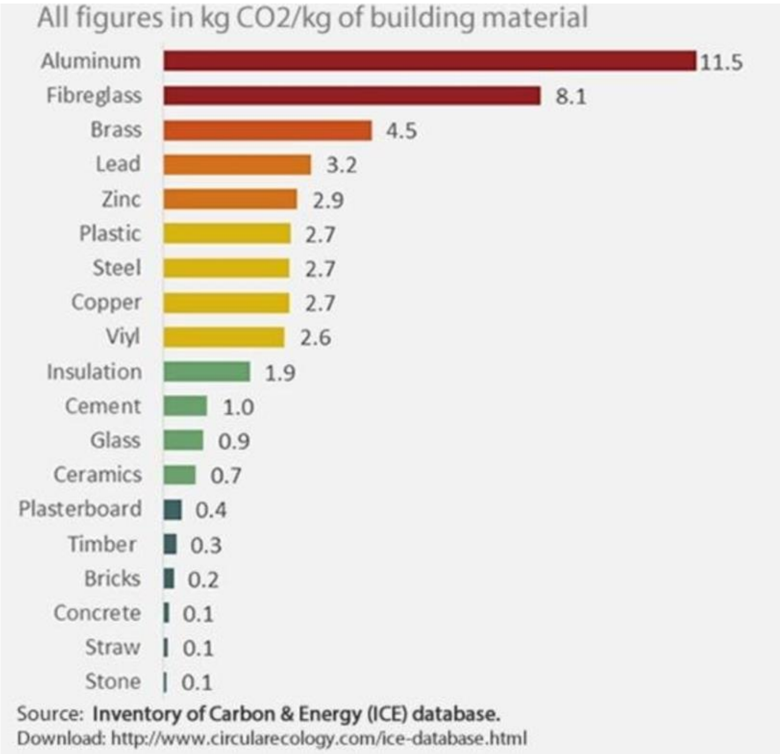

Figure 34. Building materials emissions from ICE Database.

UN actions: the UNSDg

The United Nations Sustainable Development Goals (UNSDg) are illustrated and described in the context of the Agenda 2030[110] for sustainable development by the UN. The Agenda 2030 is:

"an action program for people, the planet and prosperity signed in September 2015 by the governments of the 193 UN member countries. It incorporates 17 Sustainable Development Goals, SDGs - into a large action program for a total of 169 'targets' or milestones. The official launch of the Sustainable Development Goals coincided with the beginning of 2016, leading the world on the way to go over the next 15 years: the countries, in fact, are committed to achieving them by 2030."(*ONU, Agenda 2030, 2015*, s.d.)

[110] Agenda 2030: https://unric.org/it/agenda-2030/, here is the integral version: https://unric.org/it/wp-content/uploads/sites/3/2019/11/Agenda-2030-Onu-italia.pdf

Here is the prospect of the overall UNSDg with the objectives for individuals and countries at a broad scale (see Figure 35):

Figure 35. The UNSDg from Agenda 2030.

The research is focused mainly on two of these points that are 11 and 13, respectively "11. Sustainable cities and communities." And "13. Climate action".

Here are the infographics[111] that resume the main points of discussion (see Figure 36, Figure 37). The infographics highlight almost all of the issues discusses in the previous paragraphs concerning the most critical trends for contemporaneity. As explained, the city design has to deal with increasing global trends such as growth in population and consequent increase in urban slums, pollution and the necessity of high-quality spaces and efficient transport. City design is crucial in containing and controlling contemporary trends related to human growth and life quality.

In addition to the point "11" and "13", also the "9" could represent a strategic UNSDgoal to take into account in the research because it is related to innovation and sustainability in the industrial sector (see Figure 38).

[111] UNSDg infographic by https://www.un.org/sustainabledevelopment/cities/ and https://www.un.org/sustainabledevelopment/climate-change/

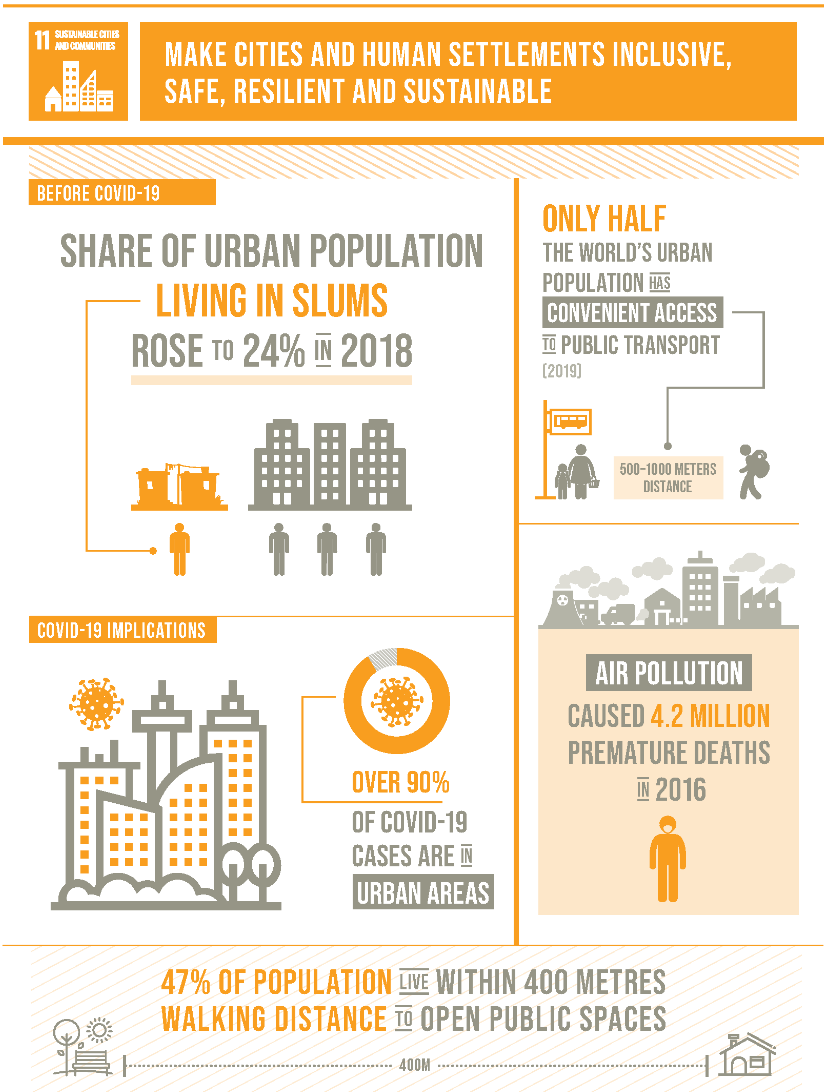

Figure 36. Point 11, UNSDg.

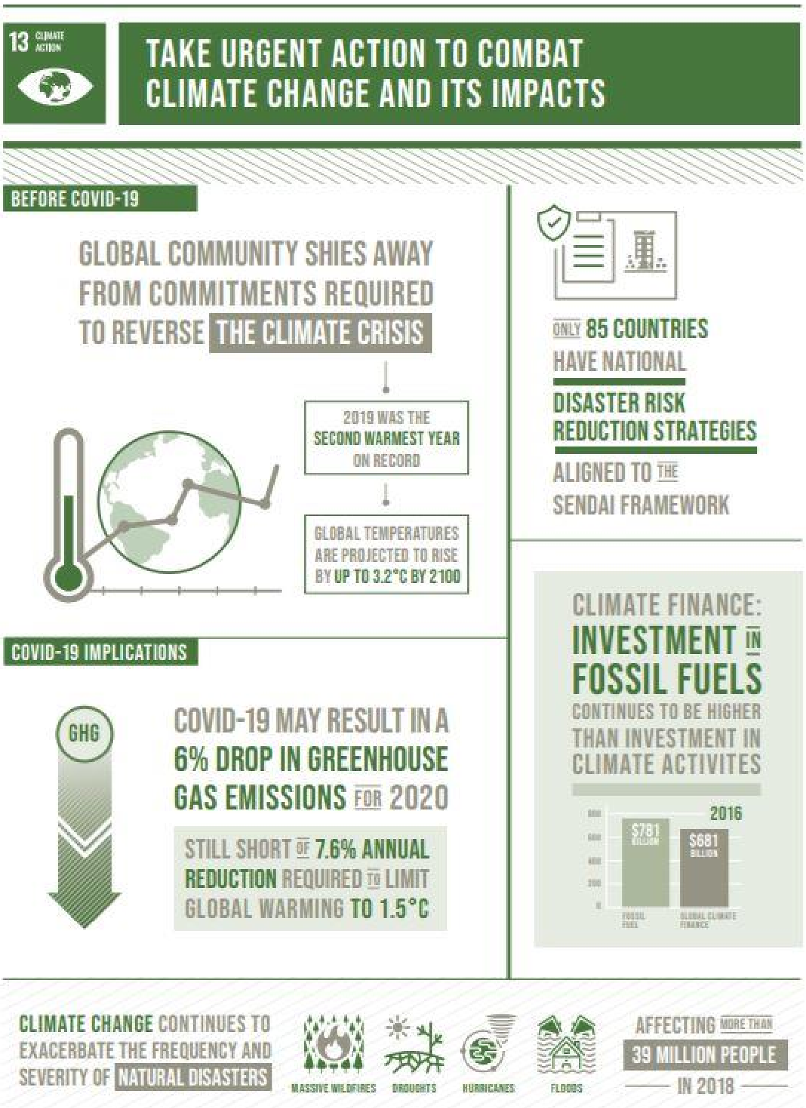

Figure 37. Point 13, UNSDg.

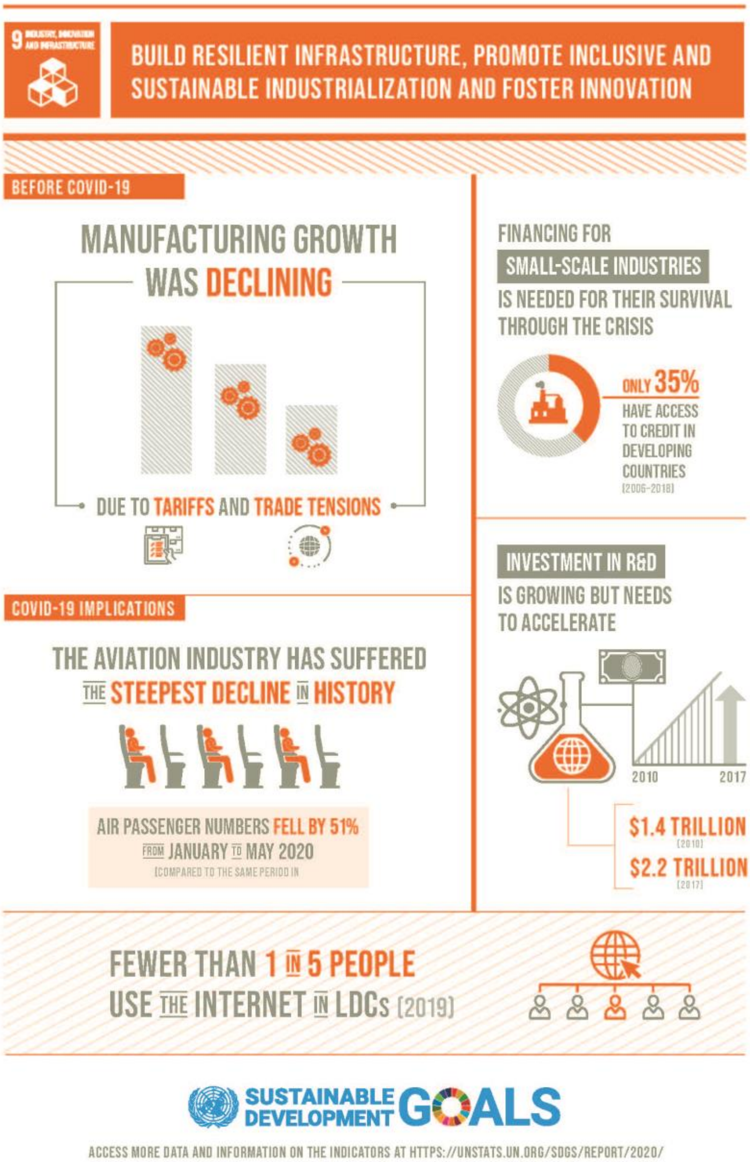

Figure 38. Point 9, UNSDg.

2.1.2 Parametric design and its power in prototyping: the case of BIM

Parametric design

The previous paragraphs highlight how a contemporary issue can not be framed into a single field of action, but it is included in a complex net of multidisciplinary relationships with a topic beyond it. This means that once picked a contemporary matter to which find a solution; it is necessary to take into account the wave of relationships in which it is situated. Managing such complexity, therefore, requires nowadays to employ technologies that embody two main characteristics:

a) great power in calculation and simulation;
b) a broad-scale impact.

Point **a)** suggests that new technologies have to manage a great amount of data coming from various sources (mobile, devices, sensors, etc.) and be able to combine them. Point **b)** provides advice consisting in designing solutions with great impact capable of involving multiple-scale. By using the huge power in simulation expressed in the previous point, new technology should also be able to simulate at a broad scale the impact of the solutions.

The rising interest in parametric design lies precisely in its ability to respond to these two requirements thanks to its ability in **prototyping**. Prototyping, in fact, embodies a great power in managing data and the ability in simulating verisimilar solutions at multiple scales that can be verified before they are put into action (see Figure 39). The definition of a "prototype" can help in understanding its potential:

"The prototype is the first example, the original model of a series of subsequent creations, built [...] in its normal size and susceptible to testing and refinements, on which the series construction is then based." (Treccani, 2022)

Parametric design owns exactly this kind of power in creating a digital model, called **Digital Twin**[112] identical for geometries and information to the real artefact, subjected to tests and simulations to obtain the most suitable design solution according to initial requirements. This suggests that the tools have to manage such a broad quantity of data, called **Big Data**, that has to be transmitted, stored and elaborated that is indispensable to employ calculation means much more powerful than in the past. But what is precisely Big Data that the architecture discipline has to take into account when addressing a design task?

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[112] The Digital Twin and the parametric modeling design topic will be fully explained in *Chapter 2, Paragraph 2.2 Parametric and Algorithmic thinking*.

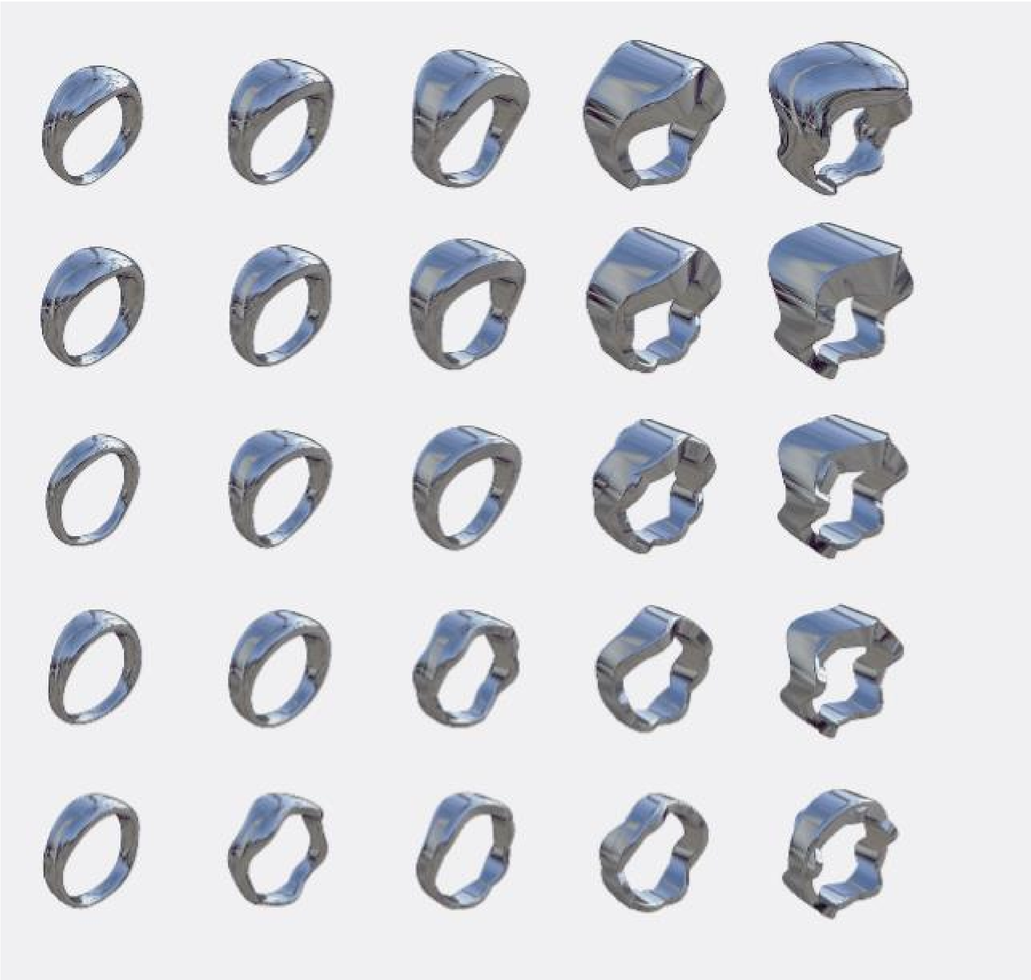

Figure 39. T. Fischer, C. Herr, Parametric jewellery design fabrication system, 2015.
(Frazer, 2016)

The UNI11337[113], a document that deals with the digital management of construction information processes, gives some guidelines to interpret the Big Data consistency.

"Big Data is a generic term used to describe the collection of data sets of such enormous size and such complex structure that their processing, using traditional data management tools such as relational database systems, is problematic."(Cyber laws, 2018[114])

These are data that come from multiple sources from our use of social networks, online purchases, streaming of multimedia content, and the sensors of devices connected to the network, which constitute the so-called **Internet of Things** (IoT). For example, in the city, the IoT involves a great variety of activities such as infrastructure, buildings, transportation, smart technologies, and moreover (Mohanty et al., 2016). These premises suggest that managing city dynamics require great potential in elaborating data from multiple sources. Tools that were traditionally employed for this scope, such as Computer-Aided Design (CAD)[115], are no longer capable of responding to this complexity. In this context, it becomes strategic to jump from an assisted digital drawing to parametric modelling capable of including information as parameters and rules for calculation. **The parametric modelling**, as Frazer suggests, consists in:

"...an algorithm that generates models consisting of geometry and attributes and uses functions and variables, including both dependent and independent variables." (Frazer, 2016)

The definition highlights that it is possible to include and represent the complexity of the objects of study from the combination of geometries and attributes with mathematical functions and variables.

However, the "technical" interpretation provided by Frazer suggests some ambiguity. If, on the one hand, prototyping owns a great power in data management, it also has some structural limits. Its incredible power in making previsions through simulations presents, in fact, two limits:

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[113] UNI11337 download at link: http://store.uni.com/catalogo/catalogsearch/result/?q=UNI+11337&fulltext=fulltext&tpqual%5B0%5D=1a&tpqual%5B1%5D=9&tpqual_var=99&ttbloc=0

[114] Definition from: https://www.cyberlaws.it/2018/big-data-legislazione-vigente/ (10/01/2022).

[115] CAD was the first numerical programming system elaborated by P. Hanratty in 1970.

1) no genius loci: the prototype is not positioned in time and space but in a virtual reality that is not subjected to external influences;
2) it is difficult to integrate the social sphere.

The list highlight that once the object of the simulation has technical aims (such as carbon emission optimization, heating and cooling demand calculation, scenarios about geometry disposition etc.), the parametric model is completely reliable. In this case, we do not need specific time and space, but we make use of general data to simulate them. However, then the simulation involves the social sphere (such as urban transformation and development, placement of new services and moreover), it is necessary to include the genius loci and the social sphere through participative processes during all of the design path. This clarification is useful in order to highlight that no tool has to be employed before defining the specific output that we want to obtain. On the other hand, the unrealistic claim to have an omni inclusive tool has to be abandoned.

Therefore, the parametric tool employed to solve sustainable targets is caused mainly by its great power in calculation and simulation and its potential impact on a broad scale. However, one of the causes resides also in the fact that parametric modelling is part of the **Building Information Modeling (BIM) process**. This aspect is crucial for two reasons:

- The parametric design could be employed for the design process in AEC[116];
- BIM is subjected to political regulations and norms.

In order to understand how much these two aspects can influence the parametric modelling employment in the design process, it is necessary to take a step back to clarify the BIM contents.

The NBIMS (National BIM Standards) defines BIM as[117]:

"Building Information Modeling (BIM) is a digital representation of the physical and functional characteristics of a facility. A BIM is a […] reliable basis for decisions during its life-cycle, defined as existing from earliest conception to demolition."

The most crucial point to highlight from the definition above is that BIM is a **methodology**, not a software. BIM **makes use of design software** that allows the

[116] Architecture, Engineering and Construction Industry.
[117] See the complete definition at: https://www.nationalbimstandard.org/about

representation of functional and physical characteristics of a facility, in other words, data and geometries of a facility. BIM, therefore, makes use of the parametric design, which is a tool employed in a broader design process. In order to be much more specific:

1. Building Information Modelling: is the methodology or the process;
2. Building Information Model: is the result, the model generated as the output of the process, the model obtained by the employment of parametric software.

Anyway, BIM and parametric design don't have an indissoluble bi-directional relationship. For example,

a) you can make use of parametric design software outside of the BIM process. For example, for creative processes outside AEC;
b) however, on the contrary, BIM can never be can't do without parametric software.

This clarification is indispensable because BIM is strictly employed to manage processes that are involved in AEC and need parametric procedures and tools. In the other situations, which are not in the AEC field or are not subjected to public procedures, it is not necessary to link by force parametric design to BIM, think for example, to an artistic installation modelling.

Why BIM

In the case of this research, instead, parametric design and BIM were tied doubled strand. Let's see the reasons.

The reasons why BIM plays a crucial role in the research is due to many various factors:

0. I decided to start my PhD path to deepen BIM in the fold of design practices. After a II level master's in BIM Manager (2017, Politecnico di Milano) and the hiring as BIM Specialist in an engineering and an architectural studio (Milan Ingegneria, Area Progetti), I desired to take the doctorate path. The aim was to go beyond parametric software technical employment and discover the theoretical and speculative side of BIM. I was interested in deepening the innovation of BIM in terms of design practice, actors relationships, new forms of collaborations, digital tools employment and moreover. Over the years, my interest grew especially in the parametric and computational design side.

1. BIM, moreover, was one of the "fixed" implications. CRH asked for BIM as a prerequisite in terms of skills for starting the collaboration. The Industry was interested in integrating the digital methodology within their workflow;

2. Working on a sustainable target that involves public/private actors, interests, constraints, financial investments, technological and knowledge resources[118] requires being part of a structured design process. In this context, the BIM methodology is efficient because it is a process that provides a collaboration platform for every stakeholder involved by allowing an easy information exchange and high-quality interoperability in terms of knowledge between actors and software (see **Figure 40**):

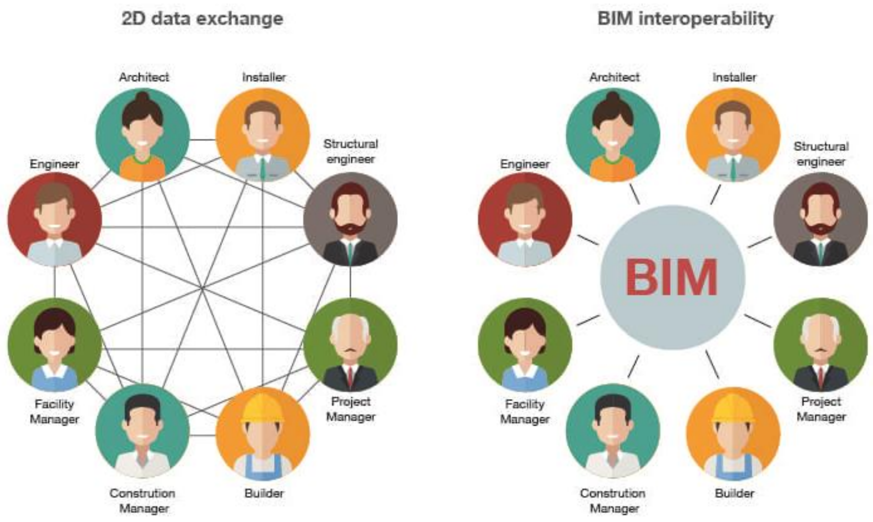

Figure 40. BIM interoperability (ACCA, 2017).

3. As said in the previous lines, BIM is efficient in managing processes that involve the AEC industry. Moreover, in this thesis, BIM fits well with a design process that implies working on a specific architectural case study. In order to reach the sustainable target proposed and described in paragraph *0.1 Research statements and question,* it was decided to create a tailor-made digital methodology that integrates parametric and computational design with LCA procedures and to test it by numerous validation on a precise architectural case study described in paragraph *3.3 Selecting the case study: an architectural prototype*. The architectural case study, consisting of a typical dutch house, was provided by Heijmans, a construction company gradually

[118] The Academy-Industry collaboration model is going to be fully described in the paragraph *1.1.3 The "machine": Academy-Industry collaboration model*.

involved in the validation phases of the methodology. Therefore, the multidisciplinary net of actors established (see paragraph *3.1.4 The stakeholder's map*), consisting of Academia, Construction Company (Heijmans) and Building Material provider (CRH), is required to be positioned in a structured design process that BIM is able to manage.

4. The strategic employment of BIM also resides in its ability to manage all of the design phases of an artefact. A parametric BIM model can manage all of the information that has been stored during the overall life cycle of a building. This kind of characteristic is strategic when stakeholders, like CRH and Heijmans, are interested in integrating LCA analysis with architectural models. Here is an infographic[119] that shows the design phases managed by BIM and the information that the model can store and elaborate on (see Figure 41):

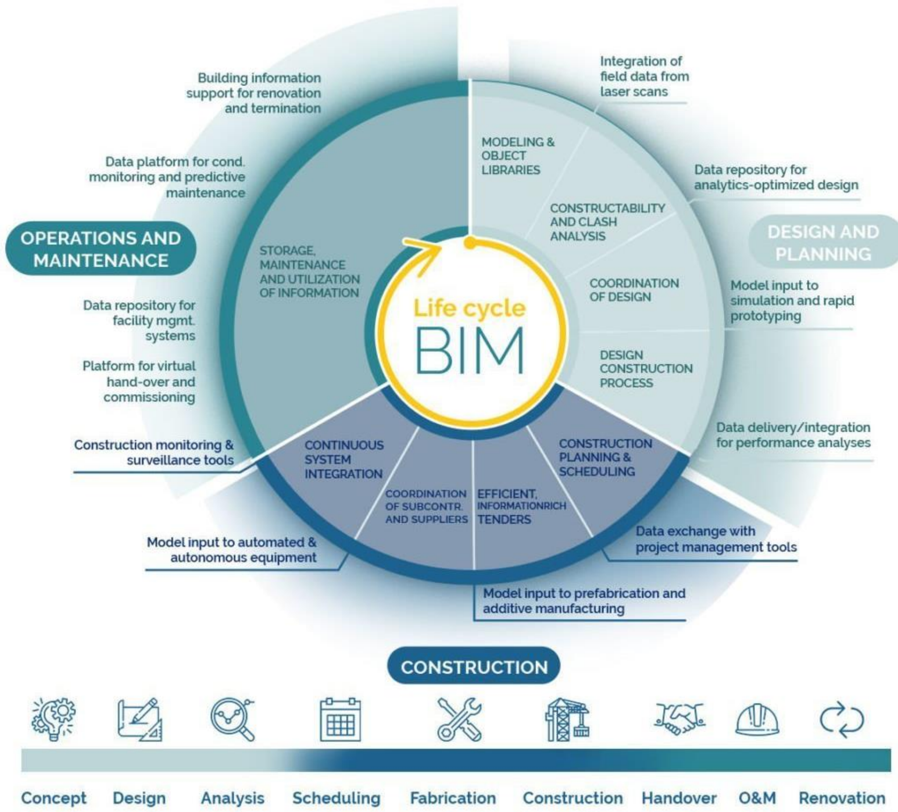

Figure 41. BIM process infographic.

[119] Image from: https://www.cemexventures.com/discover-how-bim-is-implemented-in-each-phase-of-the-construction-industry/

The infographic suggests that if BIM can manage various kinds of data (geometrical and functional) of a facility during the design, construction and maintenance phases, it could be strategically engaged in managing LCA scenarios. Moreover, the BIM model can easily interoperate with LCA software like Tally[120] and One Click LCA[121] to obtain calculations over the life cycle of a facility.

5. As paragraph *1.1.1 A wave of environmental and social issues* suggests, the UNSD goals play a decisive role in identifying the points of discussions addressed in the thesis. However, how do these points relate to the BIM discourse? United Nations identified new digital technologies as strategic in reaching a broad range of contemporary targets. The UN promoted an internal strategy called *UN Strategy on New Technologies*[122] to support the application of new technologies to accelerate the achievement of the 2030 Sustainable Development Agenda and to facilitate their alignment with the values cherished in the UN Charter and the Universal Declaration of Human Rights (UN, 2018). The internal strategy identifies the application of digital tech, artificial intelligence, biotechnology, blockchain, and robotics as the engine to accelerate the Agenda 2030 targets and pushes for training, incrementing knowledge and promoting partnerships. Partnership, established with a multi-stakeholders mechanism, is the first step to building high-level collaboration models.

6. In the end, the crucial factor that is conducting toward BIM's broad use is the progressive adoption of BIM for public tenders. Governments see the digitalization of the design process as a great help in innovating traditional and obsolete procedures that don't fit well with the complexity of our time. The design process is progressively becoming much more globalized, involving actors and site projects from distant countries, which implies the help of cutting-edge technologies to manage the system of collaboration, the exchange of data during the process, the control over the results and moreover. The digitalization of the construction sector, in this context, can provide various advantages like mainly (ACCA, 2017):

[120] Download at: https://apps.autodesk.com/RVT/en/Detail/Index?id=3841858388457011756
[121] Download at: https://www.oneclicklca.com/life-cycle-assessment-from-revit/
[122] Download at: https://www.un.org/en/newtechnologies/

1) Dispose of a platform of collaboration ACDat[123] where data, documents, and drawings are stored, managed and verified by stakeholders during all the design phases;
2) Conduct a real-time analysis over the digital parametric models during the life cycle of the building, such as volumes, costs and time previsions, energy analysis and various kinds of simulations;
3) Configure possible design solution scenarios by integrating all the necessary disciplines: architecture, structural design and systems. The constant control over the project development also advantages the reduction of the project variants;
4) Establish an integrated design.

All of the points cited are crucial and worth a deepening; however, we will address the last one, which encloses the previous three, the integrated design.
BIM substitutes the traditional linear design process (where actors intervene in the project in temporal succession) with an integrated and synergic process (see Figure 42) in which stakeholders have been involved together since the early design stages[124]. The stakeholders are called to contribute to the project simultaneously (see point 1) of the previous list about ACDat) by establishing a solid collaboration system for all of the project life-cycle. The result is a decision-making process constituted of weighted choices and systemic checks of design choices. The integrated design process embodies many advantages but requires a great effort in the initial phases in terms of actors' involvement and employment of resources (financial, software, etc.). The diagrams (see Figure 43) compare traditional flow and integrated by distinguishing actors engagement during the life cycle. Paragraph *0.3.4 Strategies for mapping the process* hosts a diagram that traces the actors and resources (software, documents, models, data etc.) involved in the research path. The objective was to highlight the actor's relationships (increasing and decreasing), the temporal employment of different resources, the recurrence of the validation test. The output was graphical restitution similar to the second diagram attached.

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[123] With the term ACDat is intended Ambiente di Condivisione Dati, it is in other words a digital platform of collaboration to store and manage data and documents of the design process. The norm UNI 11337 regulates the ACDat use and access.
[124] Definition from Biblus BIM: https://bim.acca.it/progettazione-integrata-bim/#:~:text=La%20progettazione%20integrata%20si%20basa,sistematica%20delle%20varie%20proposte%20progettuali.

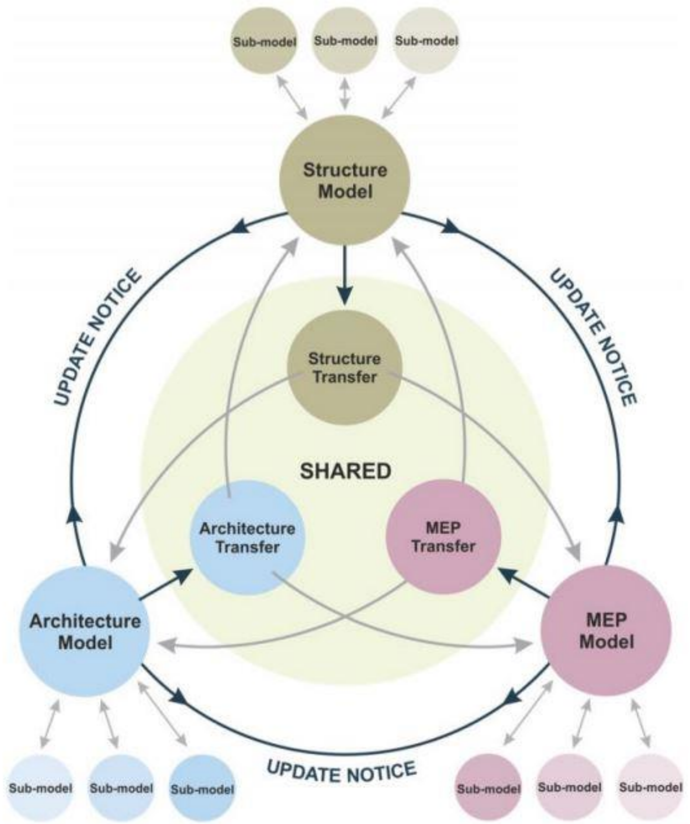

Figure 42. Integrated design process. (AEC, UK, BIM Technology protocol).

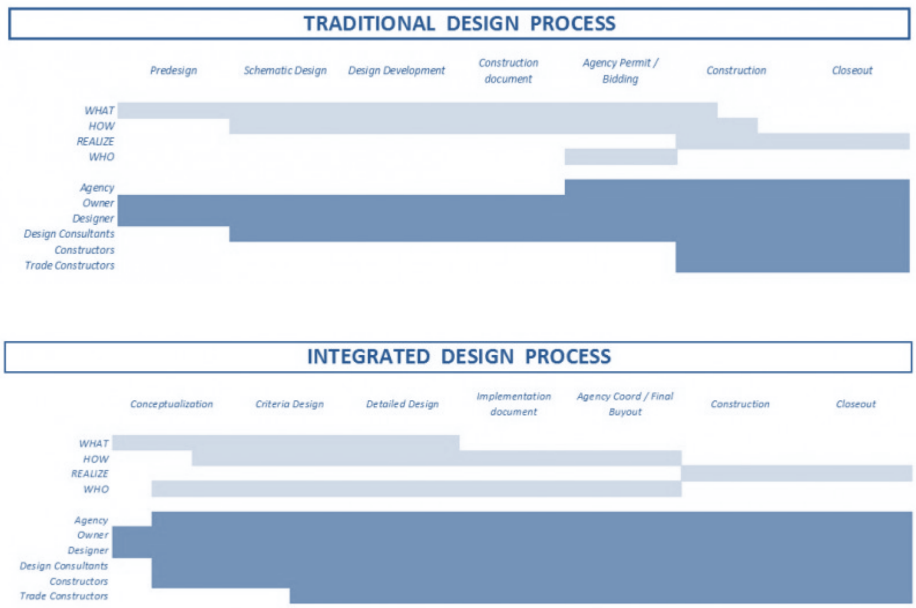

Figure 43. Traditional vs Integrated design process (ACCA, 2017).

The integrated collaborative process represents a great means of obtaining a higher quality in design, controlling time and cost variables, and making simulations scenarios broadly. Many countries are equipping themselves with their norms and tools that will allow a digitalization of the design process progressively.
In particular, in Italy, the legislation governing BIM has been introduced with art. 23 of dlgs 50/2016 and, subsequently, detailed with Ministerial Decree 560/2017 (ACCA, 2017). The dlgs contains indications for the UNI 11337 norm that regulates the BIM use in terms of products and processes (UNI, s.d.):

- models, documents and information objects for products and processes;
- evolution and information development of models, documents and objects;
- information flows in digitized processes.

The UNI11337 norm governs detailed information to manage the digitalized process of design, such as the creation and management of models and objects; models level of details (LOD) and information (LOI); exchange formats (.rvt, .ifc etc.); formal documents to manage a BIM design process (for example, the Employer Information Requirements E.I.R.); roles and responsibilities definition (BIM Manager, CDE Manager, BIM Coordinator, BIM Specialist) and moreover. In other words, it regulates all of the necessary information to manage a BIM process. The UNI11337, in conclusion, regulated the entire construction information process by defining the design phases and the progressive implementation of the digital model, from the project information model to the as-built model. To resume, the first part of the UNI 11337 standard proposes an information structure of the construction process. The construction of building work can be divided into two macro-sets or information models:

1. the project model (the stages of development: programming, design, production), see orange section Figure 44;
2. the as-built model (the operating stage), see blue section Figure 44.

The design stages are four in total (stage: programming, design, production, in use) and are divided into eight phases: from the concept of the building to management and maintenance of the building work.

The diagram (see Figure 44) shows in detail the construction information process describing and putting in relationship the design levels in public tenders and the RIBA plan of work[125]:

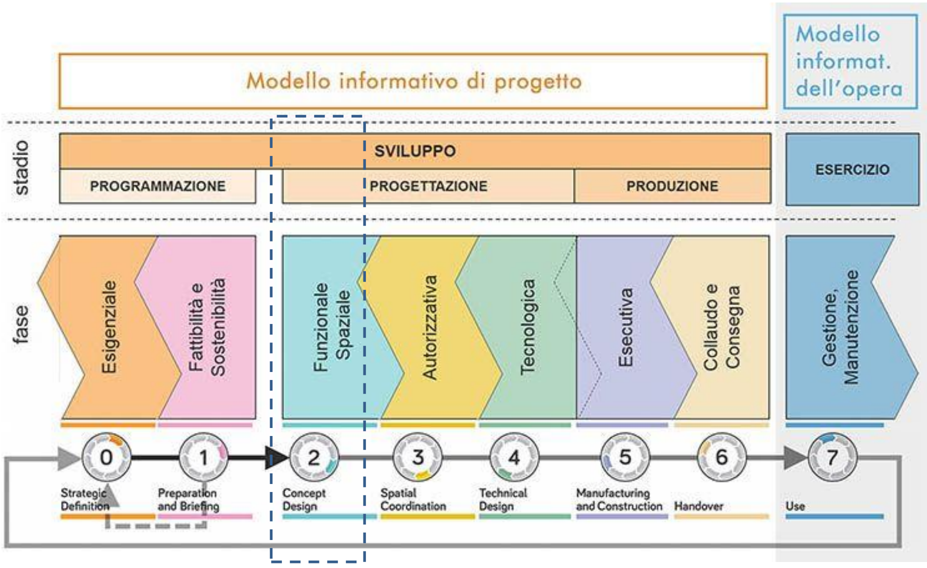

Figure 44. BIM construction informative process[126].

The diagram is instrumental in describing the design phases in the BIM construction informative process and in positioning the digital methodology proposed by the thesis[127] (see dashed light blue line Figure 44):

- the RIBA conceptual design stage, corresponding with the *stage* of Development and Design and the *phase* Functional and Spatial. The object is a project model.

Last but not least, the reason that is pushing for the gradual BIM adoption is the deadline imposed on employing new technologies for public tenders. The cited DM 560/2017 defines methods and times for

[125] The RIBA Plan of Work is published by the Royal Institute of British Architects (RIBA), it is a shared framework for design and construction that offers a process map of the desifn phases.
[126] Download at link: https://www.infobuild.it/approfondimenti/bim-building-information-modeling-e-appalti-pubblici/. Consulted 17/01/2022.

[127] To deepen the reasons of the positioning in the concept design stage, read Chapter 4. Devising the tool for planning decisions.

the gradual introduction, by contracting authorities, granting administrations and economic operators, of the mandatory nature of digital methods and tools. By 2023, for all of the construction projects with an amount exceeding one million euros, in other words, for each work. Today, in 2022, it is mandatory for complex works, which include works that embody a high interconnection of technological, structural and technological aspects or from significant construction difficulties from the plant-technological point of view (*DM 560/2017*, s.d.). Today, DM 560/2017 is adjourned with DM 312/2021, which defines new methods and times for the gradual introduction of electronic modelling methods and tools in public works contracts for construction and infrastructure.

2.1.3 The "machine": Academy-Industry collaboration model

(parts extracted from the article: Giaveno, S., Osello, A., Garufi, D., Santamaria Razo D. (2021). *Embodied Carbon and Embodied Energy Scenarios in the Built Environment. Computational Design Meets EPDs*. Sustainability, 13).

The paragraph will address the academy-industry collaboration model topic to highlight why it could represent an efficient method to address complex contemporary issues. Therefore*, why the collaboration model is strategic and how it can be established? In which way did it influence the research path in its definition and development?*

The "complexity" related to contemporary issues is the key that provokes an increasing interest in that collaboration model. Every matter related to society can't be nowadays framed into a specific perimeter of influence. For instance, an environmental problem is never only environmental; it is positioned in a net of cause-affect that comprehends political, social and economic factors. Managing such a complex wave of factors implies a step towards multidisciplinarity and new models of collaboration between subjects at different levels (De Martin, 2017). Multidisciplinary is intended both as topics and roles; that's why Industry-Academia collaboration has received increased attention. Furthermore, the collaboration model provides some solid benefits for all of the parts involved but also embodies some ambiguity. For instance, the need for innovation in the business environment and the ambition to commercialise academic knowledge intensify the demand for more industry-academia collaboration (Rybnicek & Königsgruber, 2019). However, increased collaboration between different actors also improves issues because each actor is likely to pursue different objectives and face individual constraints. While this phenomenon can enhance the value, it can also be a source of additional complications (Rybnicek & Königsgruber, 2019). Despite this, there are still many reasons for promoting the collaboration model: companies profit from qualified human resources such as researchers or students (Myoken, 2013), obtain access to technology and knowledge (Barnes et al., 2002) and use expensive research infrastructure (Ankrah and AL-Tabbaa 2015). Universities, in return, benefit from additional funding provided, access to industrial equipment, and licensing or patenting income (Barnes et al., 2002). In fact, collaboration with Industry has become an inevitable part of university funding. In many countries, international organisations and business enterprises represent a 'significant source' of funding for R&D in the higher education sector (OECD, 2015).

By taking into account these premises, it is necessary to take a step toward the double domain Academy-Industry and reflect on the role of government in the innovative model of collaboration. Governments are traditionally seen as the actor that guarantees the contractual relationship and the one that establishes the game's rules. Usually, Academy-Industry partnerships aim to respond to international policies and real-world targets at various levels, such as sustainable city growth and CO2 reduction (*ONU, 2015*). In particular, the Triple Helix model (Etzkowitz & Leydesdorff, 1995) postulates that in a knowledge-based society, the boundaries between the public and private sector, science and technology, university and Industry are increasingly fading, giving rise to a system of **overlapping interactions** (Pique et al., 2018):

(a) *the Industry operates as the centre of production;*
(b) *government acts as the source of contractual relations that guarantee stable interaction and exchange;*
(c) *Academia is the source of new knowledge and technology.*

The Triple Helix concept (see Figure 45) incorporates a set of features, relationships, and functions into its innovation system format. The relationships between components are synthesised into five primary types: technology transfer, collaboration and conflict moderation, collaborative leadership, substitution, and networking (Ranga & Etzkowitz, 2013). Here is the graphic representation of the triple relationship model:

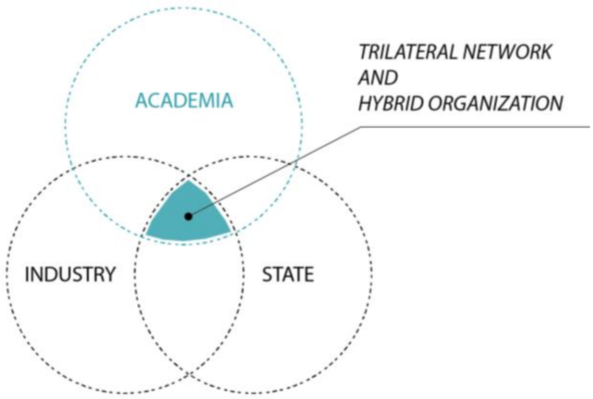

Figure 45. The Triple Helix model (Ranga & Etzkowitz, 2019)

This configuration incorporates the transition toward a knowledge society in which universities and other knowledge institutions act in partnership with Industry and government to develop joint initiatives (Etzkowitz & Leydesdorff, 1995). The most favourable environment for innovation is where the spheres meet and synergies manifest. This represents the framework where the research is located. Next, we are going to analyse how the collaboration system is composed and how it can be established by deepening specific literature and merging the theoretical study with the experience in the field. The result is a graphic diagram (see Figure 46) that resumes the funding characteristics of the Academia and Industry interaction.

Building the collaboration model

The A/I model

The academy-industry collaboration model represents a complex and balanced system constituted by various factors. In order to understand the collaboration functioning, it was necessary to deepen a specific bibliography in the field to trace a general overview of the collaboration models systems. The academy-industry interaction is, in fact, the object of specific literature dedicated to analysing the factors powering the relationship (Bruneel J., 2010; Ciborra C., 2001; De Fuentes C., 2012; Michaudel Q. (et al.) 2015; Rybnicek R., 2019,) and the best structure by which the interaction can be established (Barnes T., 2002; Chesbrough H. W., 2003; Lee, Y. 2000; Perkmann M., 2017)[128]. The result from the analysis of the specific bibliography is this graphical restitution in the diagram form that resumes the main relationships established between Academia and Industry (see Figure 46):

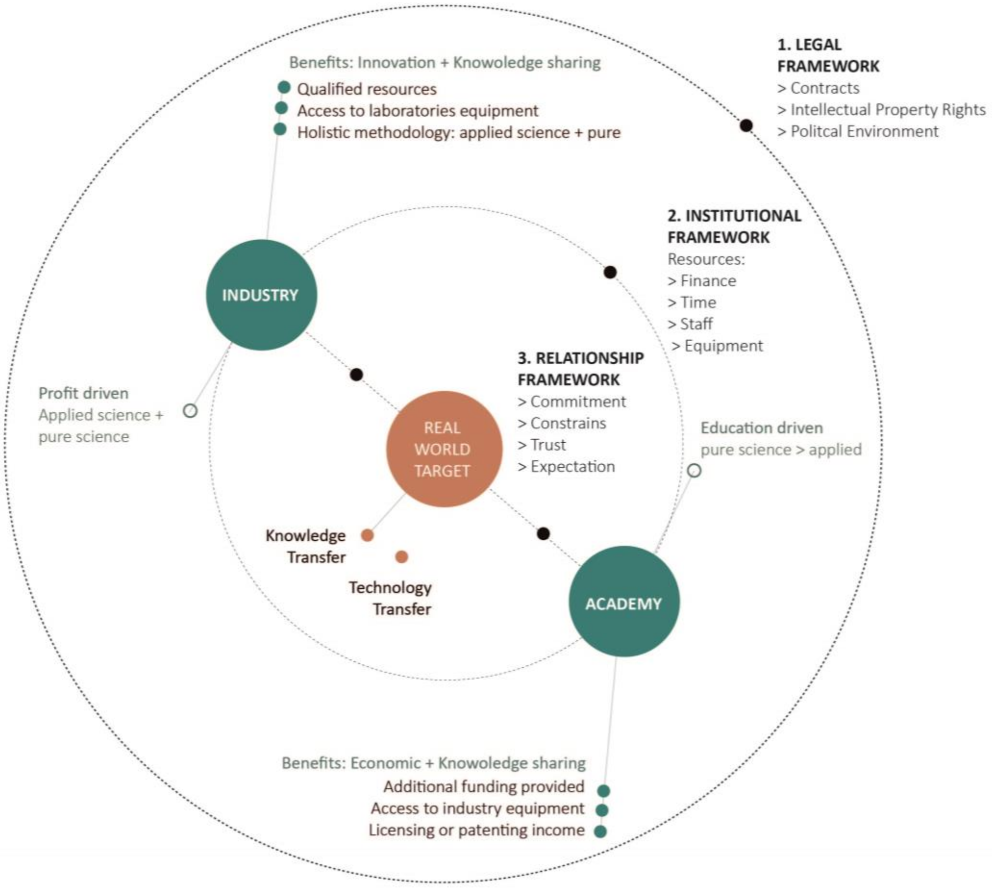

Figure 46. The machine, Academy-Industry collaboration.

128 The complete bibliography contains many other titles, here are cited the most significant.

The main factors highlighted are:

5) Benefits: in terms of innovation and knowledge sharing;
6) Transfer: in terms of knowledge and technology;
7) Frameworks: legal, institutional, relationship.

The diagram suggests that a complex balance between various forces governs the relationship. The reading of the diagram must start from the most external circle to the centre; this means that when you start establishing the collaboration model, the first action to take is defining the "legal framework" and later the "institutional" and "relationship" one (see Figure 46). In particular,

1. **the legal framework** is the most demanding in terms of time and risks because defining contracts, intellectual properties, and expectations require a great amount of time and a collaborative environment;
2. **the institutional framework** is characterized by the definition of the resources in terms of people involved, finance and technological devices;
3. **the relationship framework** is aimed at defining roles, responsibilities, actions and tools in addition to deadlines and expectations.

The centre of the diagram hosts the **real word target** positioned as the balance point between Industry and Academy. It is the point where knowledge and technology transfer manifest and take place.

In conclusion, from the diagram reading, it is possible to notice various kinds of **benefits** for all of the parties:

a. Industry, usually profit-driven, benefits from knowledge sharing, access to laboratories equipment, and a holistic vision in terms of pure science.
b. Academy, usually education driven, benefits from applied science, additional funding, access to the Industry equipment, licencing or patenting incomes.

Establishing a complementary relationship in terms of knowledge and technology could represent a success factor when it is necessary to address a real-world target, such as in the case of the thesis. Multidisciplinarity and the availability of various resources can help in responding to contemporary issues.

In this balance, Academia is strongly pushed in rethinking to his consolidated system. Academia should embody sensitivity toward socio-political conditions and promote new kinds of research with different aims also far from the traditional (De Martin, 2017). The great benefit that Academia can find in opening the boundaries of its topics and actors involved is to acquire a broad view of world dynamics. With dynamics, it is intended to consider forces beyond pure science that willy-nilly govern the world. Researchers must become skilful in interpreting political, economic and social dynamics and in acquiring sensitivity well beyond their field of research. Pure science embodies the danger of remaining framed into a “bubble” that has no links with the outside world. Academia's greatest benefit is opening the doors to the unsounded field of investigation, market dynamics, political constraints, and economic rules that the researcher should learn how to interpret and keep into account. Indeed, opening the door to a new form of partnership and collaboration makes the procedures much more complex, but the results in innovation are definitely high and unexpected.

In particular, the case of this thesis is characterized by a strict collaboration between Politecnico di Torino and CRH The Netherland that represented, at the same time, a significant constraint and opportunity for the thesis development. The net of the actors involved during the process was huge and diversified and hosted stakeholders from academia, construction company, and material providers. It will be fully explained in *Chapter 3, Building the playground*. The chapter is going to fully deepen and narrate this kind of particular collaboration model by describing the team, the resources, the constraints, and the objectives put into action during the PhD path. For the moment, the next paragraph is going to provide an overview of CRH, the building material provider partner.

CRH and the Innovation Center for Sustainable construction

CRH is the leading global diversified building materials business in the world, employing 76,600 people at 3,100 locations in 29 countries worldwide. It manufactures and supplies a diverse range of building materials and products for use in the construction and maintenance of infrastructure, housing and commercial projects. Its materials and products are used extensively, in construction projects of all sizes, across the world. CRH's businesses are focused on delivering service excellence for customers in local markets and on anticipating evolving market needs in a complex and continuously changing world. While the construction industry has typically been conservative and slow to change, the challenges and opportunities presented by climate change are driving an increased focus on innovation across the Industry.

CRH takes its role in helping to address the challenges of climate change seriously, and this is one of the reasons it established the Innovation Centre for Sustainable Construction (ICSC). The ICSC focuses on supporting CRH in achieving its commitments toward the United Nations Sustainable Development Goals (*ONU, UNSDG Linee Guida, 2015*, s.d.). As a centre of excellence, the ICSC is tasked with identifying future trends and customer needs and then transforming them into attention points for development. This also involves networking to create an ecosystem for these trends to be properly addressed, developing new ideas internally and externally, creating the internal context for external talent to become the next generation of professionals in the Industry, managing the process of market and technology readiness levels inside CRH for the identified concepts, and delivering them to the market. A very important point in the whole value chain of the ICSC is the close relationship with Universities and Public Research Centres. On the one hand, to participate actively in the development and preparation of professionals that will work in market-facing roles in the near future, contributing to the social responsibility of educating; on the other hand, on actively making sure that CRH captures the knowhow from talented people, and collaborates with the university, to develop young generations that will help solve today's challenges (see Figure 47).

Figure 47. CRH project pillars (*CRH, Sustainability Report, 2020.*, s.d.).

The chart shows the main research topics being focused on by the ICSC. The projects involve issues that are closely aligned to the UN SDGs with a direct effect on the design process and products. The ICSC focuses on different time horizons to deliver innovation: the longest term to deliver results but the shorter to medium term value is in the development of people. One of the ways ICSC is focusing on developing the next generation of professionals is by taking a serious approach to research and by participating in the co-funding of philosophical doctorates (PhDs).

This paper results from a long-lasting collaboration derived from a PhD that Politecnico di Torino and CRH are developing together to address the digital-related requirements of more sustainable and efficient building industry.

2.2 Introducing the operative proposal: a parametric tool for planning decision

"Yet digital technologies, now ubiquitous, have already significantly changed the way architecture is designed and made. They are changing how architecture is taught in school, practised, managed, even regulated." (Carpo, 2011)

The research suggests, since its premise, its ***aspiration*** in influencing the cognitive and critical debate on the ecology and parametric design intersection and, in particular, in affecting their operative strategies with a tool that embodies transformative power over consolidated procedures. Devising a *functioning* tool that *fits specific needs* and requirements and can *transform* traditional practice requires a wide multidisciplinary recognition of bibliography, matters, and tools. Moving from the theoretical plan to the practical implies addressing the matter at different scales and employing a variable use of bibliographic sources[129]. The section is, in fact, opens with wide theoretical recognition and, later, lands on the specific set of interdisciplinary implications to address when the aim is to move toward practical exploration. The two chapters' combination constitutes the background where the research proposal is grounded and shaped by its objectives and operative strategy.

However, some other factors are relevant to consider when addressing the devising of a tool and its application in a real context of action. The complexity of the task, in fact, requires opening to multidisciplinarity and collaboration models to ensure knowledge and technology transfer. This means considering the needs, expectations, and interests of the actors involved in the process. Indeed, in its theorethical and practical purposes, the research proposal was the object of long and perpetrated discussion about its consistency, aims, and outcome. The application of digital technologies to reach real-world targets demands the needed opening to multidisciplinarity and collaboration models to ensure knowledge and technology transfer. Hence, once extrapolated from the theoretical background, the speculation over digital technologies collides with market dynamics, private and public interests, economic constraints and technological equipment availability. That's why the final operative proposal is a bit re-dimensioned with respect to cutting-edge design examples and visions narrated in the previous paragraphs. The aspiration toward philosophical vision correlated with ecological

[129] Read *0.3.5 Chapters development and use of the sources*. The first chapter of the section, for example, employed in the recognition mostly books and magazines papers on ecology and parametric design. The second chapter of the section employed instead mostly scientific articles, international reports, UN guidelines and so on.

awareness and informatics revolution had to be necessarily fitted with real and reachable targets[130] imposed by the research group's needs and objectives.

From the merging of the forces described in the paragraph, the operative proposal was a tailor-made tool at the service of designers that assumes this final form:

A tool for planning decisions at a micro-scale in the conceptual design stage that generates dynamic environmental impact scenarios to create awareness of embodied carbon and embodied energy emissions related to the artefact.

The tool merges parametric and computational design potential to combine several data in the form of ***variables*** (material, environmental impact indicators) to obtain ***dynamics design scenarios***. The scenarios are represented by digital responsive models that dynamically modify their spatial configuration and environmental impact results when subjected to a different input.
The research attempts in its experimentation to reach the objective described, but even if it represents a primordial and perfectible attempt to merge ecological awareness and informatics revolution technology, it can represent a ***working prototypal of action*** toward that direction.

The following section, dedicated to *The laboratory experiment*, will illustrate the development of the articulated process that led to the tool definition. Conceiving a tool and testing the tool performance in action required many steps before reaching its final form, corresponding with the experiment perimeter definition in terms of actors involved with related roles and responsibilities, resources at dispositions, software and technologies toolkit, target and expectations, timeline and validation sessions[131]. The tool was assembled and tested by manipulating a parametric architectural prototype[132] that embodied the ability to simulate verisimilar solutions at multiple scales that can be verified before they are implemented. Just as scientists start working on small cells in the laboratory and once tested the cure, they later apply it to much more complex organisms subjected to diversified physiological influences; thus, the tool, tested on a prototype, could be hopefully applied to a larger domain scale[133]

[130] The research implications, in terms of matters and tools, were detailed described in *Chapter 1. Climate change as a design matter*, in particular in paragraph *1.1 The research implications*.
[131] The complete narration of the experiment will be object of *Chapter 3. Building the playground*.
[132] See paragraph *1.1.2 Parametric design and its power in prototyping* for the complete explanation.
[133] Paying attention to the conditions underlying the increasing in scale. The tool is conceived to be stressed by various and multiple inputs and embody the potential to be applied from the object to the city scale. Hopefully, the study could represent the scientific ground for future experimentation at a broader scale, like the urban one. See *Chapter 6. Concluding remarks*.

The laboratory experience

PART II

Chapter 3.

Building the playground

The chapter belongs to *The laboratory experience* section and intends to narrate which were the premises of the experiment. It aims to prepare the ground for the next chapter dedicated to addressing the devising of the digital tool for planning decisions. In particular, *a tool for planning decisions at a micro-scale in the conceptual design stage that generates dynamic environmental impact scenarios to create awareness of embodied carbon and embodied energy emissions related to the artefact.*

Clearly, conceiving a tool and testing its performance in action requires many steps before its definition. In particular, it is necessary to define and establish the ***perimeter of the experiment*** in terms of actors involved with related roles and responsibilities, resources at dispositions, software and technologies toolkit, target and expectations, timeline and validation sessions. In other words, it has to be constructed as what I call the ***"playground"***. The term was chosen because assembling the experiment boundaries was similar to creating a playground where actors, actions and tools were put into action to simulate an authentic design process that led to the conceiving and testing of a digital tool. Playground embodies the playful meaning of building a creative and collaborative framework in which to forge new devices and ideas.

Building the framework for actors and tools actions required a great effort in arranging a multi-layered structure of contracts, resources (finance, time, staff, equipment), roles and responsibilities (commitment, constraints, expectations) that the Academy-Industry collaboration model carried with it. The first and greater effort was to balance the forces in the great collaboration model mechanism that I called "The machine" described in *paragraph 2.1.3*. The current chapter intends to exemplify some of the characteristics of that "machine" by narrating the specific case of the research path, made of specific stakeholders (internal and external), objects of interest and targets, technological equipment and a case study to test the digital tool progression. The aim is to clarify the premises that led to the tool conception, assemblage, and test addressed in *Chapter 4. Devising a tool for planning decisions.*

3.1 Setting the experiment boundaries

Defining the boundaries of an experiment means building the framework where actors and tools will act. As the word suggests, the framework refers to a specific perimeter made of certain targets, data available, and equipment that I had to deal with in conceiving the tool. It would be possible to call the group of the cited heterogenous premises the "toolkit", which characteristics will be described in the current paragraph. In the description, my figure as ***narrator and researcher*** melts by joining the two dimensions of theoretical and methodological competencies with experience in the field (Dei, 2012). Immerse me in the context by assuming the role of *participant-observer*[134] allowed me not only to manage and transform data to obtain a technological new means but also to perceive the environment of a multidisciplinary model of collaboration emphatically. I positioned myself as a mediator between different subjects (Academia, Building Material Provider, Construction Company), and I tried to balance their relationship aimed at producing a tangible output. The narration, therefore, includes not only the technical steps run to reach a technical result but also the description of the negotiation, steps back, achievements and expectations that characterize a process governed by human relationships. The empirical experience was carried on for all three years of research. During that time, I did a prolonged stay in the Industry where I learned the principles that govern that context, in other words, the economic, political and relationship rules that I had the chance to test. Knowing and living in that context allowed me to better calibrate the preparation and the development of the tool by including forces and interests that usually are outside the Academic world. Beyond the effort of keeping together two distant realities, such as Academy and Industry, stay the comprehension of the world dynamic with a broad and a much more holistic view. Here is the narration of the laborious experience that I did as a researcher and observer in the middle of two worlds.

During the narration of the experiment, the paragraph is going to build various correlations between anthropology and ethnography by picking some aspects from both disciplines that were fertile ground for some critical reflections. The reference to both the disciplines was introduced in paragraph *0.3 Methodological Notes* that hosts the clear and personal positioning toward the topics: the participant observation, problematising perspective and contents, the relationship

[134] The participant-observation role is a clear reference to the B. Malinowsky (1844-1922) anthropological studies. To deepen my precise positioning in the research read paragraph *0.3.1 The Role that I embodied.*

between producing and thinking. The readers approaching the chapter can reference paragraphs *0.3* and *0.5. Conceptual background*.

3.1.1 The multi-site fieldwork

The intention of ***expanding*** the research boundaries outside Academia was to take the distances from an analysis only grounded on theoretical speculation. The discourse about parametric design is frequently addressed by collecting information and transmitting them by a deterministic[135] interpretation. This behaviour carries some risks; first of all, it doesn't guarantee comprehension and fosters beliefs. Otherwise, the research started with no preconceptions. Its development went hand in hand with the discovery and manipulation of digital methodologies, the establishment of new multidisciplinary relationships, with falls and achievements during the process. I knew the starting point (the toolkit) and the endpoint to reach (the embodied carbon and energy scenarios), but the means (the tool) to get there was not preconceived. The means grew together with the process, and I grew up with it myself. I led the process, in which I was an actor and observer, of changing myself and my awareness. I *proceeded together with it*[136] (Ingold, 2019). Therefore, during the years, the tool and the digital methodology to build it were subjected to doubts, tests, beat of arrest and corrections until reaching the final form. The process implied studying *with* people and learning *from* them; therefore, what we call "research" could be compared to the symbolic image of "fieldwork" introduced by the anthropology discipline (Dei, 2012): the place dedicated to empirical experience and learning. The term is here employed because, along with the research experience, it is possible to trace some symbolic similarities with the Malinowsky[137] conception of the term. For example, I did a long permanence in the place of study, learning habits and culture of the site, transcribing interviews and documents, producing notes and texts, and moreover. However, it has to be underlined that the situated conception of the fieldwork proposed by B.Malinowsky[138] is currently overcome by a multi-situated concept of field that, due to globalized communication, can no longer be framed into a single and specific place of investigation (Dei, 2012).

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[135] Determinism is here intended as a mechanistic view in which connections between facts are necessary and invariable and not subjected to doubts or variations.

[136] Tim Ingold, in *Making* (2019), suggests that the only way to build a solid knowledge is a process that implies an active following and proceed together. The mere information transmittion does not guarantee knowledge neither comprehension.

[137] The B.Malinowsky's concept of participant observation and fieldword is described in *Argonauts of the Western Pacific* (1922).

[138] The B.Malinowsky's concept of participant observation and fieldword is described in *Argonauts of the Western Pacific* (1922).

Therefore, the term "fieldwork" is here symbolically borrowed from anthropology to describe a multi-site place where empirical learning occurred. In the current research, the field, in fact, was not only circumscribed in a single and framed place. It took place across the Innovation Center of Sustainable Technology (CRH) based in Amsterdam and the BIM laboratory Drawing to the Future in Politecnico di Torino. Moreover, it took place through physical and virtual relationships and the exchange, of tangible and informatic objects. The balance between actors and roles belonging to *the Machine* cited was governed both in-person and online. I positioned myself, sometimes in person and online, as a mediator, both actor and observer, and completely immersed myself in the context of the Laboratories by learning power relations, interests, workflow and behaviour. I became part of the net between the actor and the narrator of the story. My roles were mainly three:

1. To open a broad investigation, critical, comparative, creative and multidisciplinary aimed not only to document a process but also to create a means able to produce an effect in the world;
2. To manage as a mediator the complex net of roles, responsibilities, interests, constraints, objectives etc. (see paragraph *1.1.3 The "machine"*);
3. To narrate the story by describing and traducing the experiences conducted and assimilated both as an actor and observer.

As the mediator of a net of actors involved, my position was part of a broader panorama of stakeholders fully explained in the next paragraphs. The complexity that multi-site fieldwork and its globalized relationships and information exchange carries with it is strictly connected with the necessity of new digital technologies able to grab and manage those intricate implications. See paragraph *1.1.2 Parametric design and its power in prototyping* to discover the precise reasons.

3.1.2 The actor's map: roles and responsibilities

As introduced in the previous paragraph and in particular in *2.1.3 The "machine",* many complementary and multidisciplinary relationships were built during three years of research. The section will finally unfold, which is where the role, responsibilities, and relationship are established. The diagram (see Figure 48) describes a polarized model:

- on the one hand, **the Academy** (Politecnico di Torino, KTH Stockholm);
- in the other **the Industry** (CRH, Heijmans).

However, the polarities meet and link each other by different kinds of relationships established during the time:

A) dot-bold for the "heavy" and frequent relationship;
B) dot-thin for the relationship that is meaningful in the same way but less frequent.

Moreover, the diagram suggests information about the involvement in the research by employing different bullet sizes for every stakeholder to which it was assigned a caption to describe the name, affiliation (Academy, Industry), role and **responsibilities** (capital-bold).

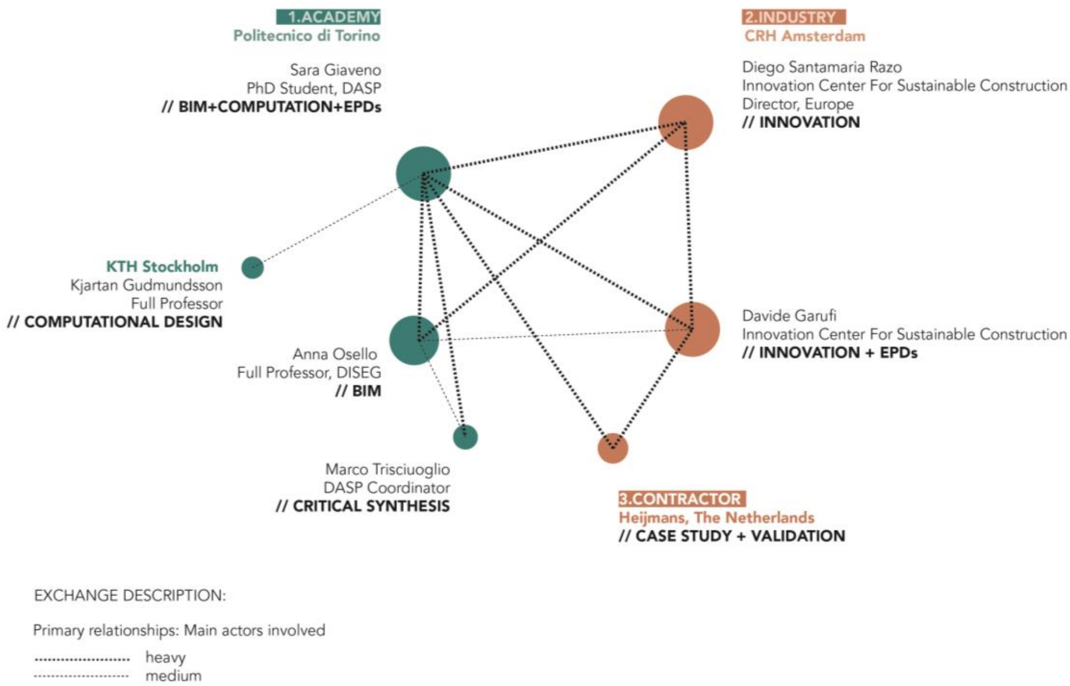

Figure 48. The actor's network: roles and responsibilities.

This kind of graphic representation is useful for interpreting the relationship that linked the actors during the research development, the exchange, the power relations, and the contribution in terms of knowledge sharing.

3.1.3 Defining gap and target

Once clarified roles and responsibilities, the following step was to define a series of meetings to find the research's target in chronological order. As it was described at the beginning of the current chapter, nothing except the target to reach was fixed before beginning the research path. The objective was clear from the starting point, but the way to reach it was subjected to attempts and tests along the PhD paths. However, preliminary meetings were helpful in deepening and discussing the “fixed” implications of the thesis methodology that had to take into account in the development of the tool. Those implications, fully described in paragraph *2.1 The research implications: matters and tools*, worked as levees to direct research and to find the best way to reach the target.

By resuming, the “fixed” implications imposed from the beginning of the research activity were[139]:

a. Establishing an Academy-Industry collaboration model;
b. Considering two main UNSDg, especially 11 (sustainable communities) and 13 (climate action);
c. Employing BIM methodologies;
d. Focusing on construction materials and related carbon emissions.

Those points were the object of long and repeated meetings aimed at merging the implications to find a suitable research objective to reach. The proposal, in the end, consisted in:

To obtain Embodied Carbon (EC) and Embodied Energy (EE) scenarios of construction materials by employing BIM methodologies and parametric and computational design.

It is clear that the target included some ***elements of indeterminacy***:

1. Which was the user of those scenarios, and how to make their creation and readiness user-friendly?
2. Which could be the better design phase to perform those scenarios?
3. Which could be the way to obtain those scenarios? By an Excel sheet, LCA software or a parametric tool?
4. How to use BIM to reach that target? Should we start with a complete model or with a prototype?

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[139] Read *Chapter 2. Interpreting implications as a design matter* for full desciption.

5. The consistency of those EC and EE had to be defined. Which were the elements those scenarios had to report, and in which units? For which materials? Should the calculation be included in the BIM model or exported in other formats?

The answers to these questions came during the time; it took almost six months to deepen the background and propose the tool's first version. To discover every answer related to the question listed, see *Chapter 4. Devising the tool for planning decisions*. However, at the moment, we are not interested in deepening the tool but in unfolding the reasons that led to the research target definition.

The step that precedes the tool proposal consisted of deepening the background of the existing methodologies to discover the current way to run the integration between BIM and Life Cycle Assessment to obtain embodied impacts.

From a list of almost twenty articles, I selected the seven fundamentals that proposed the most creative solutions (Röck et al., 2018; Peng, 2016; Najjar et al., 2017; Lee et al., 2015; Seo et al., 2007; Shin & Cho, 2015; Basbagill et al., 2013). Then, I choose nine categories of analysis to classify them:

1. **Author / Title**
2. **Research group**
3. **Topic**
4. **Case study:** building typology
5. **Operative strategy:** main passages for BIM and LCA integration
6. **Input Data:** BIM and LCA databases needed
7. **Tools for data analysis:** types and number of software employed
8. **Data exchange procedure:** Excel sheet, script
9. **Results:** type of visualization, ex. charts

This classification procedure led me to create a benchmark of the existing and current procedures to obtain embodied impact by merging BIM and LCA. From the analysis of the results, it was possible to: observe the trends, identify the most common software, highlight the potential and weaknesses of the procedures, identify the necessary input data and, in conclusion, focus on the existing gaps. Here is the image of the overall benchmark (see Figure 49), (see the extract in Figure 50 and *Appendix A* for full image resolution):

cat.	1. AUTHOR // TITLE	2. RESEARCH GROUP	3. TOPIC	4. CASE STUDY	5. OPERATIVE STRATEGY	6. INPUT DATA	7. TOOLS FOR DATA ANALYSIS	8. DATA EXCHANGE PROCEDURE	9. RESULTS
1	Röck M., Hollberg A., Habert G., Passer A. (2017) *LCA and BIM: Visualization of environmental potentials in building construction at early stages*	TU Gratz (Austria); ETH Zurich	**Decision making in early design stages:** construction options and their embodied environmental impacts.	Complete Residential building	**Conceptual BIM Model** to evaluate the variety of materials composition + LCA Database + script.	**1. BIM Model LOD 200** [foundation slab, ex. walls, fllors, roofs, windows, int. partition] **2. LCA Database** Impact x Area for building elements [impact/m2] **3. Script** total impact [m2BE]x[GPW/m2BE]	Autodesk REVIT EXCEL Database Autodesk DYNAMO	Script Dynamo: BIM Model bill of quantities and properties of building elements + LCA impact x area > total embodied impact. **BIM SOFTWARE, SCRIPT SOFTWARE**	**Total embodied impact** of building for different construction **options + visualization**
2	Pang C. (2014) *Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling , Elsevier, Journal of Cleaner Production 112, pp. 453-465, 2016.*	School of Architecture, Nanjing, PR China	Estimation of **Co2 emission** during life cycle to perform quantitative analysis	Complete Office building	LCA modeling of physical processes and BIM Model + Energy simulation tool for building perfomance.	**1. BIM Model** [bills of quantities] LOD? **2. LCA (ICE) Database** LCCO2 building emissions in construction (including production) /operation / demolition. Env Impact Ind [COE] **3. Energy simulation tool** to simulate performance with 3D design interface	Autodesk REVIT EXCEL Database Autodesk ECOTECT	From BIM to EXCEL Sheet **BIM SOFTWARE, ENERGY SIMULATION SOFTWARE**	**Charts** of total CO2 emissions in LCA
3	Najjar M., Figueiredo K., Palumbo M., Haddad A. (2017) *Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building, Elsevier, Journal of Building Engineering, 14, pp.115-126, 2017.*	Escuela Politecnica Rio De Janeiro	To empower **decision-making processes** in construction sector and to achieve sustainable development.	Complete Office building	Simulation with 2 types of building materials (modern / traditional) in BIM model to support decision making process. BIM Model + LCA Database + Energy performance tool + LCA tool	**1. BIM Model** [Material quantities, local climate] LOD? **2. LCA Database** **3. Energy performance tool** **4. LCA tool** Environmental impacts of materials **5. LCI Dataset** for TALLY **6. Tool for results Restitution**	Autodesk REVIT EXCEL Database Green Building Studio Autodesk **TALLY** in REVIT + **GaBi** Database Adobe **Photoshop**	From BIM to EXCEL Sheet **BIM SOFTWARE, ENERGY SIMULATION SOFTWARE, LCA TOOL**	**Charts** of enviromental impacts, cfr: modern/typical building materials
4	Lee S., Tae S., Roh S., Kim T. (2015) *Green Template for Life Cycle Assessment of buildings based on BIM: Focus on embodied environmental impact.*	Hanyang University, Korea	To assess **the impact** of the substances discharged from **concrete production** process on **6 env impact categories** : GWP, ADP, AP, EP, ODP, POCP.	Complete residential building	Green BIM Template (GBT) + Library of major building elements. LCI database + BIM Model + Unit conversion factor to enable evalutaion of embodied env impacts. Parametric Lybrary: Libray information + Library Data matching > Library Draw > Modeling > LCA Results.	**1. BIM Model LOD 300** quantity take-off [units of volume or surface area] **2. KOREA LCI Database** of impact factors and major building materials [Ready mixed concrete, steel, glass, concrete block, insulation material, gypsum board] by 6 impact categories Env Impact Ind [GWP, ADP, AP, EP, ODP, POCP]	Autodesk REVIT EXCEL Database	Database link to BIM Model. Impact Evaluation results can be extracted in Revit. **BIM SOFTWARE**	**Green template** -based embodied environmental impact evaluation of a test building **+ Library** of major building elements
5	Shin Y., Cho K. (2015) *Bim application to select appropriate design alternative with consideration on LCA an LCCA.*	Chosun University, Republic of Korea	To improve the LCA and LCCA performance by 3D parametric modeling.	Complete office building	Data required LCA and LCCA + BIM Model + Tool for energy analysis. (no LCA tool)	**1. BIM Model** [site, structural columns, bearing wall and slab, external skin] **2. KOREA LCI Database** [production, transport, assembly of materials] Env Impact Ind [COE] **3. Tool for Energy simulations** for Archicad	Graphisoft ARCHICAD 15 EXCEL Database Eco Designer in ARCHICAD	From BIM to EXCEL Sheet **BIM SOFTWARE, ENERGY SIMULATION SOFTWARE**	LCA **charts** (year) and **worksheets** for construction phases.
6	Seo S., Tucker S., Newton P. *Automated material selection and environmental assessment in the context of 3D building modeling. Journal of Green Building, volume 2, Number 2.*	CSIRO Sustainable Ecosystems, Australia	To provide eco-efficiency performance by directly link materials and their env impacts in BIM Models	Complete existing building	BIM model + LCI and LCC database > Eco-indicator 99 LCA Method > comparison Existing / Alternative 1.	**1. BIM Model** LOD? **2. Australian local LCI database** for emissions and resources usage of building products construction (including production) /operation / demolition	Graphisoft ARCHICAD EXCEL Database	LCI Database link to BIM Model (between material components in BIM model and LCI database of materials resource usage and emissions). **BIM SOFTWARE**	**Chart** environmental impact of alternative design and **benchmark** studies
7	Basbagill J., Flager F., Lepech M., Fischer M. (2012) *Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts*	Department of Civil and Environmental Eng., Stanford University	To provide a method for applying LCA to early stage decision-making in order to inform designers of the relative environmental impact importance of building component material	Complete residential building	BIM Model + Maintenance, repair, replacement schedule > Calculation of pre-operational carbon footprint > Energy simulation tool > LCA Tool > total embodied carbon > sensitivity analysis	**1. BIM Model** LOD? **2. Tool for Maintanance** **2. Tool for Energy consuption** **3. LCA tool** Env Impact Ind [EIF]	Dprofiler CostLab (online database) eQuest (automatically from Dprofiler) SimaPro, ATHENA EcoCalculator	From BIM to EXCEL Sheet	**Tables** of impact allocation and reduction to determine in which building components embodied impacts are concentrated

Figure 49. BIM and LCA integration benchmark.

5. OPERATIVE STRATEGY	6. INPUT DATA	7. TOOLS FOR DATA ANALYSIS	8. DATA EXCHANGE PROCEDURE
Conceptual BIM Model to evaluate the variety of materials composition + LCA Database + script.	**1. BIM Model LOD 200** [foundation slab, ex. walls, fllors, roofs, windows, int. partition] **2. LCA Database** Impact x Area for building elements [impact/m2] **3. Script** total impact [m2BE]x[GPW/m2BE]	Autodesk REVIT EXCEL Database Autodesk DYNAMO	Script Dynamo: BIM Model bill of quantities and properties of building elements + LCA impact x area > total embodied impact. **BIM SOFTWARE, SCRIPT SOFTWARE**
LCA modeling of physical processes and BIM Model + Energy simulation tool for building perfomance.	**1. BIM Model** [bills of quantities] LOD? **2. LCA (ICE) Database** LCCO2 building emissions in construction (including production) /operation / demolition. Env Impact Ind [COE] **3. Energy simulation tool** to simulate performance with 3D design interface	Autodesk REVIT EXCEL Database Autodesk ECOTECT	From BIM to EXCEL Sheet **BIM SOFTWARE, ENERGY SIMULATION SOFTWARE**
Simulation with 2 types of building materials (modern / traditional) in BIM model to support decision making process. BIM Model + LCA Database + Energy performance tool + LCA tool	**1. BIM Model** [Material quantities, local climate] LOD? **2. LCA Database** **3. Energy performance tool** **4. LCA tool** Environmental impacts of materials **5. LCI Dataset** for TALLY **6. Tool for results Restitution**	Autodesk REVIT EXCEL Database Green Building Studio Autodesk **TALLY** in REVIT + **GaBi** Database Adobe **Photoshop**	From BIM to EXCEL Sheet **BIM SOFTWARE, ENERGY SIMULATION SOFTWARE, LCA TOOL**

Figure 50. Extract from the BIM and LCA benchmark.

Classifying articles and analysing them was a strategy necessary for unfolding the **most common trends** in addressing BIM and LCA integration and highlighting the methodologies' **weaknesses**. From the benchmark, it was possible to extract the starting point "toolkit" to run the integration, consisting of *Input data, Tools for data analysis, Output* (see Table 1):

Input data	Tool for data analysis	Output
1. BIM model LOD 200/300	a. BIM software	Embodied carbon calculation (charts)
2. LCA analysis and database	b. LCA software	
	c. Energy software	

Table 1. BIM and LCA integration toolkit.

By reassuming, first of all, the common trend suggests the necessity of a BIM model LOD 200/300 and an **LCA database** from an online source or .xls. LOD 200/300 refers to the model's Level of Development (geometrical and informative attributes) expressed on a numerical scale. UNI 11337-4[140] suggests that the **LOD 200** is related to a conceptual model that contains generic forms and geometries not yet developed in detail. To be clear, the definition of LOD 200 provided by the UNI norm is:

"*..the model element is approximate as graphically within the model a generic system, object or assembly with approximate quantities, size, shape, position and orientation."* (UNI 11337-4)

According to RIBA[141] (see Appendix B), the level of model development cited could be related to **the Concept design stage**, which is the phase of the Architectural concept of a project where project briefs and preliminary strategies occur. Moreover, to run the simulation is necessary to employ three kinds of software (BIM, LCA, Energy) and be able to manage the related databases. By reassuming (see Table 2):

---

[140] See 4 section of the UNI 11337 for the complete LOD explanation.
[141] RIBA Plan of Work, see at link: https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work. Check Appendix B.

BIM skills	*LCA skills*	*LCA software licence*	*LCA database*	*Design stage*
Medium	**High-Medium**	Yes	Online LCA databases	**Concept, & Technical**

Table 2. Requirements from current methodologies.

The step subsequent to the benchmark creation was interpreting the features of the current methodologies to highlight weaknesses and potentiality. Clearly, the articles' review strategies host some difficulties and disadvantages, mainly related to BIM and LCA high-medium skills required to users, the necessity of multiple software licences, and the complexities in creating and managing LCA databases.

The new methodology

However, the intent of the research was ***not to test or employ one of the current BIM and LCA integration strategies***. The objective was to highlight the weak points of the existing methods to propose a new methodology aimed at creating a user-friendly tool for EC and EE scenarios. The process consisted in highlighting the difficulties encountered in the benchmark analysis, which were considered as the "gaps", and proposing, in return, potential advantages and new user-friendly strategies:

a. **Difficulty:** usually, LCA analyses are conducted in the Development phase, where geometrical and informative data is more available. However, at the moment of the Development phase, the influence of design choices is low.
Proposal: employing LCA in the **Concept design** stage greatly influences design choices and low costs for changes.

b. **Difficulty:** few methodologies consider the portion of emissions related to Embodied Energy impact.
Proposal: including the EE output.

c. **Difficulty:** creating, managing, reading and interpreting an LCA database require high-medium skills in the LCA sector.
Proposal: skipping the passage of a complex LCA analysis and employing only selected LCA data could facilitate the calculation phase. Therefore, the suggestion is to choose a simplified database, like the Environmental Product Declaration (**EPDs**), to run the simulation with ready-made data useful to EC and EE calculation. Moreover, unskilled users in terms of LCA can easily run the simulation in this way.

d. Difficulty: the professional use of an LCA tool requires the payment of a licence and high-medium skills in the calculation.
Proposal: employing **a script** linked to the BIM model instead of an LCA tool can avoid some difficulties. In particular, the payment of an LCA tool licence and the necessity of LCA skills. In fact, the user should only link a ready-made script with the BIM model to easily obtain EC and EE scenarios.

e. Difficulty: charts and tables usually express the EC and EE calculation.
Proposal: Create dynamic EC and EE diagrams in .pdf or .xlm formats that stakeholders can easily interpret and share. Graphical scenarios could help in results intelligibility.

By resuming, the collection of the proposal highlighted the various necessity of skipping some difficulties became the ground were to finding the research target:

A tool for planning decisions at a micro-scale in the conceptual design stage that generates dynamic environmental impact scenarios to create awareness of embodied carbon and embodied energy emissions related to the artefact.

The tool merges parametric and computational design potential to combine several data in the form of ***variables*** (material, environmental impact indicators) to obtain ***dynamics design scenarios***. The scenarios are represented by digital responsive models that dynamically modify their spatial configuration and environmental impact results when subjected to a different input.

In other words, the proposal consists in creating user-friendly carbon emission scenarios in the concept design stage by employing the integration between parametric, computational design and EPDs database.

By reassuming, here is a chart to compare the requirements imposed by current methodologies (see Table 2) and the one embodied in the new tool for decision-making proposed (see Table 3):

BIM skills	*LCA skills*	*LCA software licence*	*LCA database*	*Design stage*
Medium	**Low**	No	Online EPDs databases	**Concept**

Table 3. The requirements in the new tool for decision-making.

The paragraph gave an overview of the reasons that led to the research target definition. To have a complete framework, they should be integrated with the implications described in paragraph *2.1 The research implications: matters and tool.* To discover step by step the definition of the new tool, the tests, and the graphical output obtained, all of the answers are collected in *Chapter 4. Devising a tool for planning decisions.*

3.1.4 The actor's workflow

Setting the experiment target trigged the workflow definition. First of all, the term “workflow” intends to indicate the informatic management of the working process. The workflow includes the activities and tasks division, the roles and responsibilities assignment, deadlines, process validations, exchange information regulation, and all aspects embodied in the working process management (Del Giudice & Osello, 2021). All of these actions and activities must be coordinated and organized from the beginning of the work. Therefore, I started managing the resources (actors, equipment, technologies and moreover) and assigning roles and related tasks. I started by identifying the main actions to develop:

1. BIM modelling
2. EPDs database creation
3. Project validation sessions
4. Tool devising
5. Coordination

Then, I assigned these tasks to the stakeholders involved in the process:

a. Politecnico di Torino: academy
b. CRH: building material provider
c. Heijmans: construction company

The result can be described by the graphical restitution below (see

Figure 51), which connects actors and tasks. The diagram also considered the municipality's role in providing requirements for public tenders.

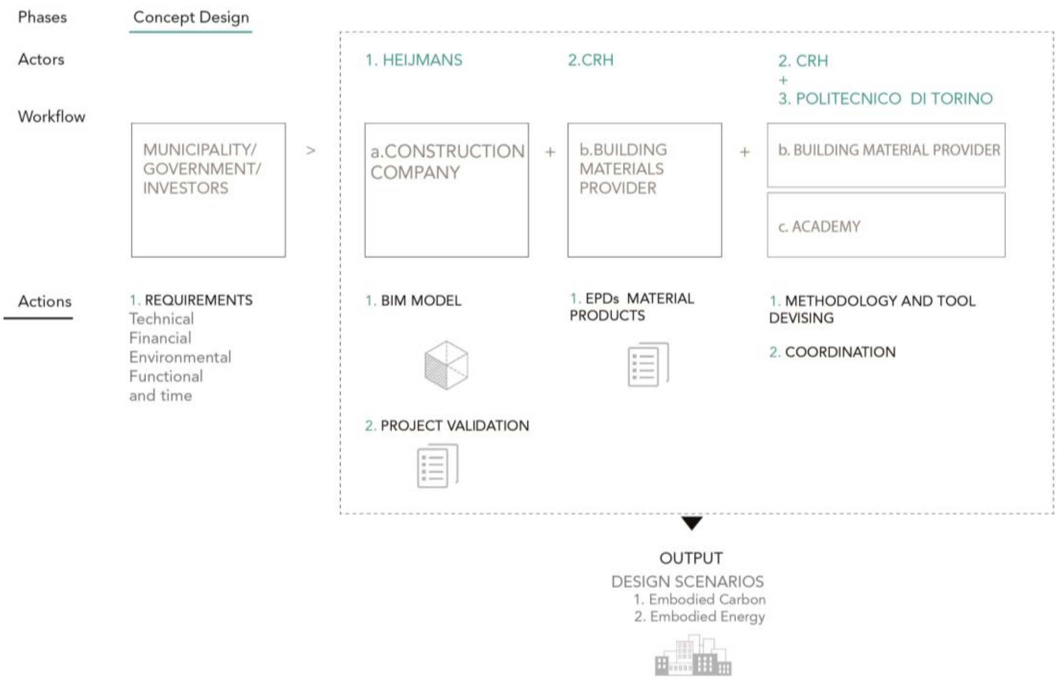

Figure 51. The workflow.

By reassuming, in order, Heijmans became the BIM model provider and the reference for the validation sessions[142]; CRH was invested by the role of creating the EPDs databases and helping in coordination activity and methodology supervision; Politecnico di Torino was responsible for the tool devising, methodology supervision and coordination. The workflow, and its organization, were aimed at a common scope: devising a tool for EC and EE scenarios. The workflow interactions made by actors and action lasted during the three years of research and allowed the constant progression and enhancement of the methodology since the complete definition of the tool. The detailed process developed over time is described by a graphical mapping process in paragraph *5.1 Interpreting the process.* Let's take a look at the maps for further curiosity.

[142] The validation session were conducted with monthly deadline by meetings that involved Heijmans, CRH and Politecnico di Torino.

3.2 Making the toolkit

The current section describes the toolkit from a much more technical perspective to clearly explain the technological choices made. In particular, the toolkit comprehends four kinds of means to perform the simulation to obtain EC and EE scenarios. In terms of requirements and specific technological means, the list (see Table 4) is the result obtained from the study conducted in paragraph *3.1.3 Defining gaps and targets* aimed at selecting the best way to reach impact scenarios target.

BIM Modelling	*LCA calculation*	*LCA database*	*Link parametric and computational models*	*Output*
Autodesk Revit 2021	**Dynamo script**	From online EPDs databases to **chart.xls**	**Shared Parameters.rvt**	**Diagrams.html Charts.rvt**

Table 4. The chart of requirements.

The choices described in the chart were not casual but driven by strategic aims, market logic, decision-making process coming from validation sessions with the stakeholders involved in the process. The following paragraphs are aimed at narrating the reasons behind the technical choices.

3.2.1 Software and model uses

The software choices were made during the time and were subjected to multiple tests and validations. The first necessity was to identify software for parametric modelling. The **Autodesk Revit** selection occurred mainly for two reasons:

1. The stakeholders involved (CRH and Heijmans) had previous knowledge of the software and were interested in implementing its use in their design workflow, mainly due to the impending obligation for public tenders.
2. The bibliography recognition about the current methodologies (see paragraph *3.1.3 Defining gap and target*) to integrate BIM and LCA suggested using Revit software due to its compatibility with LCA plug-in (Tally, One-click LCA) and its efficiency in managing BIM modelling (Röck et al., 2018; Peng, 2016; Najjar et al., 2017; Lee et al., 2015).

The decision to not employ existing software but devise a script was undertaken after attempts and decision processes. When the necessity of creating a script was embraced (see for the details paragraph *3.1.3 Defining gap and target*), the choices for a computational design software fell on **Dynamo** due to simple reasons:

1. Dynamo is a Revit plug-in, a characteristic that ensures high interoperability with the parametric software. The script is strictly related to the parametric model attributes and information, and this guarantees a real-time reading of results in terms of geometries and calculation.
2. The Autodesk software house provides an online guide for free learning.

As anticipated in the previous paragraphs, the choice was to employ a script linked to the BIM model instead of an LCA tool to avoid some difficulties. In particular, the payment of an LCA tool licence and the necessity of LCA skills. However, it was necessary to use LCA data, particularly the EPDs database, to run the EC and EE simulation. Currently, there is no standard for the EPDs database, which implies the difficulty of linking Dynamo directly with the EPDs data. Therefore, the strategy was to create an **Excel** standard format table that transcribed the data needed for EC and EE calculation (see paragraph *4.1.1 Materials and Methods* for further details). Here is some consideration:

1. There is not a standard format for EPDs. Excel allows the creation of a standard template for Dynamo, but the data must be manually transcribed; therefore, it is necessary to avoid possible errors.
2. Excel perfectly fits with Dynamo software.

In conclusion, the last step consisted in defining the model uses that identify and collate the Information Requirements that need to be delivered as – or embedded within – 3D digital models[143]. It is a standard to help in describing and transmitting information, documents, and data uses. In particular, the classification of the research study is (see Table 5):

Code	4250
Mode use series	simulating and quantifying
Model use	Life Cycle Assessment

Table 5. Model use.

143 See https://bimexcellence.org/wp-content/uploads/211in-Model-Uses-Table.pdf for further details and information about BIM uses.

In particular, Life Cycle Assessment is a model use to represent how multiple methods are applied to BIM models to identify and assess the environmental impacts of building products and materials over their whole life[144].

3.2.2 Selecting the case study: an architectural prototype

The case study choice was the object of several discussions among the stakeholders involved in the process (see paragraph *3.1.2. The actor's map*). Subsequent meetings led to the selection of an ***architectural prototype*** as the object for testing the assembling of the new tool. In particular: an architectural model, conceptual prototype, LOD 200[145]. Clearly, working on a prototype implies some criticalities and limits that it is necessary to take into account and be conscious of[146]; however, it embodies some potentiality that well fits the thesis purpose:

1. The prototype is an objected not situated, which implies the impossibility to subject your model to social and environmental implications (that need to be artificially simulated);
2. Prototype well fits a grade of the detail requested in the **Conceptual design stage** (RIBA, 2020), in which the digital model should correspond to a LOD 200[147]: a model or an object with generic dimensions, forms, and quantities (ACCA, 2017).
3. Prototype embodies a high grade in manipulation: forms, quantities, materials, and dimensions can be modified easily without great constraints. Therefore, a prototype is suitable when the simulation's **purpose is to test the technical requirement of a methodology.**

Once defined that employing a prototype well fitted with the necessities imposed by the workflow and the research purposes, the subsequent step was looking for an architectural model to select as a case study. Heijmans, the construction company, proposed one of its dutch residential BIM models thought for a new expansion in Amsterdam. The dutch house case study was cleaned of some accessories details to fits with LOD 200 requirements. At this point, the Architectural Prototype[148] became an object subjected to manipulations in terms

[144] BIM Dictionary, see https://bimdictionary.com/en/life-cycle-assessment/1
[145] See paragraph *3.1.3 Defining gap and targets* for further details about LOD and (ACCA, 2017).
[146] Read *0.5 Conceptual background* and *Chapter 6. Concluding remarks.*
[147] LOD 200 corresponds with LOD B (UNI, 11337).
[148] Along the thesis the Architectural Prototype will be written in capital letters to indicate the case study.

of forms, geometries, and materials that embodied the scope of reaching the final form of the digital tool.

Chapter 4 and, in particular, *paragraphs 4.1.4* and *4.1.5* about the validations sessions and the making of the scenarios, explain in detail the progression of the digital tool development as the result of multiple tests on the Architectural Prototype. Here are some images captured from the Revit digital model (

Figure 52, Figure 53, Figure 54, Figure 55):

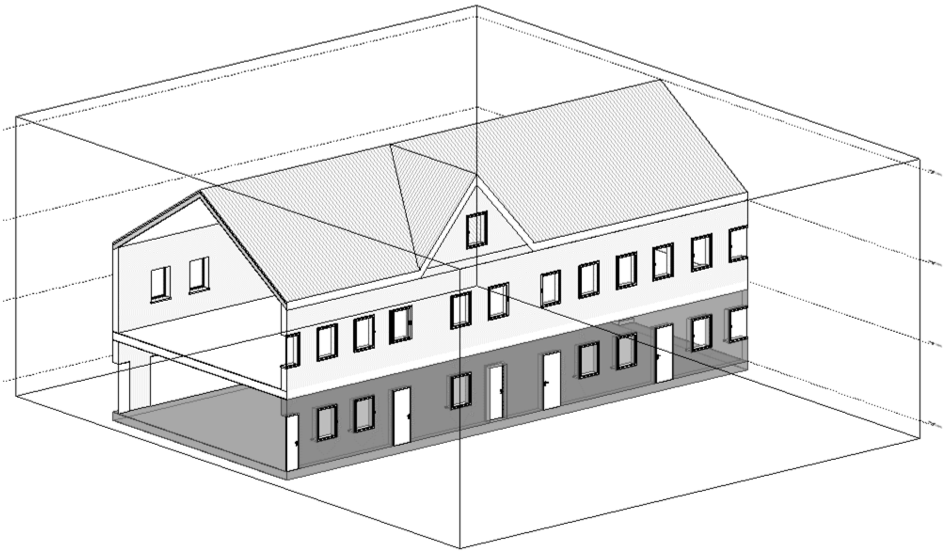

Figure 52. The Architectural Prototype in perspective by Heijmans.

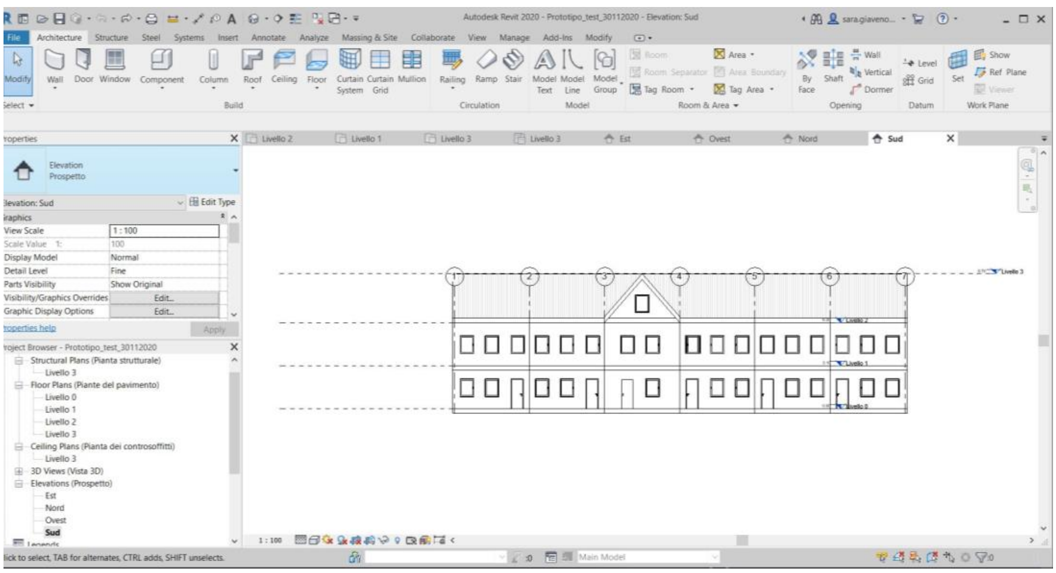

Figure 53. The architectural Protoype elevation Sud, Revit interface.

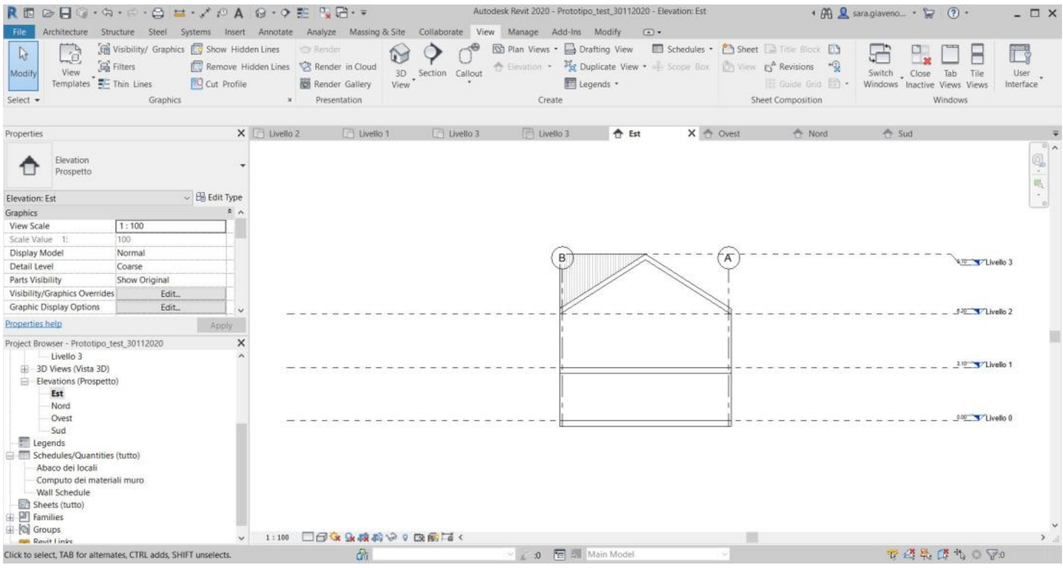

Figure 54. The Architectural Prototype Est elevation, Revit interface.

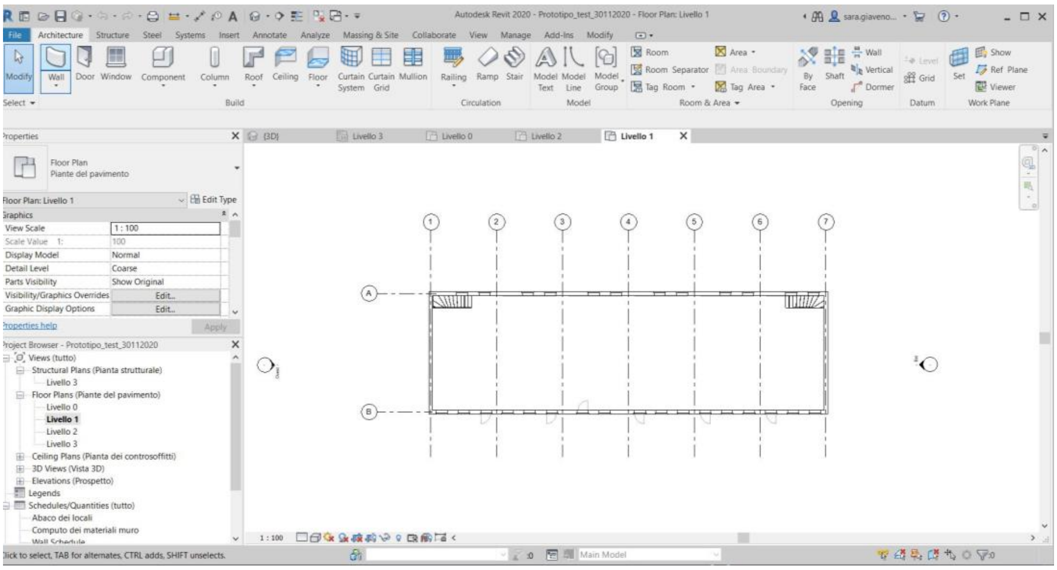

Figure 55. The Architectural Prototype, plan, level 0, Revit interface.

Chapter 4

Devising the tool for planning decisions

The chapter[149] belongs to *The laboratory experience* section, and it is dedicated to practically addressing the tool devising, describing the phases of creation and validation and positioning toward existing methodologies. It illustrates and discusses the original contribution of the thesis.

The chapter makes use of the discussed notions, implications and premises of the experiment to narrate the stages that led to elaborate a digital tool addressing the research proposal[150]. At this point, the laboratory experience is instrumental in setting up the socio-technical context where the tool can be assembled and tested. In particular, the chapter unfolds the detailed phases of the tool assembly work, the methodology set up for its realization and the chronological validations. It illustrates the outcome, consisting of a digital tool for planning decisions that merges parametric and computational procedures to create environmental impact scenarios, in the form of dynamic diagrams, at a micro-scale in the conceptual design stage. The chapter documents the detailed assembly work and illustrates the tool's functioning in its process and results. It unfolds the digital tool's model/data responsiveness, its potential in hybrid configurations and decision-making scenarios creation.

The next chapter will is dedicated to tracing the critical discussion and observations of the process and results in their theoretical and practical challenges and the transformative tool power over traditional design practices.

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149 (parts extracted from the article: Giaveno, S., Osello, A., Garufi, D., Santamaria Razo D. (2021). *Embodied Carbon and Embodied Energy Scenarios in the Built Environment. Computational Design Meets EPDs*. Sustainability, 13).
150 Carefully read *Chapter 2* and *Chapter 3* for preliminary notions.

4.1 The assembly work

4.1.1 Materials and methods

The first step consisted of studying the findings from the specific literature concerning BIM and LCA integration, analyzing the related issues listed in the previous chapter, and looking for a gap in the current methodologies.

The strategy adopted was ***not to test a current method but to create a new one aimed at building a tool***. In particular, we focused our attention on creating a new digital method to perform impact analysis without the need for high skills in BIM and LCA software and licences. In addition, a strategic requirement identified was, however, avoiding the impact evaluation during the latest phases of design (Development and Technical, see Figure 56) to focus on the conceptual design stage where the influence on design changes is great, and the costs of them are very low. The concept is well expressed by the Mc Leamy curve (Ilozor & Kelly, 2012) (see Figure 56) that compares the design effort in the different design phases that occurred between the employment of the traditional design process and integrated design process (BIM methodologies). The effort in the BIM process (green line) is focused on the conceptual stage, where the influence of choices is very high.

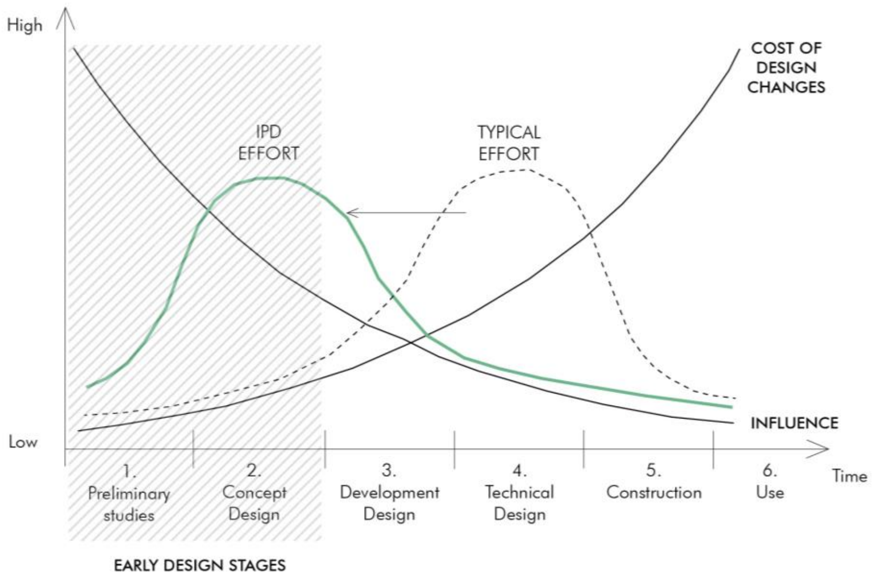


Figure 56. Mc Leamy curve.

Introduction to methodology requirements and EPDs

Later, we listed a series of indispensable requirements (see Table 6) to simplify the conditions imposed by the traditional methodologies by taking into account some comparison parameters:

1. BIM skills
2. LCA skills
3. LCA software licence
4. LCA database
5. Design stage

The result was a tailor-made list of requirements to perform impact evaluation simulations by avoiding high skills and licences (see Table 6):

BIM skills	*LCA skills*	*LCA software licence*	*LCA database*	*Design stage*
Base	**Base**	NO (script)	**EPDs** (simplified for few impact categories)	**Conceptual**

Table 6. Requirments from the new digital methodology.

The main hypothesis, according to the chart above, is described below. It highlights the advantages that the new methodology could provide:

a) **To bypass the use of the LCA software in favour of a tailor-made script** created with Dynamo (already integrated into the Revit software);
b) To select specific values of LCA called **EPDs** (Environmental Product Declaration) in order to consider the whole life of the building;
c) To focus on the **conceptual** design stage.

At that moment, it is necessary to clarify the EPD definition and justify its employment. An EPD (Environmental Impact Declaration) is a declaration about the environmental performance of a product or service: this declaration follows the voluntary certification scheme expressed by the ISO 14025 standard and, for buildings, also by the standard EN 15804. The recipients of an EPD are all the company's stakeholders that produce a product or provide a service and all those who are directly or indirectly involved in the use of that product/service. Moreover, the EPDs results are presented in a user-friendly interface, and they are summarized through the use of life cycle indicators and seven main ***environmental impact indicators:***

1. Global Warming Potential (GWP)
2. Ozone Depletion Potential (ODP)
3. Photochemical Ozone Creation Potential (POCP)
4. Acidification Potential (AP)
5. Eutrophication Potential (EP)
6. Abiotic Depletion Potential for No Fossil Resources (ADPE)
7. Abiotic depletion potential for fossil resources (ADPF)

These indicators are listed with the corresponding values for every design phase from production to the recycling potential[151]:

- A1–A3 Production
- C1 De-construction
- C2 Transport
- C3 Waste processing
- D Recycling potential

However, in order to calculate the Embodied Carbon and Embodied Energy scenarios, it is not necessary to consider all of the information contained in the EPDs chart but only focus on a few impact categories suited for $kgCO_2$ and MJm^3 calculation. To calculate:

1. The embodied Carbon (kg CO_2 eq) for a single product and the whole building;
2. The embodied Energy (MJm^3) for a single product and the whole building.

One environmental impact indicator and three life cycle indicators were employed (see
Table 7):

Environmental impact indicator	GWP (Global Warming Potential)	**kg CO_2 eq**
Life cycle indicators	PENRT (Total use of non-renewable primary energy resources)	**MJ**
	RSF (Use of renewable secondary fuels)	**MJ**
	NRSF (Use of non renewable secondary fuels)	**MJ**

Table 7. Indicators employed in the tool.

[151] The final version of the tools contains the values from phase A1-D.

The indicators listed were employed due to their power in influencing the embodied carbon values and the embodied energy calculation; however, the list of indicators considered can be implemented according to need.

Here is attached a chart of typical EPDs extracted from the Okobaudat database[152] (see
Table 8).

Indicator	***Unit***	***Production A1-A3***	***De-Construction C1***	***Transport C2***	***Waste Processing C3***	***Recycle Potential D***
Global warming potential (GWP)	kgCO2 eq.	84.48	0.3623	1.404	3.52	−0.9855
Ozone Depletion Potential (ODP)	kg R11 eq.	$7.576\text{x}10^{-13}$	$1.208\ \text{x}10^{-16}$	$4.646\ \text{x}10^{-16}$	$1.994\ \text{x}10^{-14}$	$-1.902\ \text{x}10^{-14}$
Photochemic. Ozone Creation Potential (POCP)	kg Ethene eq.	0.002	0.000	0.000	0.002	0.000
Acidification potential (AP)	kgSO2 eq.	0.106	0.001	0.002	0.022	−0.002
Eutrophic. potential (EP)	kg Phosphate eq.	0.019	0.000	0.000	0.003	0.000
Abiotic depletion potential for non-fossil resources (ADPE)	kg Sb eq.	0.000	$3.07\ \text{x}10^{-8}$	$1.181\ \text{x}10^{-7}$	0.000	$-2.19\ \text{x}10^{-7}$
Abiotic depletion potential for fossil resources (ADPF)	MJ	433.2	4.891	18.82	57.03	−11.92

Table 8. Precast concrete EPDs chart from Okobaudat.

However, the EPDs databases are currently under development; no common format and template have already been standardized. Due to the ***lack of an EPD format and template***, it is necessary at the moment to create a standard chart.xls to integrate the EPDs values into Dynamo. A Dynamo script, in fact, is programmed to read values by following columns and lines, implying a necessary use of a template for multiple simulations.

[152] Okobaudat is an online database available at the link: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=bdda4364-451f-4df2-a68b-5912469ee4c9&version=20.19.120&stock=OBD_2021_II&lang=en

Adding computational power

According to the *Introduction to methodology requirements and EPDs* paragraph, one of the greatest tool requirements is to bypass the use of an LCA tool to avoid:

1. high-medium LCA skills,
2. the payment of a licence,
3. anticipate decision before Development and Technical phase.

In order to bypass these steps, the strategy was to combine parametric architecture with visual programming and an EPDs database. The following chart shows all of the possible ***advantages*** coming from the new methodological proposal consisting of the integration between a BIM software (.rvt), a Dynamo script (.dyn), and an EPDs database (.xls) during the concept design stage (see Table 9):

Tool advantages

Devising and employing a Dynamo Script
1. Dynamo is a Revit Plug-In: a direct link between the 3D model objects and the EPDs calculation into Dynamo;
2. The creation of dynamic impact scenarios for decision making with a single click;
3. No skills or licence for any LCA software is required;
4. No technical skills for impact analysis are necessary.
Dynamic impact scenarios for Concept Design
I. Anticipate impact analysis from the Technical Design Phase to the Concept; II. Reduce design changes in the latest phases of design; III. Add quality in design; IV. Promote the use of sustainable products.

Table 9. New tool advantages.

4.1.2 The methodological proposal: impact evaluation in the concept design stage

The methodological framework consists of ***integrating the potential of BIM modelling with visual programming calculation through the use of a script and an EPD database.***

Here is the chart (see Table 10), which resumes the main data in terms of software, format and information:

	BIM Modeling	**Visual Programming**	**Program Operator**
Software	Revit (2020)	Dynamo	Oekobaudat EPDs.pdf
Format	.rvt	.dyn	.xls
Information	LOD 200		(GWP), (PERNT, RSF, NRSF) A1-D

Table 10. The methodological framework.

The information listed in the chart above is combined into a graphical workflow that contains the **actors** involved in the project:

a. POLITO, Academia;
b. CRH, Building Materials Provider;
c. HEIJMANS, Construction Company based in the Netherlands)

The chronological **activities** of each stakeholder:

1. Creation of the EPDs for materials employed in the simulation;
2. Creation of an EPDs.xls format suitable for Dynamo;
3. BIM Model creation LOD 200 (focus: walls, floors, stairs);
4. Devise a Dynamo script for EC and EE calculation;
5. Test the integration between the model and the script;
6. Save diagrams.html and consult tables.pdf;
7. Compare diagrams.html with solutions (parameters: form/materials) for decision-making.

The **responsibilities** in the process and the **tools employed:**

I. Autodesk Revit (2020): BIM modelling
II. Dynamo: script creation
III. Online Database: EPD selection
IV. Excel: EPD format for Dynamo

The entire **workflow** cames from the combination of actors, actions, responsibilities and tools and it is divided into several steps listed below:

Actor/ **CRH**; Action/ Creation of the EPDs chart for several materials;
Actor/ **POLITO**; Action/ Transform the EPDs into a .xls format for Dynamo;
Actor/ **HEIJMANS**; Action/ Create a 3D Model LOD 200;
Actor/ **POLITO**; Action/ Create a Dynamo script for EC and EE calculation;
Actor/ **POLITO**; Action/ Test the integration: model and the script;
Actor/ **POLITO**; Action/ Save diagrams and consult tables;
Actor/ **POLITO-CRH-HEIJ.**; Action/ Compare scenarios for decision making.

The digital methodology

The graphical methodology of the activities (see Figure 57) combines actors, actions, tools, input and output and responsibilities. By reassuming the graphical methodology here are the main passages:

I. The EPDs results from online databases are converted into a template.xls. The data **EPD.xls** are linked in the script.dyn;

II. The artefact is modelled in LOD 200 (computational design level of detail) with Revit Autodesk software; the **model.rvt** is connected to the Dynamo plug-in;

III. The **scrip.dyn** merges the EPDs.xls data with the geometric info of the parametric model. The script combines three kind of variables:
   a. The volume of the geometrical entities;
   b. EPDs data and related environmental impact indicators;
   c. The typology of materials

IV. The script combines data in a dynamic graphical output consisting in **diagrams.html** and charts.rvt.

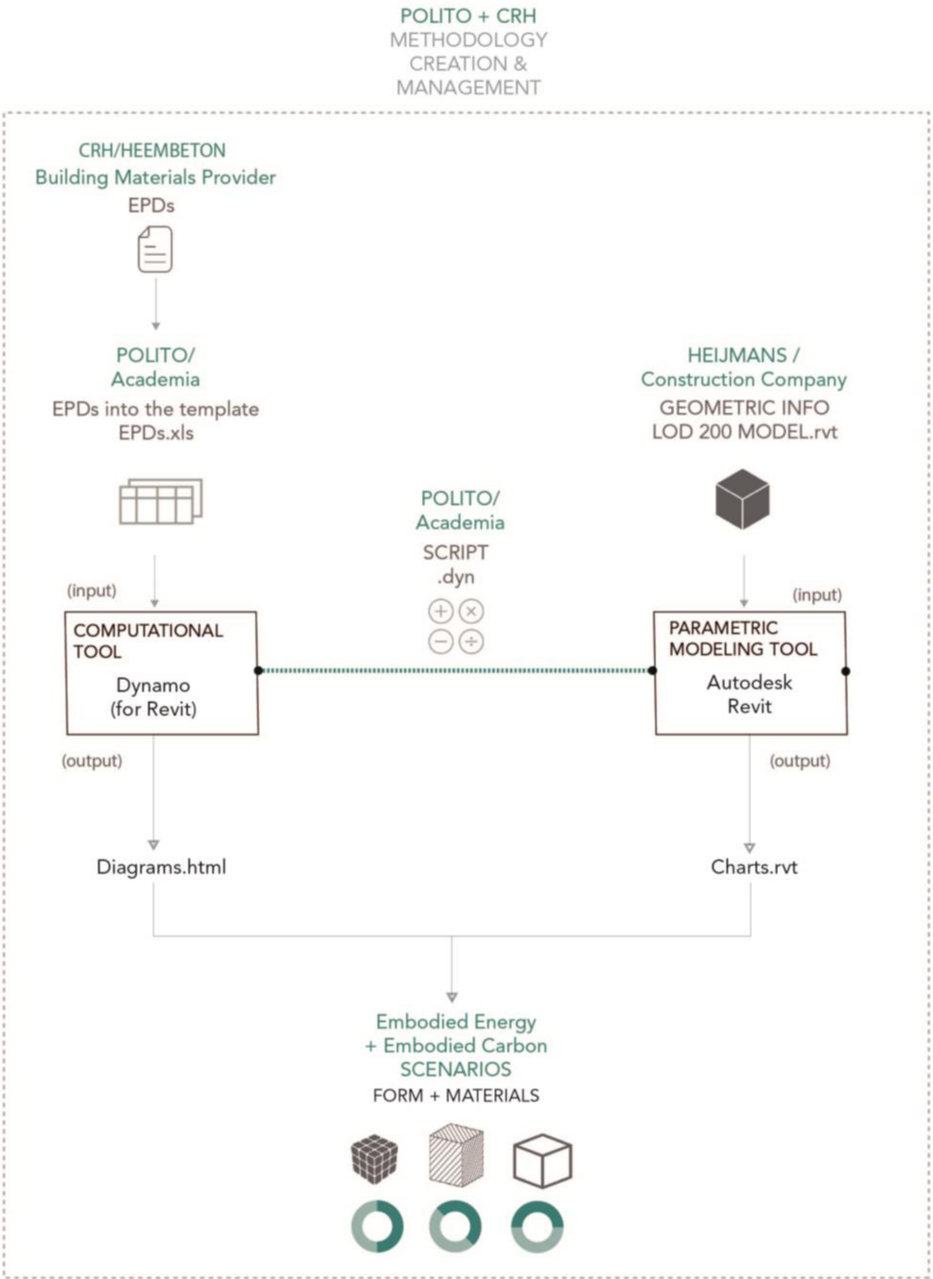


Figure 57. The graphical methodology.

4.1.3 Programming the script: integration between parametric and computational design

The following section is dedicated to explaining the script assembly by showing details related to the four blocks programmed:

- **a.** The Embodied Carbon calculation;
- **b.** The Embodied Energy calculation;
- **c.** The Shared Parameters creation;
- **d.** The Diagrams creation.

a. <u>The Embodied Carbon calculation</u>

The Embodied Carbon calculation requires some passages:

Previous: Select an EPD of material to simulate and put the **GWP** data into a template.xls. Sum the GWP A1-D to obtain the overall value for Dynamo simulation (box rounded); keep attention if the value is expressed for one cubic meter. Here is attached an example (see

Table 11):

161.7						
GWP A1-D SUM						
GWP A1-A3	GWP C1	GWP C2	GWP C3	GWP C4	GWP D	SUM
1,55E+02	3,30E+00	4,55E+00	3,06E+00	1,57E+00	−5,778E0	
155	3,3	4,55	3,06	1,57	-5,78	161,7

Table 11. Example for EC EPDs template.xls

Phases of the script creation:

Block A: Import the chart EPD.xls into Dynamo (GWP kg CO_2 eq phase A1–D) (see Figure 58, see Figure 59);
Block B: Type selection (walls) and quantities extraction from Revit Model (category: walls) (see Figure 60, see Figure 61);
Block C: The Embodied Carbon formula: link the quantities in m^3 of every architectural category with the GWP value in kg CO_2 eq (expressed for one cubic meter). The result is the overall kg CO_2 eq for the architectural category considered, in this case, walls (see Figure 62).
Repeat the passages for the other architectural categories: floors and stairs.

Block A.

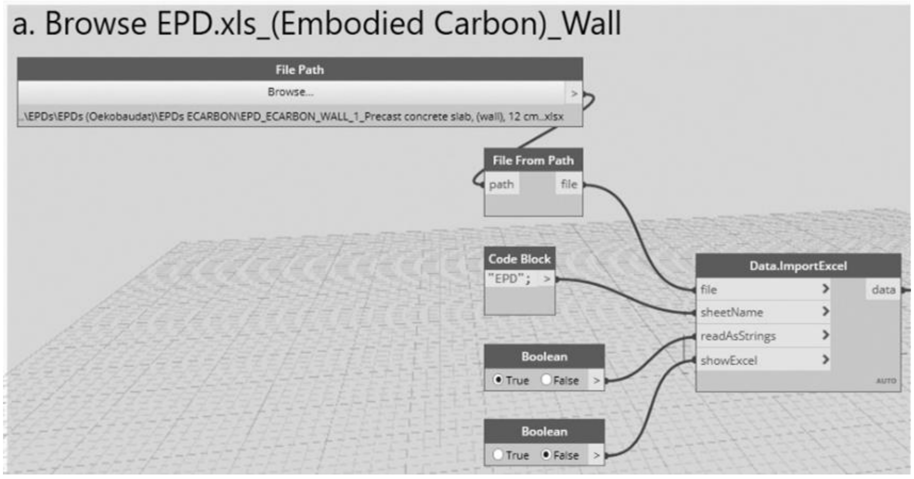


Figure 58. EPD.xls import in Dynamo.

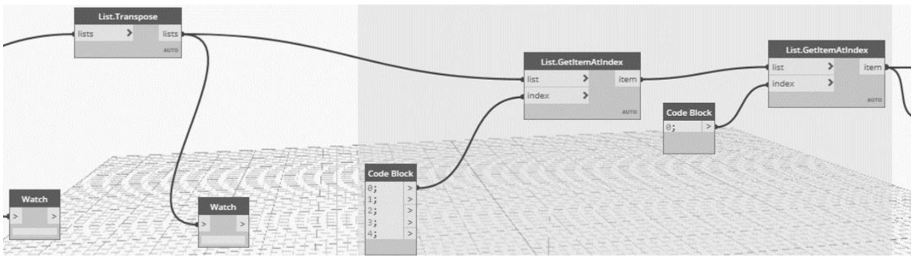


Figure 59**.** Select the EC. Sum

Block B.

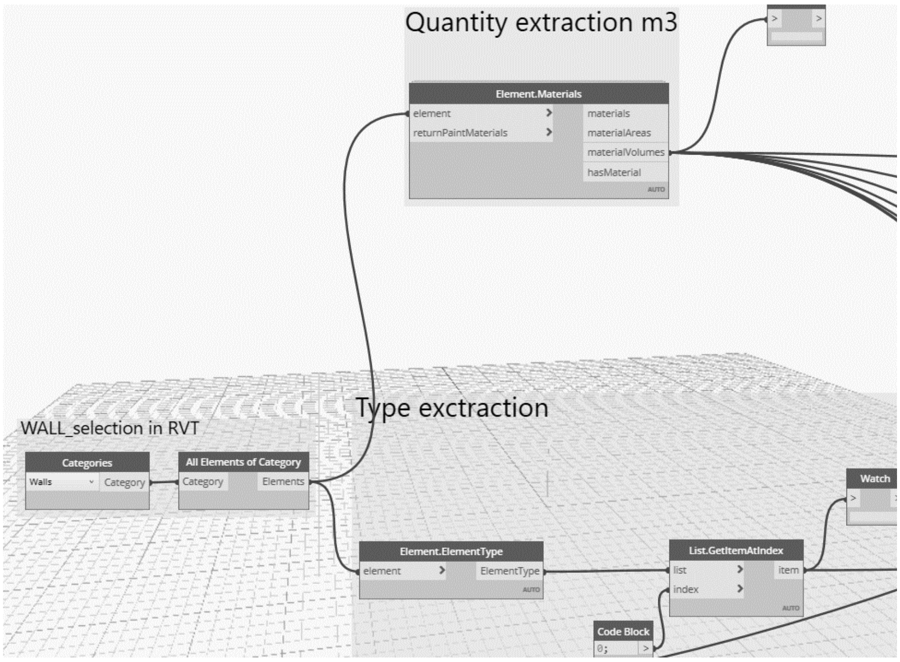


Figure 60. Type selection and quantity extraction from Revit model.

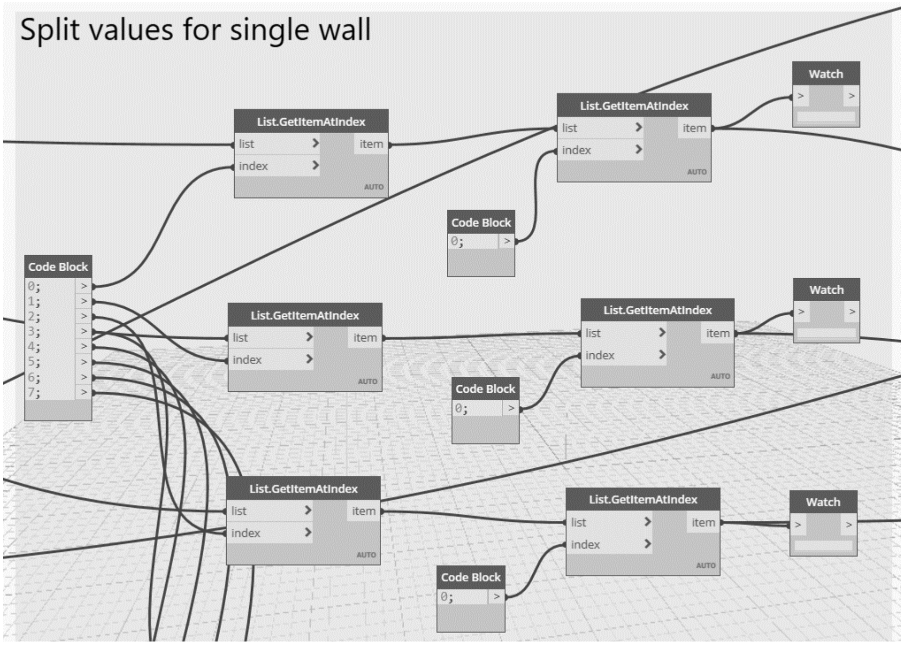


Figure 61. Organizing EC data.

Block C.

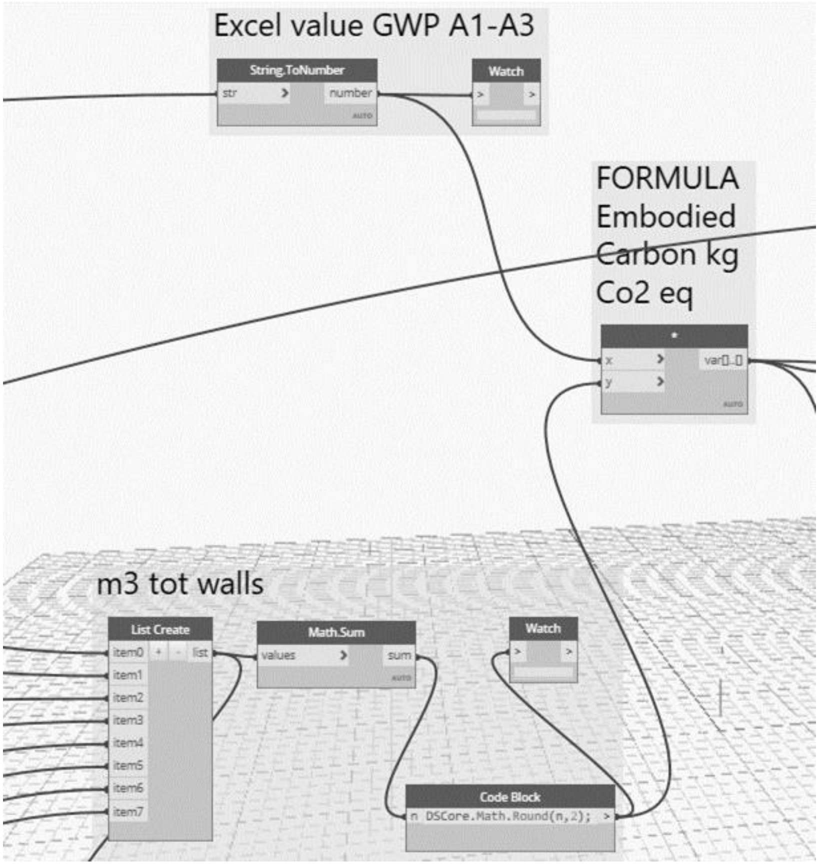


Figure 62. Embodied Carbon calculation formula.

b. The Embodied Energy calculation

The Embodied Energy calculation requires some passages:

Previous: Select an EPD of material to simulate and put the **PERNT, RSF, NRSF** data into a template.xls. Sum the PERNT, RSF, NRSF A1-D to obtain the overall value for Dynamo simulation (box rounded); keep attention if the value is expressed for one cubic meter. Here is attached an example (see Table 12):

551.68	0	0	551.68
PENRT	RSF	NRSF	PENRT_RSF_NRSF SUM
4,83E+02	0	0	
4,90E+00	0	0	
1,89E+01	0	0	
5,85E+01	0	0	
-1,32E+01	0	0	
TOT			
551,68	0	0	

Table 12. Example for EE EPDs template.xls.

Phases of the script creation:

Block D: Import the chart EPD.xls into Dynamo (PERNT, RSF, NRSF in MJ, phase A1–D) (see Figure 63, see Figure 64).
Block E: Type selection and quantities extraction from the Revit Model (category: walls) (see Figure 65, see Figure 66);
Block F: The Embodied Energy formula: link the quantities in m^3 of every architectural category with the PERNT, RSF, NRSF total MJ. The result is the overall MJm^3 for the architectural category considered, in this case, walls (see Figure 67).

Repeat the passages for the other architectural categories: floors and stairs.

Block D.

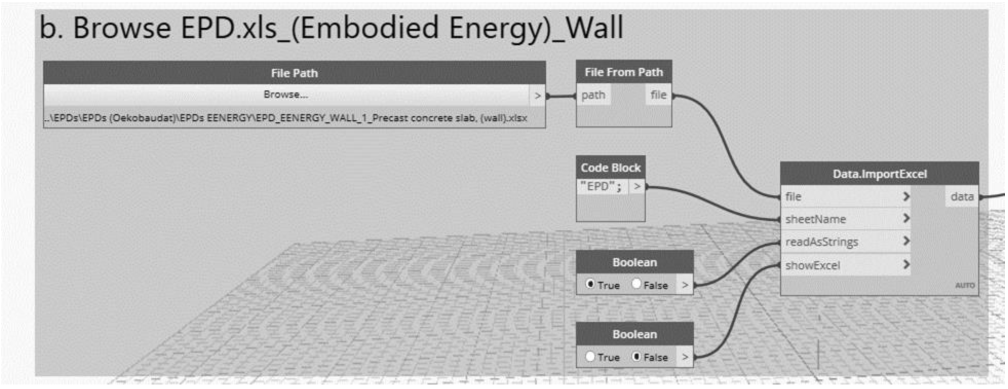


Figure 63. Import EPD.xls values for EE calculation.

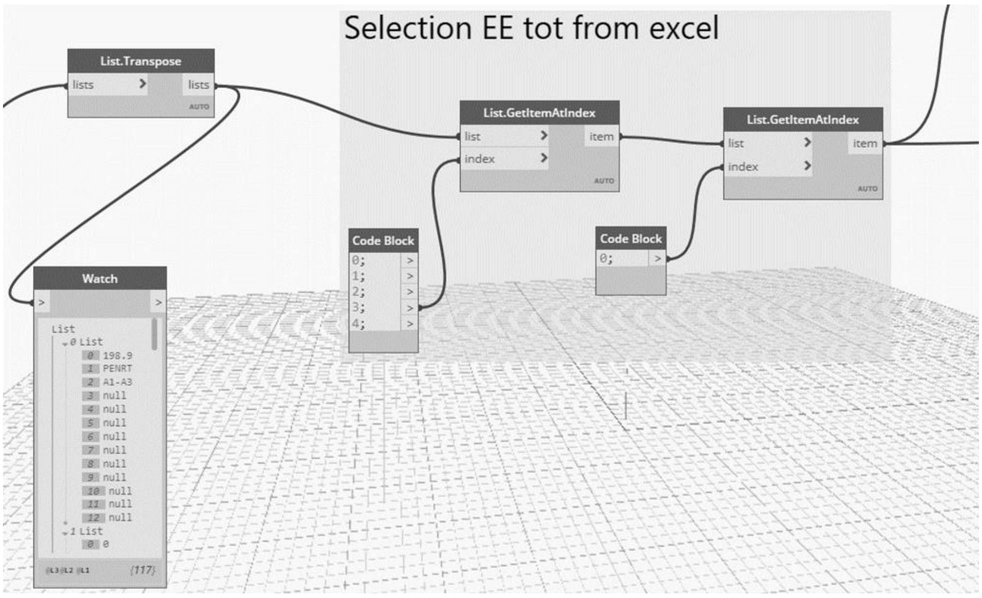


Figure 64. Select the EC sum.

Block E.

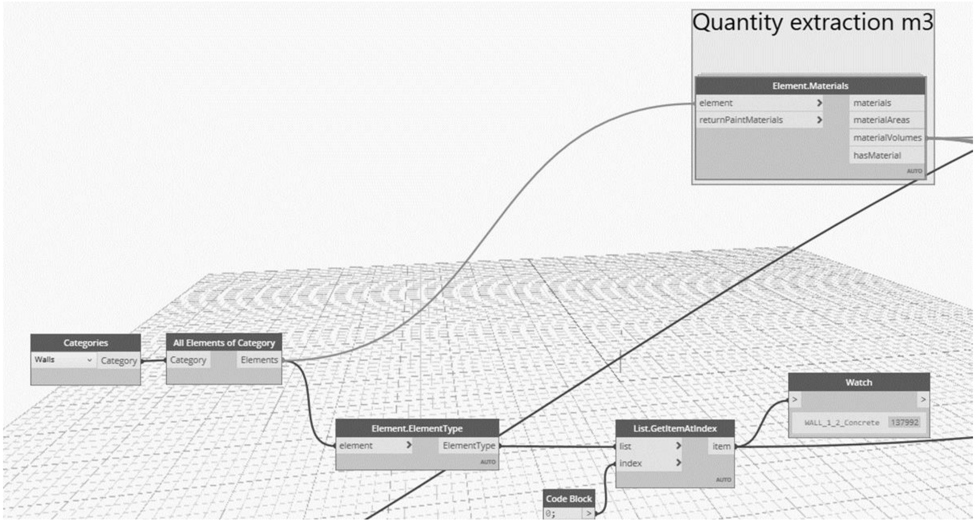


Figure 65. Type selection and quantity extraction from Revit model.

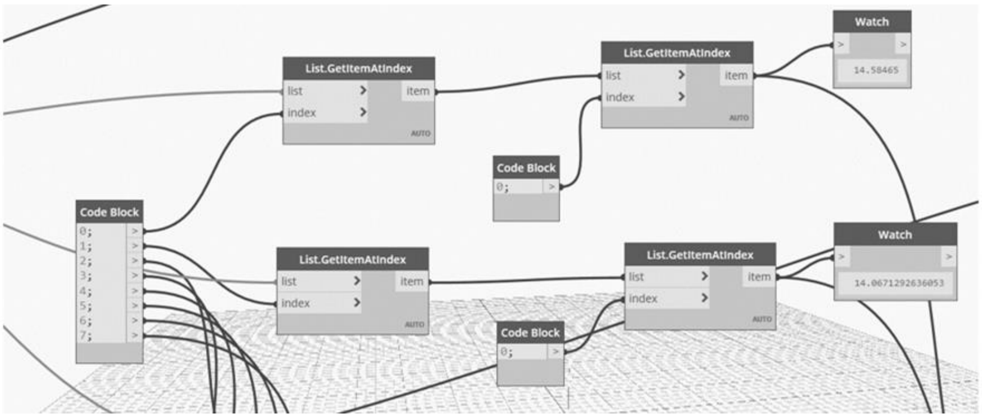


Figure 66. Organizing EE data.

Block F.

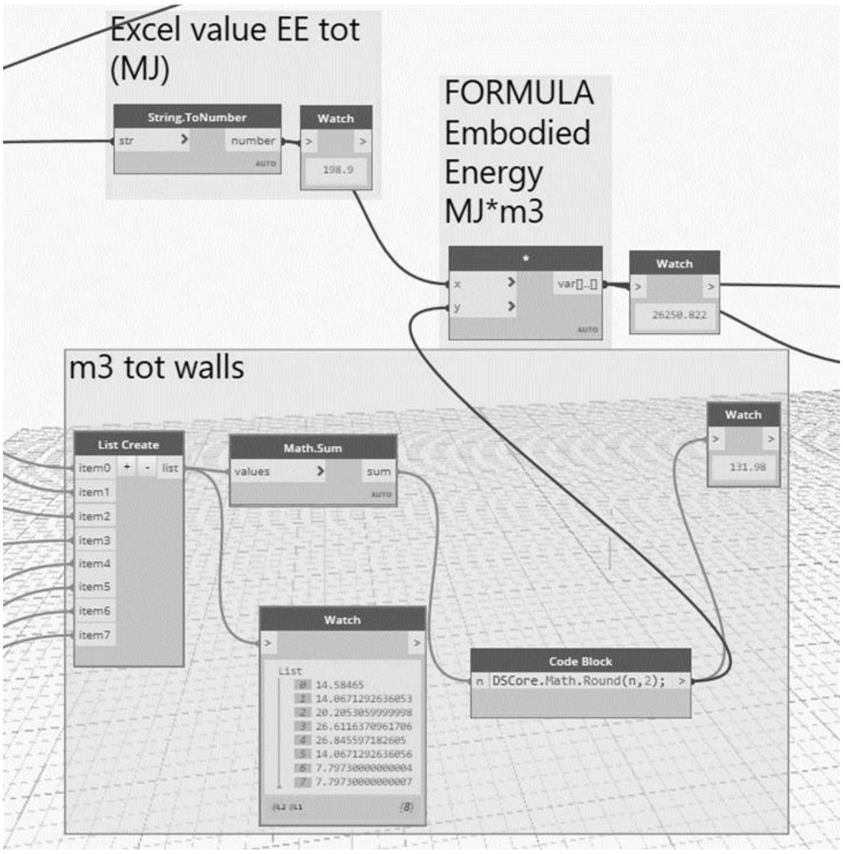


Figure 67**.** Embodied Energy calculation formula.

Now that EC and EE are calculated for both a single element of a model category and the overall categories, it is necessary to make them readable outside Dynamo. ***To perform the readiness of the scenarios***, it is necessary to program the script for **two tasks**:

- **I.** The shared parameters creation: to read the calculation directly into the Revit model by questioning the “Edit Type” within the family;
- **II.** To create EE and EC scenarios.html: to export the diagrams.html outside the software and make them sharable.

c. <u>The shared parameters creation</u>

The Shared Parameters (SP) creation is a passage commonly developed into the Revit model. It is needed to link data with multiple families in the format.rvt. However, creating SP into Revit requires medium-high skills in BIM model management. Therefore, the proposal is to build the SP directly into Dynamo so the end-user can skip the passage of the creation and does not need to acquire more competencies in BIM model management.

Block G: Create the block for the SP and repeat the action for every category involved in the Embodied Carbon and Embodied Energy calculation, in this case, floor, walls, stairs (see Figure 68).

Block G.

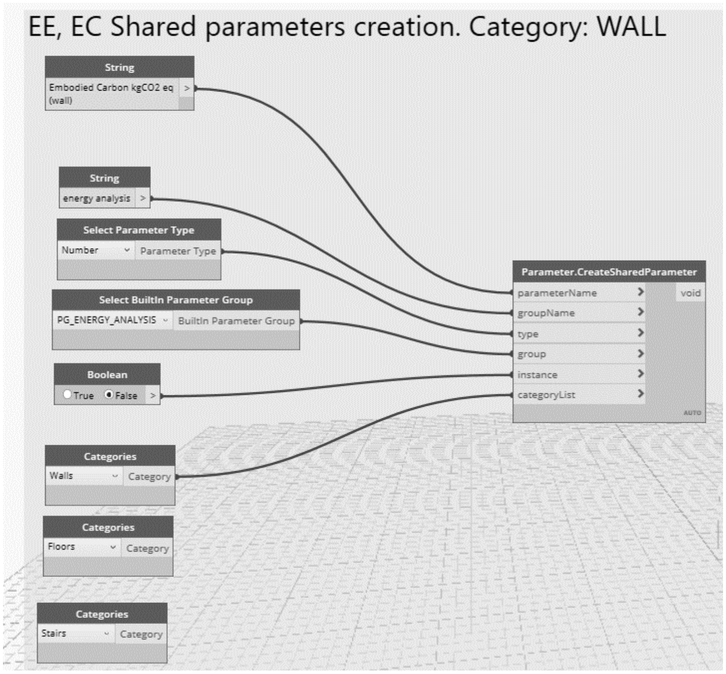


Figure 68. Shared parameters creation.

d. <u>The diagrams creation</u>

The diagrams.html is useful to visualize the EC and EE calculation results outside the software. The diagrams.html are tailor-made programmed, in terms of data and graphical output, to be shared and read easily by other stakeholders.

The diagrams block is organized with the following steps:

Block H: Insert the overall results related to EC calculation (see Figure 69);
Block I: Choose the type (e.g., pie chart) and the style (colours, lines, etc.) of your diagram (see Figure 70);
Block L: Choose the export format: .pdf or .html (see **Figure 71**).

Finally, repeat the passages for the Embodied Energy chart creation.

The graphical output coming from the diagram creation and the possible employment will be explained in detail in the following paragraph. The objective is to highlight the advantages and disadvantages of the method and underline the digital tool's potential.

Block H.

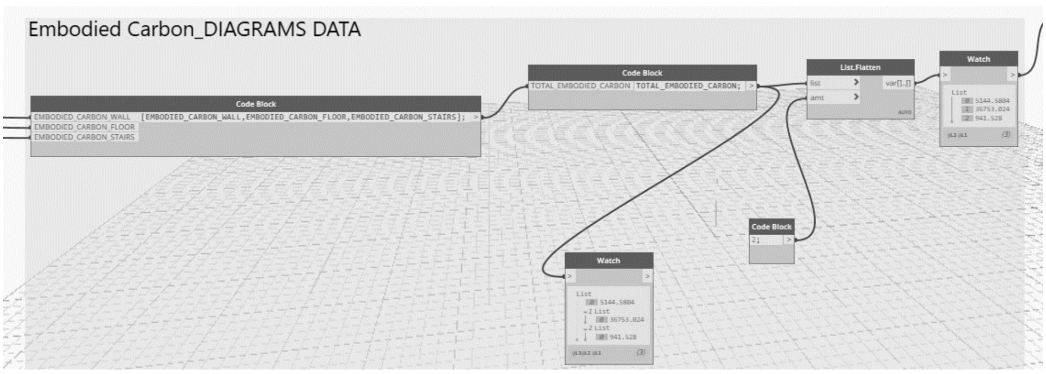


Figure 69. Select the EC values.

Block I.

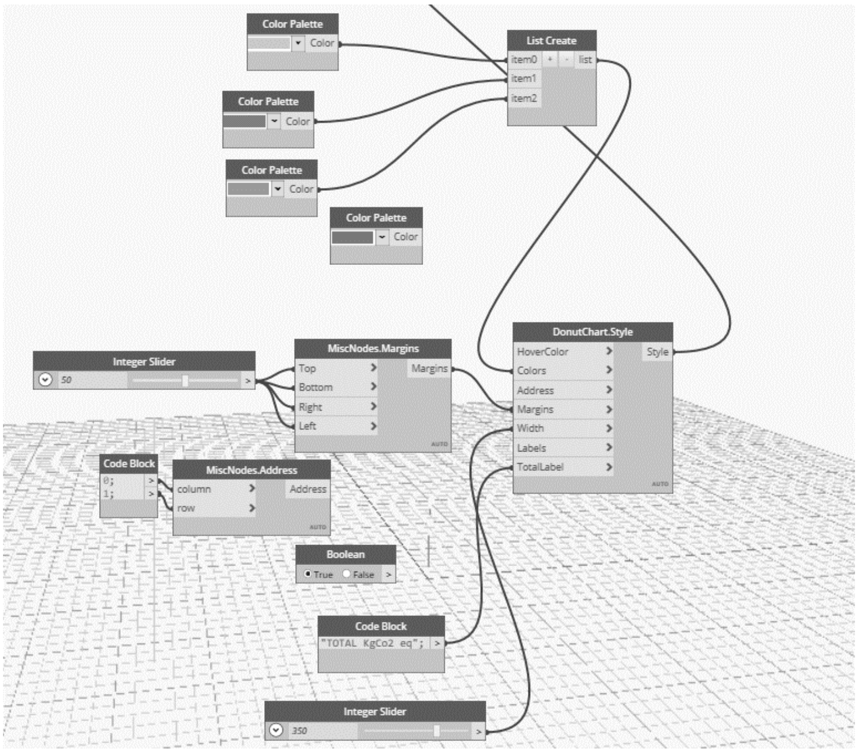


Figure 70. Define the graphical style of the diagram.

Block L.

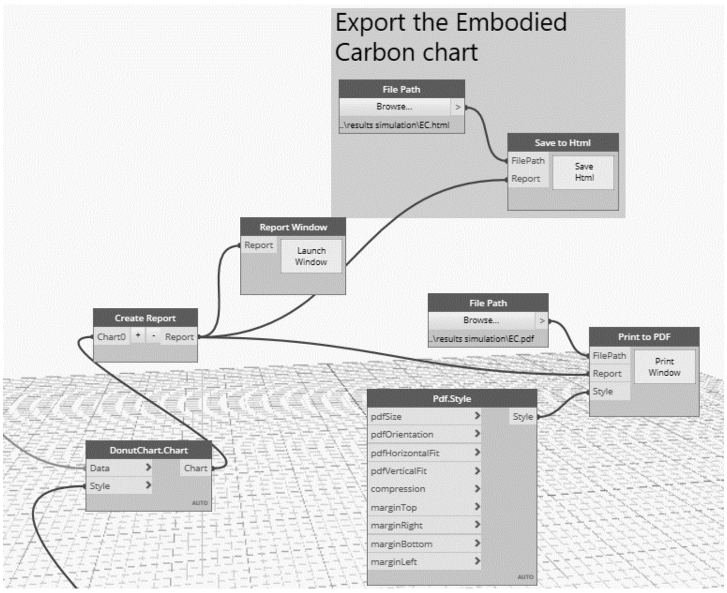


Figure 71. Choose the export format.

4.1.4 Validation phase: shaping the final requirements

The validation phases were conducted by opening some revision sessions of the tool aimed at collecting suggestions and advice from stakeholders in the building sector. The validation sessions were structured in:

a. Stakeholders interviews;
b. Test of the tool with specific EPDs;
c. Simulations with Revit models prototypes LOD 200;
d. Test of the methodology requirements.

The actors involved in the validation sessions were both internal (involved from the beginning of the process) and external (see Table 13):

Internal	***External***
Politecnico di Torino	Heijmans (construction company)
CRH (building material provider)	KTH (Academia)
Heembeton (CRH company)	

Table 13. Actors involved in the validation sessions.

The validation sessions were strategic to devise a tool that better fits with the necessities of the stakeholders in the market concerning a tool for EE and EC decision-making in the conceptual design stage. Together, we defined the **generic and specific requirements** to test during the validation sessions and the related information that the methodology should embody to obtain a tailor-made result progressively (see Table 14).

Tool requirements

N°	*Requirements*
1	Phase of design
2	Software
3	Formats
4	Model
5	Building Typology
6	EPDs Phases
7	EPDs Database
8	Categories for simulation
9	Input
10	Output
11	Results
12	Stakeholders
13	User actions

Table 14. List of the requirements.

The tool versions

Before reaching the final version, the tool had to be subjected to several validation sessions that were fixed with a monthly deadline aimed at verifying the progression of the tool in terms of requirements. During the sessions, the internal and external actors put the tool to the test and suggested advice to reach a better version of the tool. The improvement of the tool was aimed mainly to reach these ***objectives***:

1. Achieving a good integration between parametric model and computational design to avoid the employment of a LCA tool;
2. Allowing a user-friendly EC and EE scenario creation procedure;
3. Embodying EPDs data from production to recycling potential;
4. Devising a clear way to read the simulation results.

The validation sessions were useful for the both purposes of reaching the **objectives** listed and **solving the weaknesses** crosschecked in the previous tool versions.

Tool 1.0

The first version of the methodology and its features are described in the following chart (see Table 15). The tool was tailor-made for the conceptual design stage, and therefore, it allows to work on a design prototype LOD 200 that contains general information about geometry (walls, floors, stairs)[153]. The main parameters that the tool can manage are two:

- Form
- Materials

The tool manages .xls, .rvt and .dyn formats and combines their information about EPDs, BIM model and script to obtain Embodied Carbon and Embodied Energy scenarios. Version 1.0 fits for EPDs value from the single phase of the production A1-A3[154] , and it is tested on a single online database[155]. Moreover, the first version of the methodology allowed to read the EC and EC scenarios only via chart.rvt[156] and its export in .pdf.

---

[153] See paragraph 3.3 for the details about the prototype.
[154] For an example of EPDs chart see Table 8. Precast concrete EPDs chart from Okobaudat.
[155] The database tested is Okobaudat, see: https://www.oekobaudat.de/en.html
[156] See paragraph 4.1.5 for the details about the chart.rvt.

Through the various validations, many of the requirements remained fixed; however, we had to work on expanding the EPDs phases to include data until recycling and to improve the readability of the results.

Here is the chart of the Tool 1.0 (see Table 15):

Requirements	***Validation I** (09/2020)*
Phase of design	Concept Design
Software	Excel (input), Revit + Dynamo (simulation)
Formats	.xls, .rvt, .dyn
Model	LOD 200
Building Typology	Prototype (residential)
EPDs Phases	A1-A2 (GWP, PENRT, NRSF, RSF)
EPDs Database	Online (Okobaudat)
Categories for simulation	Walls, floor, stairs
Input	EPDs.xls (EE, EC); Revit Model.rvt LOD 200, script.dyn
Output	EC, EE scenarios
Results	Charts.rvt .pdf
Stakeholders	Construction C + Building M Provider + Academia
User's actions	(5) 1. Model.rvt LOD 200, 2. Shared Parameters.rvt, 3. Upload EPDs.xls in script.dyn, 4. Run the script, 5. Read charts.rvt and export chart.pdf

Table 15. Tool 1.0 requirements.

Tool 1.0 includes some features that are necessary to underline in order to focus on the next validation. Here is the list of the **weaknesses that were object of the next development and validation**:

(a) The EPDs chart from the online database has to be converted in a template.xls to be read by Dynamo (there is not at the moment an EPD standard);

(b) During the first validation it was employed only a single online database to test the tool's performance;

(c) Tool 1.0 considered only the EPDs values A1-A3 about the production phase;

(d) The results from Tool 1.0 were readable only into the Revit model by questioning the "edit type" of the elements or by exporting the abacus.pdf from Revit.

(e) To read the results into Revit, the Shared Parameters (SP) must be created that require a medium skill in the use of the software.

Tool 2.0

Tool 2.0 maintained almost all of the features listed for Tool 1.0 but ***implemented*** some of the weaknesses cited before:

(d) The results readability is expanded through the devising of tailor-made diagrams.html created into Dynamo and exportable directly from the software;
(e) The creation of the SP is performed directly into Dynamo, therefore, the User's actions are reduced to 4. Moreover, the user should not be necessary medium-skilled in the use of Revit software;

Here is the chart of the Tool 2.0 (see Table 16):

Requirements	***Validation II*** *(03/2021)*
Phase of design	Concept Design
Software	Excel (input), Revit + Dynamo (simulation)
Formats	.xls, .rvt, .dyn
Model	LOD 200
Building Typology	Prototype (residential)
EPDs Phases	A1-A2 (GWP, PENRT, NRSF, RSF)
EPDs Database	Online (Okobaudat)
Categories for simulation	Walls, floor, stairs
Input	EPDs.xls (EE, EC); Revit Model.rvt LOD 200, script.dyn
Output	EC, EE scenarios
Results	**Charts.rvt + Diagrams.html**
Stakeholders	Construction C + Building M Provider + Academia
User's actions	**(4)** 1. Model.rvt LOD 200, 2. Upload EPDs.xls in script.dyn, 3. Run the script, 4. Save the .html diagrams

Table 16. Tool 2.0 requirements.

Tool 3.0

Tool 3.0 maintained almost all of the features listed for Tool 2.0 but implemented some of the weaknesses cited before:

(b) To test the Tool 3.0 performances were employed multiple EPDs databases such as Environdec[157] and Dycore[158];
(c) Tool 3.0 considered all of the EPDs values A1-D from production to recycling potential.

Here is the chart of the Tool 3.0 (see Table 17):

Requirements	***Validation III** (08/2021)*
Phase of design	Concept Design
Software	Excel (input), Revit + Dynamo (simulation)
Formats	.xls, .rvt, .dyn,
Model	LOD 200
Building Typology	Prototype (residential)
EPDs Phases	**A1-D** (GWP, PENRT, NRSF, RSF)
EPDs Database	Online (Okobaudat, Environdec etc)
Categories for simulation	Walls, floor, stairs
Input	EPDs.xls (EE, EC); Revit Model.rvt LOD 200, script.dyn
Output	EC, EE scenarios
Results	**Charts.rvt + Diagrams.html**
Stakeholders	Building M Provider + Academia
User's actions	(4) 1. Model.rvt LOD 200, 2. Upload EPDs.xls in script.dyn, 3. Run the script 4. Save the .html diagrams

Table 17. Tool 3.0 requirements.

The only ***weakness*** that was not solved was the first one due to the lack in the technological development of the EPDs standard:

(a) The EPDs chart from the online database has to be converted in a template.xls to be readed by Dynamo (there is not at the moment an EPD standard).

---

[157] Link at Environdec database: https://www.environdec.com/library
[158] Link at Dycore database: https://www.dycore.nl/over-dycore/veiligheid-duurzaamheid-en-mileu

The toolbox

The chart below (see

Table 18) resumes the final technical requirements needed to employ the tool and run the simulations.

Validation Sessions	***Key points of the Digital Methodology***	***Notes***
a. Generic features		
1. *Digital Methodology tools*	Parametric + Computational	
2. *Software*		
a. modeling	Revit	
b. computing	Dynamo	
c. data elaboration and restitution	Dynamo	Diagrams.html
3. *Design phase*	Conceptual	
4. *Level of development 3D model*	LOD 200	Masses and geometries
5. *Building profile*	Prototype	Residential
6. *Parameters*	Materials and Form	
7. *Categories*	Walls, Floors, Stairs	
b. Embodied Energy and Embodied Carbon scenarios		
8. *EPDs database*	From online database to .xls	No standard for EPDs
9. *Link scenarios and model.rvt*	Script.dyn	Shared Parameters
10. *Data Restitution*	Dynamo diagrams.html	
11. *File needed for simulations*	**1.** Revit file LOD 200	
	2. EPDs format.xls	
	3. Dynamo script	
12. *EPD categories for Embodied Carbon*	GWP (A1-D)	
13. *EPDs categories for Embodied Energy*	PERNT (A1-D)	
	RSF (A1-D)	
	NRSF (A1-D)	

Table 18. The toolbox.

4.1.5 The decision-making scenarios: form and materials

The decision-making scenarios aim at performing Embodied Carbon and Embodied Energy calculations by employing as variables the **three parameters**:

- Form
- Materials
- Environmental impact indicators

Advantages

The advantages coming from the employment of the decision-making diagrams lie in the fact that:

a) The diagram got a **user-friendly interface** that permits **easy reading of** the information;
b) The diagrams can be **easily exported** in .html and .pdf, which are convenient formats to exchange information;
c) the data in the diagram is **“dynamic”** if the model is modified in terms of EPDs and form (and therefore quantities and volume) the diagram changes the scenarios calculation automatically;
d) the potential of integrating parametric and computation design lies in its **power in prototyping**, in other words, in easily creating multiple prototypes to compare almost infinite alternatives by employing form and materials as variables.

Here is a graphical interpretation of the scenarios for the decision-making associated to forms the EE and EC diagrams (see Figure 72):

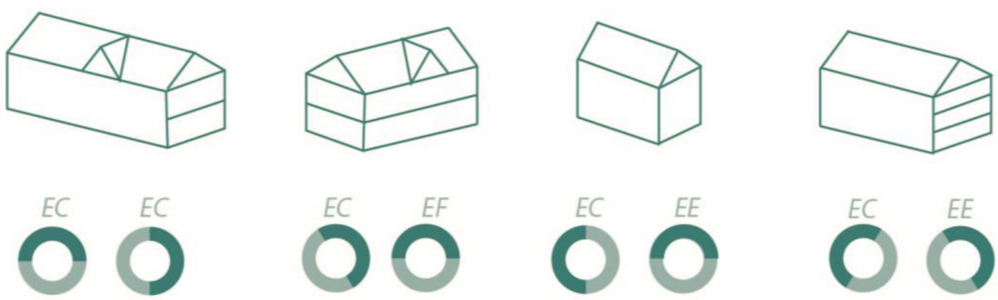


Figure 72. Scenarios graphical interpretation.

In particular, the results from Embodied Carbon and Embodied Energy simulations are expressed in two ways:

1. **Dynamic diagrams**: that can be exported from Dynamo in .html and .pdf format;
2. **Revit charts:** can be read by questioning he “Edit Type” in the model.

Moreover, the results are calculated with two degrees of detail:

I. For the single architectural element;
II. For the overall building.

The first way listed is about diagram creation. To obtain the diagrams, a portion of the script was created to transpose the EC and EE calculation into a visual graphic (see paragraph 4.1.3, Block H, I, L). The diagrams display the information by employing a particular unit and the two degrees of detail (see Table 19):

Simulation	***Units***	***Elements***
Embodied Carbon	(kg CO_2 eq)	(a) for the overall building, (b) for the single architectural element (wall, floor, stairs)
Embodied Energy	(MJm^3)	(a) for the overall building, (b) for the single architectural element (wall, floor, stairs)

Table 19. The scenarios result in details.

1.Dynamic diagrams

Reading the results

The first way of consulting scenarios is through the diagrams reading. The paragraph shows in detail the graphical restitution coming from the portion of the script dedicated to the creation of the diagram (see paragraph 4.1.3). The result is a ***fast visual comparison between design alternatives*** in terms of form, environmental impact indicator and materials obtained from the script. The dynamic diagrams allow for the easy creation of scenarios useful for the decision-making processes.

The diagrams are programmed as ***pie charts*** in which every colour is associated with a ***model category***: the floor is dark blue; the stairs are green; the wall is light blue (see Figure 73).

Once the simulation categories are expanded, other section of the pie chart can be added easily (see paragraph 4.1.3, Block H, I, L).

How to read the results? Here is an example of the pie chart diagram.html; by moving the mouse arrow over the section is possible to visualize the partial results for every category, by positioning the mouse in the canter of the pie chart is possible to read the overall result for the entire prototype (see Figure 73):

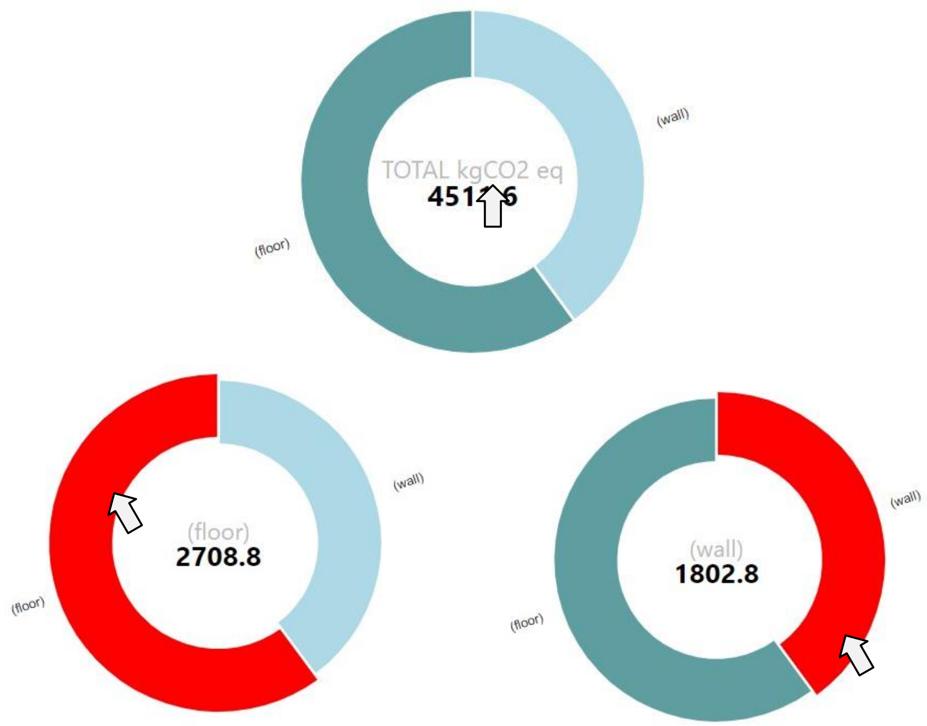


Figure 73. Pie chart diagram, partial and overall result.

4.1.6 Simulation options

The tool can calculate the various type of EC and EE simulations by associating EPDs and geometries and using them as **variables** to create alternatives. The tool provides many options to run the simulations (see Table 20) to test two kinds of variables: materials and form.

The chart below explains the type of simulation options:

Option	***Type of simulation***	***Objective***	***Variables***
a.	Combine one EPD with a single model prototype	Testing materials for EC&EE scenarios	Materials (EPDs)
b.	Combine multiple EPDs with single model prototype	Testing materials for EC or EE scenarios	Materials (EPDs)
c.	Combine one EPD with multiple model prototype	Testing prototypes for EC or EE scenarios	Form (.rvt prototype)

Table 20. Type of simulations.

Simulation type a.

This simulation consists in ***combining one EPD with a single model prototype.***

Here is the case of an EPDs for precast concrete[159] combined with the geometries of the Prototype (see paragraph 3.3). The two diagrams show the EC and EE calculations for every architectural element of the model (see Figure 74):

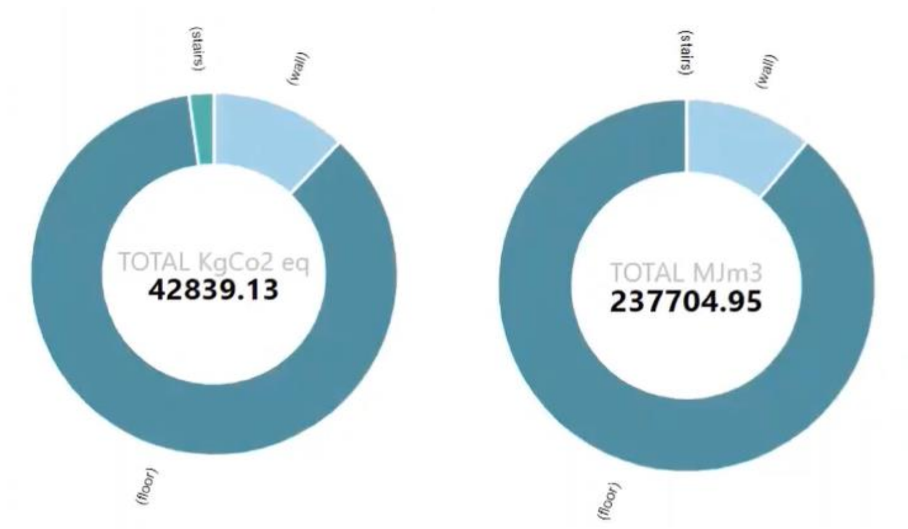


Figure 74. EC and EE diagrams for precast concrete EPD.

[159] Source for the EPD of precast concrete Ökobaudat: https://www.oekobaudat.de/en.html

Simulation type b.

This simulation consists in combining ***multiple EPDs with a single model prototype.***

Here is the case of two EPDs, one for precast concrete and the other for aerated concrete[160], combined with the geometries of the Prototype (see paragraph 3.3). This time, the simulation is focused on comparing the EC values of two different EPDs for the same Prototype. The result (see Figure 75) is a fast visual comparison between design alternatives. Once the graphs have been created, it is possible to save them or share them with other stakeholders to discuss the most sustainable choice.

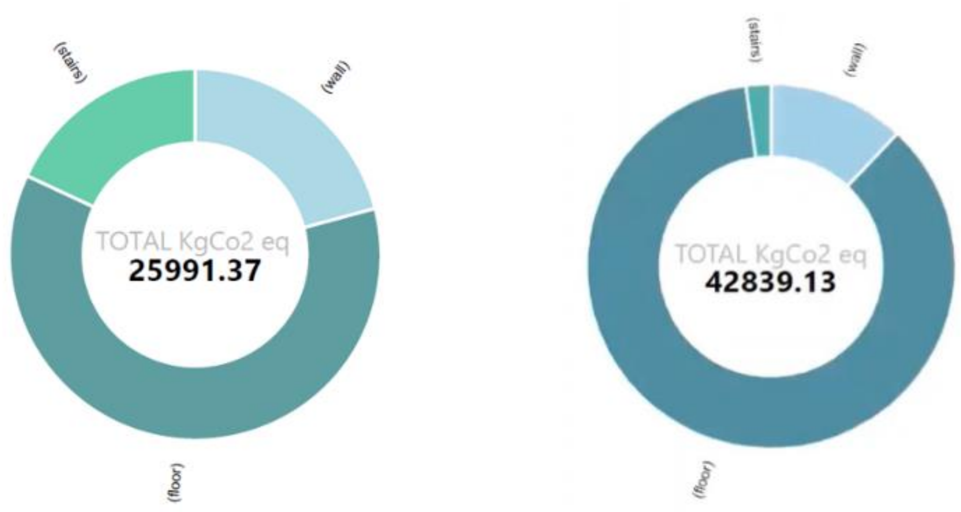


Figure 75. EC diagrams for precast and aerated concrete EPDS.

[160] Both of the EPDs were picked from Ökobaudat online database: https://www.oekobaudat.de/en.html

Simulation type c.

This simulation consists in combining ***one EPD with multiple model prototypes.***

Here is the case of two prototypes tested with the same EPDs packages to obtain the EC simulation. To simplify the calculation only two categories for simulation were considered (see Table 21):

Categories	***Online database***
Walls	Ökobaudat precast concrete wall
Floors	Environdec[161] precast concrete floor slab

Table 21. EPDs for simulation type c.

Once selected the EPDs, the simulation was run with the same EC value selection for both the prototypes (see Figure 76):

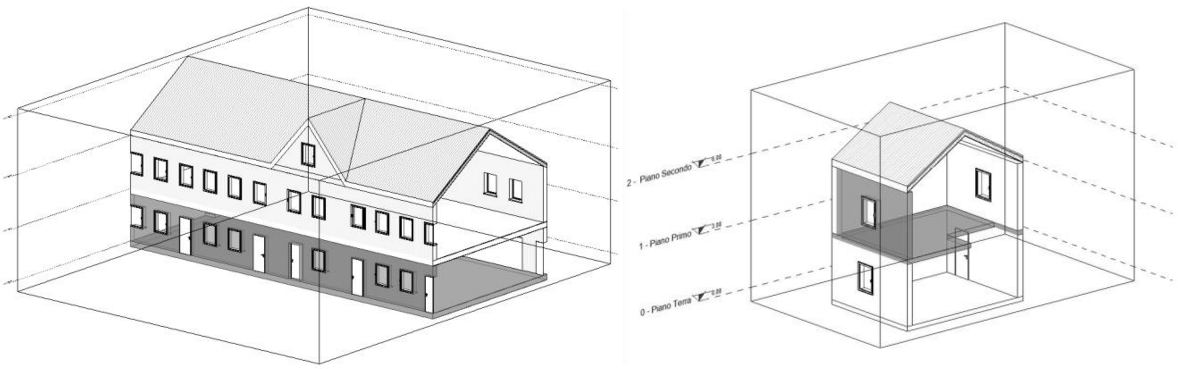


Figure 76. Prototype LOD 200 a. (left), prototype b. (right).

[161] Source for the EPD of precast concrete Environdec: https://www.environdec.com/library

The result coming from the combination of geometries and EPDs are expressed as follows (see Figure 77):

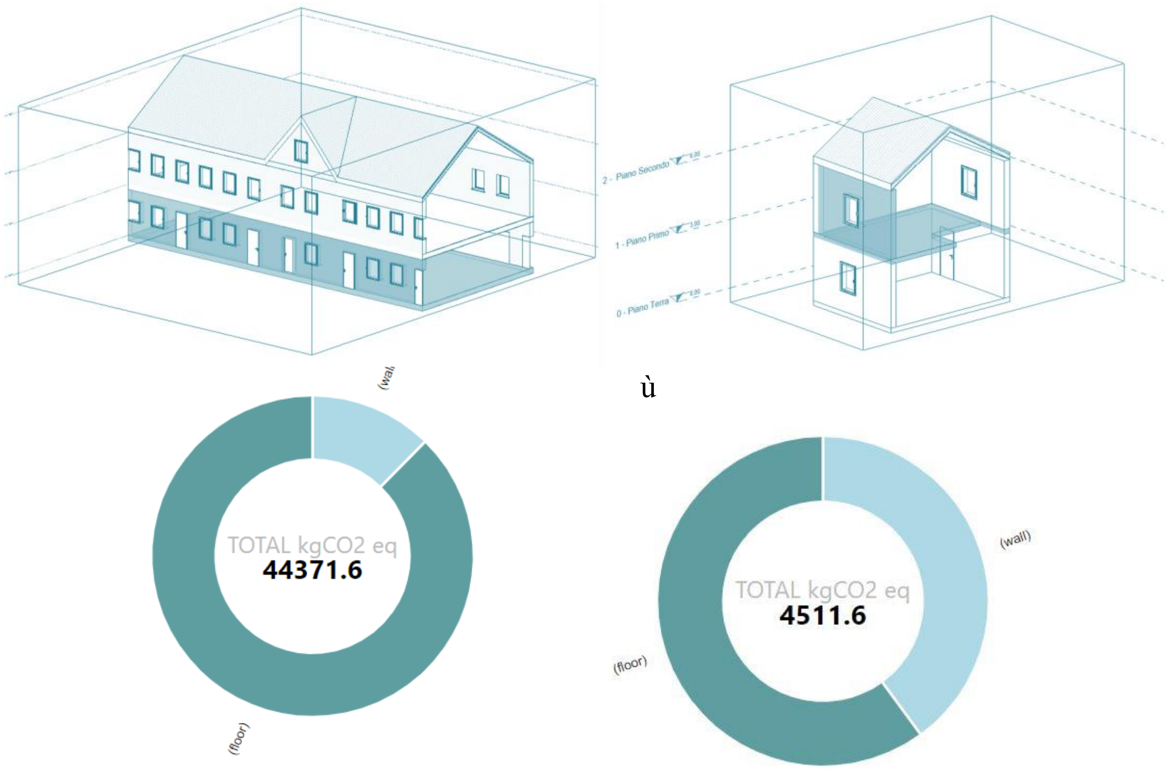


Figure 77. simulation type c.

The combination between prototypes and EPDs is ***maybe the most strategic solution*** for an efficient decision-making process because involving geometries and materials choice can drastically influence the number of emissions. The tool, in fact, allows manipulating form and geometries to obtain automatic impact scenarios useful for the concept design stage, the phase when the influence on design choices is great and the cost of changes is very low (see paragraph 4.4.1., Figure 57).

The step beyond consists of building a tool's graphical interface supported both by pc and mobile devices. The tool could be thought of as a plug-in for Revit models supported by a user-friendly interface that contains visual information about EC and EE simulations. By selecting the EPDs and running a button linked to the script, the user could obtain the real-time results of the simulations related to the building model and the comparison of the alternatives in terms of emissions amount. Currently, a project for a digital interface is currently under development as follows (see Figure 78, Figure 79):

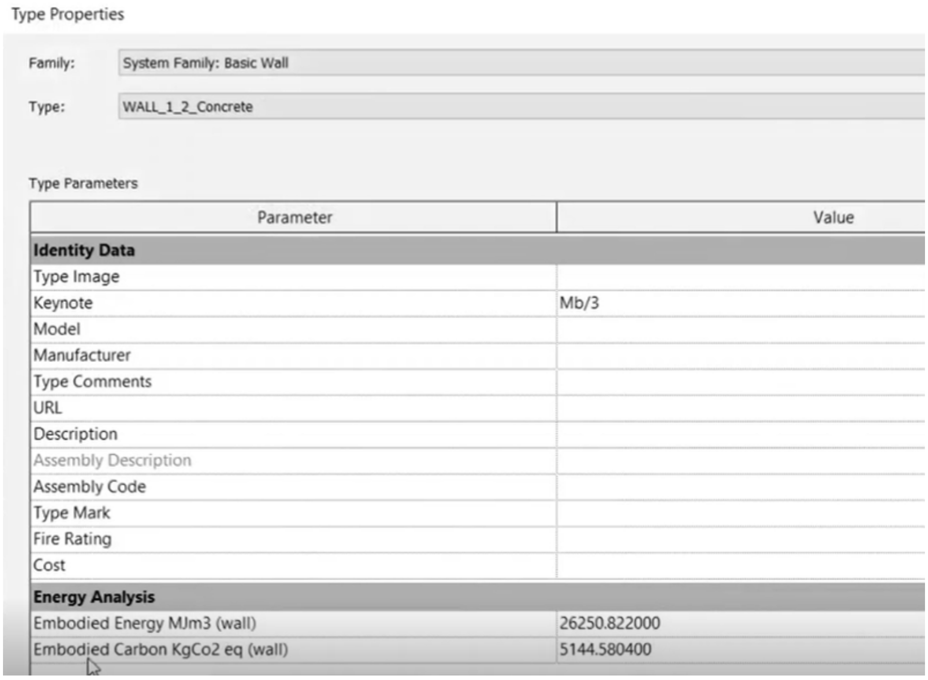
Figure 78. Tool configuration for mobile devices, EC scenarios.

Figure 79. Tool configuration for mobile devices, EE scenarios.

2. Revit charts

The second way of consulting scenarios is through the Revit charts.

By setting the Sharing Parameters into Dynamo, it is possible to fill the EE and EC results directly into the Revit model. This operation produces dynamic results coming from the simulation directly into the model. By questioning the "Edit Type" and reading the "Energy Analysis" section into the architectural category selected for the simulation, it is possible to read the EC and EE results for a single element (see Figure 80):


Type Properties

Family: System Family: Basic Wall

Type: WALL_1_2_Concrete

Type Parameters

Parameter	Value
Identity Data	
Type Image	
Keynote	Mb/3
Model	
Manufacturer	
Type Comments	
URL	
Description	
Assembly Description	
Assembly Code	
Type Mark	
Fire Rating	
Cost	
Energy Analysis	
Embodied Energy MJm3 (wall)	26250.822000
Embodied Carbon KgCo2 eq (wall)	5144.580400

Figure 80. Tool results from Revit "type properties" of the element.

Reporting the simulation results into the model permits to easily question every architectural element involved in the simulation and to export and to share the results with the stakeholders involved in the process. The results can be shared in two ways:

1. By directly sharing the BIM model and the Dynamo script. In this way, every stakeholder can question the element and read the results of the simulations directly into the model;
2. By exporting with an abacus.pdf, the EE and EC result for the single architectural element and for the entire building.

The following paragraph is dedicated to fully illustrating the possibilities provided by the tool in action by testing multiple EPDs.

4.2 The tool in action

The chapter illustrates a real test conducted with the tool. The aim is to show the digital tool's potential when employed for calculating multiple EPDs (see *Chapter 3. Building the playground* before reading the current section).

4.2.1 Testing the prototype/ simulation type b.

The case study adopted is the Prototype LOD 200, and to simplify the calculation, the categories considered for the test were only two: walls and floors.

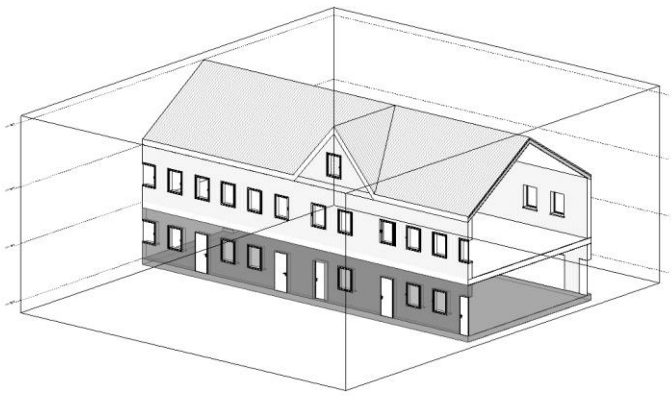


Figure 81. Prototype LOD 200.

Here is attached the chart of the EPDs selected from the Environdec[162] and Ökobaudat[163] database; the materials listed and their combination are the objects of the current simulation type b (see Table 22):

Categories	**Environdec**	**Ökobaudat**
Walls	1) Precast concrete three layers wall 2) Precast concrete massive wall	3) Precast concrete wall
Floors	a) Precast concrete floor slab b) Precast concrete hollow core slab	c) Precast concrete slab

Table 22. EPDs selection for scenarios.

[162] Source for the EPD of precast concrete Environdec: https://www.environdec.com/library
[163] Source for the EPD of precast concrete Ökobaudat: https://www.oekobaudat.de/en.html

Once selected the EPDs the simulation consisted in calculating EC and EE:

a) For single category
b) For combination scenarios

The results were a series of diagrams aimed at showing multiple design possibilities in terms of EC (see
Figure 82, Figure 83):

Figure 82. EC scenarios for every model category and EPD.

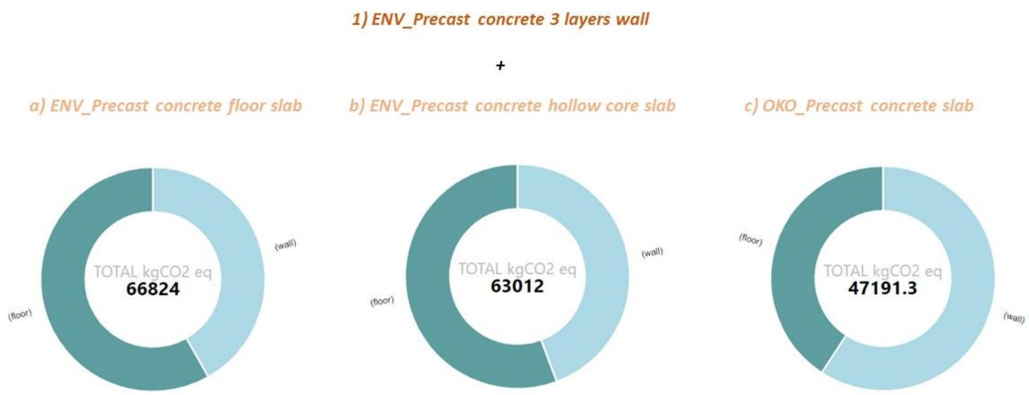


Figure 83. EC combination scenarios.

The results were a series of diagrams aimed at showing multiple design possibilities in terms of EE (see Figure 84, Figure 85):

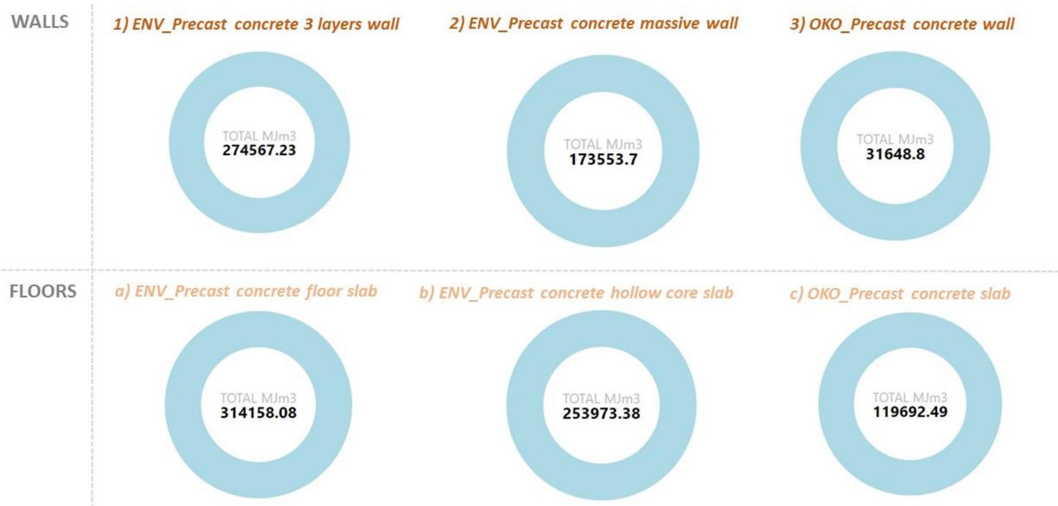


Figure 84. EE scenarios for every model category and EPD.

Figure 85. EE combination scenarios.

Observatory

on the experiment

PART III

Chapter 5.

Investigate through observation

The chapter opens the section dedicated to the *Observatory on the experiment*. The section traces the critical discussion and observations of the process and results in their theoretical and practical challenges. Its commitment consists in outlining a knowledge account founded on the ***observative and practical involvement*** in the research process. The first chapter builds a theoretical reflection by employing the laboratory experience process as a means of interpretation. It unpacks the research path stages and highlights its performative characteristics to trace the innovations that parametric practice can trigger in the design discipline. The aim is not to provide an exhaustive enquiry on the parametric in the fold of design but to extract some reflective observations grounded on a practical experience and put them in dialogue with a bibliographic background. It links back to the outcomes with the initial research questions and tries to respond to how designer investigate the potentiality of parametric design in contributing to the ecological debate and ***produce knowledge*** about it and in which terms do the parametric tool employment trigger innovation in the design process and gain ***transformative power*** over communication procedures, the creative process, and the designer's role.

The thesis narration, particularly in the current section, embodies a double scope: ***documentary and transformative***[164]. The documentary purpose is accomplished by employing a narration that illustrates the chronological development of thoughts, implications, and controversies addressed in the research path. The result is a ***diachronic plan of narration*** that describes the research complex of changes evolving over time. The position adopted is the participant observation (Dei, 2012) which implies a modality of knowledge from "within"[165] with direct, practical and sensorial participation with the object of

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[164] Read paragraph *0.3 Methodological notes* for the detailed description.
[165] From T. Ingold, *Making*, Raffaello Cortina Editore, 2019.

study. The researcher, therefore, adopts toward the object an integrated process of knowledge founded on iterative process exchange during the object study and, in this case, production. The term *"making of",* which is related to the tool devising, includes the double meaning of "construct" and "interpret". Therefore, it evokes the ***iterative process between producing and creating knowledge*** and learning by doing. By embodying this binomial as the key reading, the *observatory* ***investigates the methods to build a theoretical reflection on process and results when it is grounded in the context of a practical experience.***

The method of investigation proposed refers to Tim Ingold's theories[166] around the forms of comprehension and the ways knowledge can be structured. According to Ingold, simple information transmission does not guarantee knowledge nor much less understanding. Knowledge creation only happens when we become part of the process, grow with it, and let ourselves be changed by it. That statement assumes that ***knowledge is an "active" process*** during which we learn *from* and *with* the object of study. How does it is possible to establish the relationship between producing and thinking? First of all, the two terms must be put in order. By considering a curious metaphor from Adamson[167], we could assume that a philosopher and an artisan could respond in two different ways: the one *produces by thinking*, the other ***thinks by producing.*** The work developed in the thesis could be assimilated to that carried by the artisan, which creates knowledge through practical and observative involvement. Ingold calls this practice the *art of investigating*[168] where thoughts proceed in simultaneous response to the change and flow of the materials we have available. In this sense, research is an experiment not aimed at a mere hypothesis verification but open to multiple and changeable possibilities. Therefore, the investigation proceeds in real-time correspondence with the outside world with a speculative approach opened to unpredictable developments typical of artistic practice[169]. Such as an artisan could do, I retraced, during and after the process, the operative stages, achievements, errors and attempts to create a knowledge account grounded on my observative and practical involvement. The result attempts to critically discuss the characteristics of innovation carried by parametric practice in the design discipline and their effectiveness in contributing to multidisciplinary issues. The final aim does not embody the willingness and presumption to provide a comprehensive account of parametric discipline in the fold of design; it aspires to narrate a

[166] T. Ingold, *Making*, Raffaello Cortina Editore, 2019.
[167] See G. Adamson, *Thinking through craft*, Bloomsbury, 2007.
[168] See T. Ingold, *Making*, Raffaello Cortina editore, 2019, p. 23.
[169] Ingold suggested to incorporate some features of the artistic practice to go beyond the binomial practice/theory. See T. Ingold, *Making*, Raffaello Cortina editore, 2019, p. 25.

particular story, to pull the strings of a process and highlight its outcomes (made of attempts, changed views, and diverse theories answers to certain conditions).

5.1 Interpreting the process

The paragraph intends to shift the focus from the object to the process to ***unveil*** a net of interactions, connected actions with multidisciplinary intentions, values and meaning.

The laboratory experience (in terms of relationship establishment, tool devising, information exchange, knowledge transfer and moreover) became ***instrumental*** in reflecting on the innovation in the design discipline, in creating knowledge over parametric design in the fold of ecological challenge as the result of weaving between thought and production. A certain kind of knowledge built today on the complementary relationship between speculation and action could be strategic in avoiding common and false beliefs, especially around parametric practice and its multidisciplinary employment issues. The current historical moment corresponds with a primordial soup where parametric ontology is under moulding by attempts at definitions of vocabulary, theory, method, concepts and assumptions. In this precious and fragile moment, the risk of taking for granted common myths is very high. Adopting the problematisation approach, at this stage, helps in examining beliefs considered socially true by putting that ***knowledge as a problem,*** facilitating new viewpoints, reflection, and especially, ***action to emerge*** (Foucault, 1962) by adopting a ***problem seeking*** approach.

The analysis was conducted by considering two plans of interpretation and their influence on consolidated design practice. ***The innovation in the design process when subjected to the parametric practice and new collaboration models.*** The elements of parametric procedures, such as concept, methods and tools, are here submitted to critical analysis. It consists of classifying them as "problems" (with transformative power over the world) that must be exemplified, analysed, and interpreted to reach back to why they are imposing as the response to a current situation. Moreover, the research path process is analysed under the lens of new forms of collaboration, such as Academy-Industry collaboration models, to highlight the innovations that a new approach in technology and knowledge exchange can carry. *How to conduct this kind of interpretation?*

The strategy was to employ a graphical mapping of the process to unpack the chronological stages of the research path and highlight the hidden relationships between actors and entities. Therefore, the mapping strategy is aimed at unfolding exchange, relationships, and change in practice difficult to read without interpretation instruments. The objective is to narrate these changes in practice provoked by the adoption of new technologies and collaboration models.

5.1.1 Mapping the process: actors/actions

Strategies for mapping the process ground their roots in the studies conducted by Bruno Latour, Michael Callon and John Low, better recognized as "ANT" (Actor-Network Theory). The cornerstones of the theory are founded on the awareness that a scientific fact is the product of an intricate network of relationships in which *human* and *non-human* actors interact (Latour, 2013). Latour wondered about a ***representation modality*** that could be able to make readable the multi-dimension and heterogeneous net that characterizes the scientific-technological issues. A certain kind of representation to draw a complex system of ramifications and implications characterized by indeterminacy and uncertainty. The design process itself could be grouped into these kinds of issues. It is a process and a continuous flow in transformation (Latour and Yaneva, 2008) made of a plurality of entities that combine influence and outcomes in space and time. This vision, then, brings reflections on the role of the project in its technical, symbolic and political dimensions (Armando and Durbiano 2017). The representation modality embodied by the mapping system is capable of unfolding inner and hidden stratifications (see Figure 86 and Appendix B).

The mapping system proposed here embodies some cornerstone principles. First of all, it aims to draw a ***multidimensional analysis*** of actors, actions, entities, facts, and tools.

Secondly, it represents an ***interpretative instrument*** to unfold connections and trace visual relationships. It improves understanding and ***decoding***.

Thirdly, it employs a ***diachronic narration plan*** that illustrates the chronological development of thoughts, implications, and controversies addressed over time.

The principles converge to open the debate about the ***innovation in the design process when subjected to the parametric practice and new collaboration models.*** How does it is possible to make a process readable? The methodology consisted of **unpacking the stages** of the research path and representing it in a diachronic map that can unfold its development during temporal phases. The map identifies the crucial steps of the research development and positions actors, related actions and tool employment according to some analysis categories as follows (see Table 23):

Actors/ Actions	Tools
Internal	Contracts
External	Documents
Presentations	Parametric models
Crucial meetings	Databases
Validations	Software
PhD visiting	Methodology upgrade

Table 23. Categories of analysis.

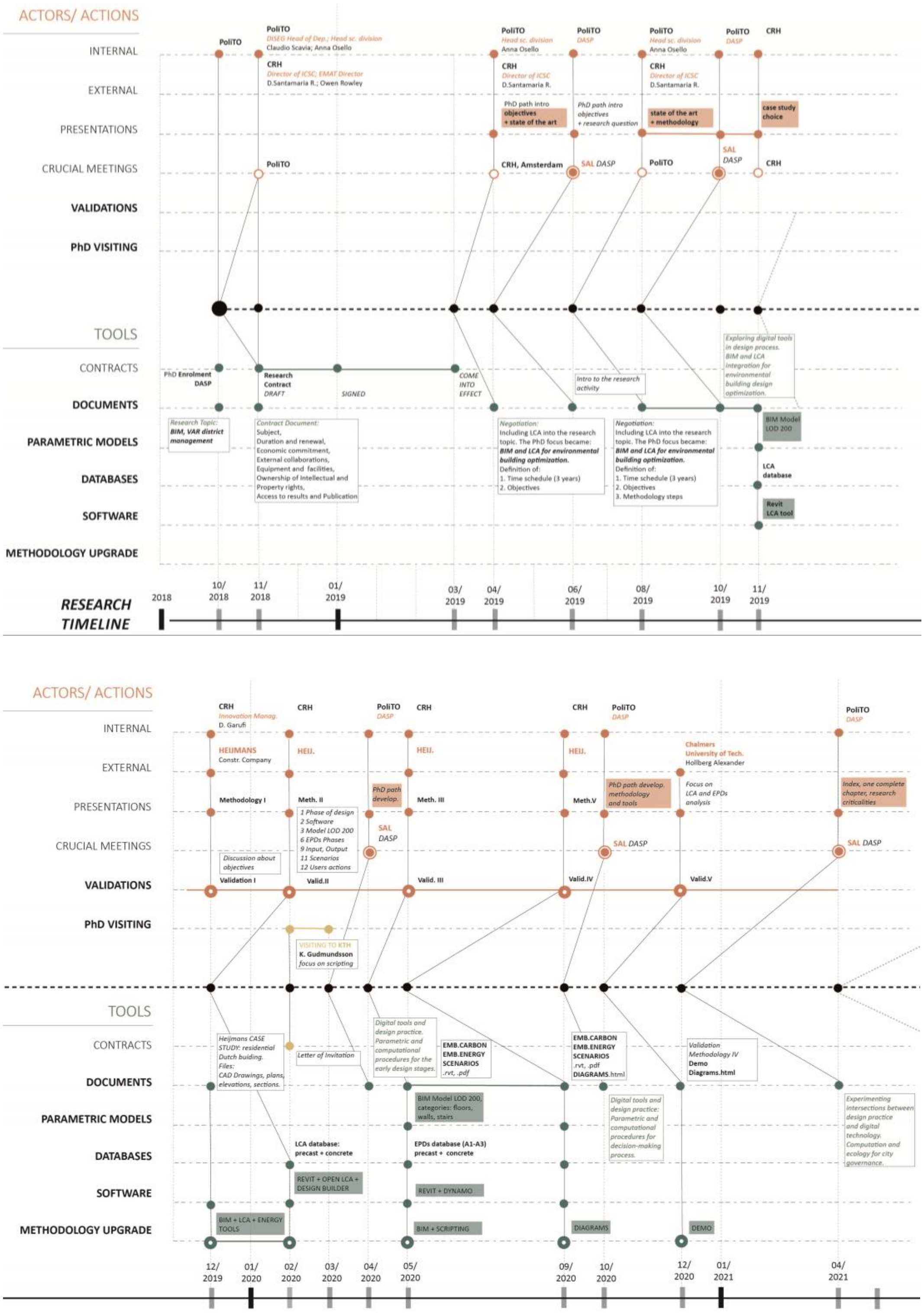

Figure 86. Extract from the process mapping (see Annex B).

The map combines these categories according to chronological order to make visible and readable the hidden relationship established between actors and entities[170] . The result is the graphical and readable restitution of relationships and exchanges that took place in the research path. However, the objective did not lie in the narration plan of the process but in tracing some consideration over it. In other words, it highlights the innovation in the design process pushed by parametric practice and new collaboration models. To conduct the interpretation were chosen some dimensions of investigation (see Table 24):

Internal / external relationship
Formal communications
Validations
Contractual dimension
Documental dimension
Parametric modelling
Methodology upgrade

Table 24. Categories of interpretation.

The categories of interpretation (see Table 24) were put as a layer on the map to extract some tendencies and recurrent actions (see Appendix C for the full resolution image and Figure 87):

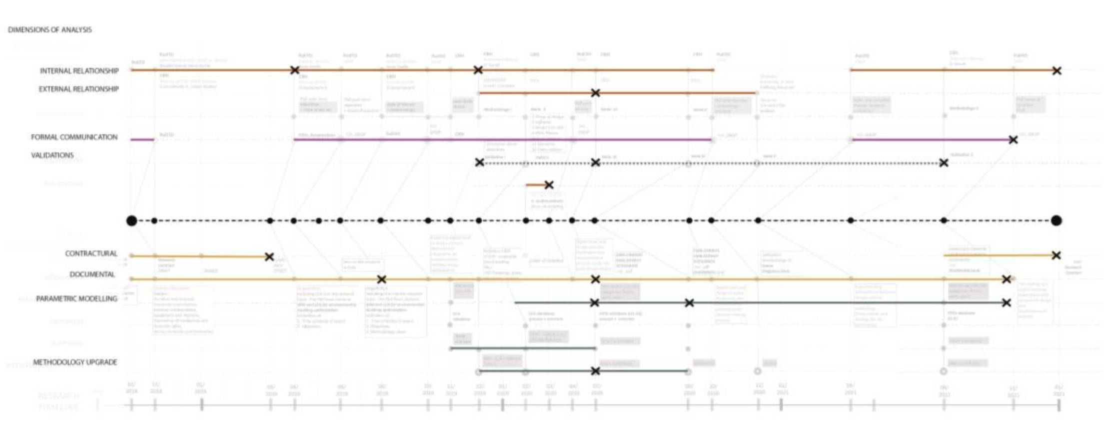

Figure 87. Process interpretation.

At this moment, it is possible to trace some considerations about the research path development and the influence of parametric procedures and the academy-industry collaboration model in the design process.

[170] For the full image see Annex B.

5.1.2 A revolution in communication

The paragraph opens with the most crucial questions investing in nowadays parametric design debate: *in which terms do the parametric tool employment trigger innovation in the design process and gain transformative power over communication procedures?* The paragraph tries to interpret the matter by converging reflective observations grounded on the laboratory experience and putting them in dialogue with a bibliographic background.

The focus reflection of the proposed paragraph is thinking about the digital revolution as a revolution in communication. The wide production and diffusion of *rich data* permit the diffusion of knowledge concerning the market and political orientation, health, private preference, and moreover (Ferraris, 2018). According to Ferraris, the fourth technological revolution[171] is a revolution concerning writing in terms of registration, archive and memory. Admitting that in the industrial revolution, technology was aimed at production; today, in the digital revolution, technology is mainly aimed at producing and registering information; which consequences are there on the architectural design discourse?

As the map suggests (see Figure 88, Appendix C for full resolution), the validation process coincided with the parametric modelling phase within the current project. The parametric model was the object of the progressing tests and verification in the validation phase when internal and external stakeholders were involved simultaneously.

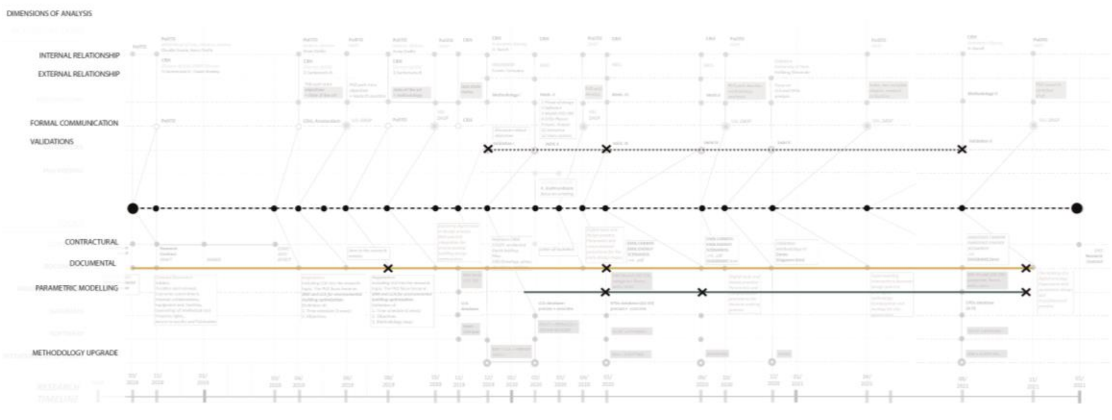

Figure 88. The parametric modelling phase.

[171] M. Bunz, *The Silent Revolution. How digitalization transforms knowledge, work, journalism, and politics without making too much noise*, London, Macmillan, 2013.

No physical drawings were exchanged; the validation occurred directly into the parametric model, which ensured a platform of communication for the stakeholders involved in the process. The model represented a platform of collaboration in constant evolution in time and space, a place that is dedicated to data elaboration and to archive the historical memory of the project. The model itself embodied the contractual dimension and became the means of negotiation in the documental phase; it was the object of the mediation between the needs and the objectives of different actors.

The city is gradually configuring as a complex permanent broadcast and becoming a giant information-rich communication platform constituted by unprecedented complexity. The level of complexity that the built environment has to deal with is provoked by the increasing of relations, information exchange, simultaneous events, and more that characterize contemporary social life. The city itself and its infrastructural space are becoming the communication means of information enclosed in diffused and invisible mechanisms (Easterling, 2019). The infrastructural space links with the power of digital technologies and software to become at effects a channel for information diffusion. The author of this change is definitely the interaction between people and technology in developing social and technical nets opened to multidisciplinary fields of knowledge, like informatics, social sciences, architecture and urbanism, theories of communication by opening the debate beyond traditional boundaries and scientific authority. Managing the infrastructural space means, therefore, coping with a ***narration***.

If the built environment regulates communications and is also responsible for its transcription and society's memory, consequently, there is a broad "embedded knowledge"[172] accumulated within spatial frames that must be read, managed, stored, and generally navigated. The built environment to adequately respond must configure itself as an interface of "multi-modal communication" (Schumacher, 2012a) and exchange between humans and computers. Therefore, it can be affirmed that architecture is gradually embodying the task of ***framing communicative interactions***. In which way architecture can perform this activity? Architectural space should incorporate the task of framing and facilitating activities and related situations and communications. The architectural setting separates and connects social actors and their activities by facilitating exchange and inscription as a physical apparatus. In particular, the built environment shifts from the conventional conception of a place made by the mere assemblage of components to include relations between people and the environment, information broadcast, data flows and permanent sharing.

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[172] In P.Schumacher, *The societal function of architecture*, IOA Silver lecture, Vienna, 2011.

The change in perspective toward the shift in communication tasks concerns the architectural object that became an information-rich interface and the design process that turned from a linear to an integrated conception. The relevance of communicating information is highlighted by the introduction of BIM methodology in the design process, which already contains in its acronym the term “information”. According to Ferraris[173], BIM offers a documental perspective on design objects and processes by including not only the spatial dimensions but also the temporal ones. BIM radically changes the perspective on the ***design object, interpreted as “information flux”,*** and on the ***design process, defined as a “construction information process”***[174]. The concept itself of “flux” calls into question the ***temporal dimension*** and proposes a shift in mind regarding the linear design process. The traditional design process is characterized by actors' linear and subsequent involvement and a type of communication “one to one”. The ***integrated process***[175] proposed by the BIM methodology allows multidisciplinary actors to be involved simultaneously in the decision-making process by communicating through a collaboration platform and working on the same digital model (see Figure 42, Figure 43, paragraph 2.1.2). The simultaneous involvement of various actors with a different backgrounds on the same project document, which is gradually enriched by multiple and varied information over time, radically changes the way of “doing design” and perceiving the architectural object. Managing a design object is not only intended to manipulate the assemblage of physical forms but a flow of information in constant change. Architecture object embodies the task of structuring the frame of the communicative interaction, archiving the memory of the progressive enhancement, and incarnating the role of a communication platform. In conclusion, we could assume that the digital revolution is, first of all, a revolution in communication interaction.

Moreover, maybe in contrast with common belief, when we talk about digital and parametric procedures, the “document”, intended in its extensive definition, remains the protagonist of the design process and the relationship interchange. I talk about common beliefs because thinking about digital pushes us to consider the exchange of objects as “immaterial”; instead, it's all about materiality. Digital is highly material; think of devices, connection tools, storage systems, databases, and other means to guarantee connection and memory. It has never stopped creating documents and writing but also in a different way. To all effect, the capital of the informatics revolution of our century remains the documental capital

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[173] M. Ferraris, *Scienza Nuova,* Rosenberg & Sellier, 2018, p. 42.

[174] BIM introduces new terminologies to describe design object and process in which the concept of “information” is predominant. See Acca, *Guida al BIM*, 2017.

[175] For further information see paragraph *2.1.2 Parametric design and it power in prototyping: the case of BIM.*

(Ferraris, 2018) and what we consider the Fourth Revolution is (Roncaglia, 2010), first of all, a revolution concerning the technologies of writing. Never before have we been so abundantly invaded by documents (Big Data) because every recipient of the information is also its producer, think, for example, to the social network. We are assisting to the explosion of the writing, which implies that registration and memory are the protagonists of our relationship processes. *In which way does this tendency particularly involve the design processes?*

The map helps us in questioning the matter. With the documental dimension, it is intended the map layer dedicated to tracing the creation, the exchange and the registration of written procedures regulating objectives, progressive achievements, and negotiation between actors and entities (see Figure 89, Appendix C for full resolution):

- The documental interchange was the most long-lasting and took place from the very beginning of the process until the closing.

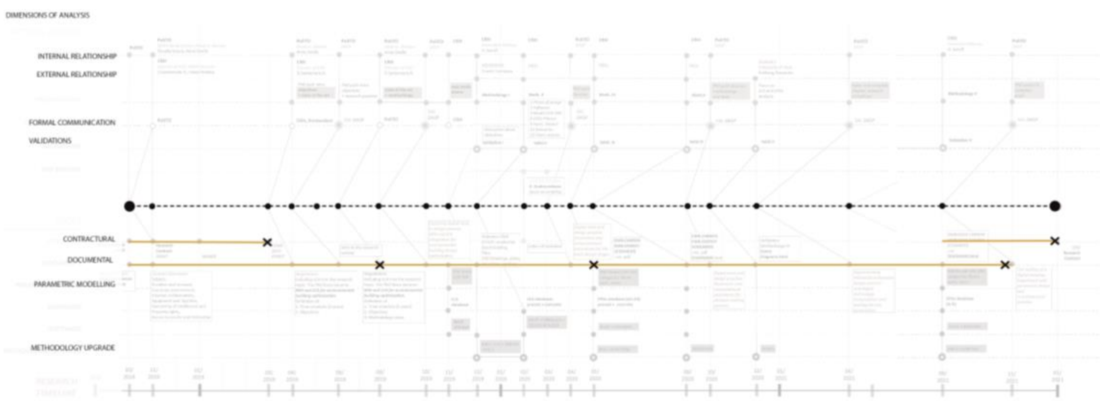

Figure 89. The documental dimension.

BIM technologies offer and favour a documental perspective over the design objects by real-time registering the changes in the spatial and temporal dimensions of the entities. In addition to those, it can take into account financial flows, environmental simulations and data coming from sensors, geographical information and moreover. In other words, BIM merges the temporal dimension with the spatial and material one; it is, in all effect, a digital database, an archive in which the flow of the information is stored under the form of "parameters" and elaborated in real-time. BIM model is properly a document which use is regulated by other documents, like norms and manuals. The breaking feature compared to previous methodologies, however, is that the parametric tools not only **store a temporal and spatial memory** but also **manipulate** that memory to obtain simulations and unexpected results.

The objective of the reflection lies in considering digital technologies in their materiality in terms of entity and results, in their ability to amplify our possibilities of communication and memory, in pushing for a change in mind that can conduct us to consider a database reading as a book reading.

5.1.3 Multidisciplinary collaboration and the designer's role

The paragraph is complementary to the previous one but shifts the focus to a particular side: *in which terms do the parametric tool employment trigger innovation in the design process and gain transformative power over the creative process and the designer's role?*

The research in question strongly supports that the ***mutual contamination*** between sciences and humanities ensures an interdisciplinary synthesis with richer results obtained by single disciplines. Actors from architecture and research, engineering, building material, and construction melt their competencies to reach a design objective that opens its boundaries beyond the construction world. Considering technique and humanities, not in contraposition but linked by an essential connection, provides better individuation and analysis of the changes that impact society. It is fundamental to recognize new experimental collaboration models between universities and local and global entities contributing to economic, social, and cultural development to go beyond self-referential models governed by specialist disciplines.

According to M. Ferraris[176], it is possible to trace challenges that universities should embrace in the next years. First of all, it would be gradually much more necessary to recognize and interpret the complexity of the events and the changes taking place. In this regard, a multidisciplinary involvement can ensure a superior synthesis of interpretation elements and communication strategies. Secondly, it is necessary to go beyond the idea that the immediate profitability of a certain kind of knowledge can represent the measurement criterion that gives it legitimacy. It should be well known that human processes can't be read in terms of production and economy, but they embody a certain level of indeterminacy released from mechanical rules. Therefore, in the long run, something considered not helpful or profitable today can reveal strategic employment in the future. Thirdly, letting filter a humanistic culture in all of the knowledge areas, especially technical ones, could limit demagogy and other weaknesses of contemporary democracies (Ferraris, 2018).

The university should embody the role of the interpreter of the transformative dynamics in place, produce and manage innovation, discover emerging needs and

[176] M. Ferraris, *Scienza Nuova*, 2018.

equip itself in responding to these. In this regard, the interaction between universities and industry must develop on ever more intertwined levels grounded on cooperation and collaboration to develop and manage base research, applied research and medium-long term research (De Martin, 2017b). The advantages are multiple and mutual. Industry gains sensitivity toward humanities and benefits from knowledge sharing and base research; university, on the other hand, benefits from technology sharing and processes typical of applied science[177]. The result is the essential connection between technique and humanism. In conclusion, University should reflect on its role and responsibility and recognize the challenges that characterize our epoch and the next decades at a local and global level: democratic, environmental, technological, economic and geopolitical[178].

The current research path exemplifies its process and results in the tendency toward multidisciplinarity. By employing the map (see Figure 90, Appendix C for full resolution) as a tool for interpretation, it is possible to highlight some considerations:

- The highest moment of the digital methodology upgrade corresponds with the most profound involvement of internal and external actors. The relationship exchange was at its highest when internal (Polito, CRH) and external (Heijamns and KTH) stakeholders started their collaboration with Validation appointments.

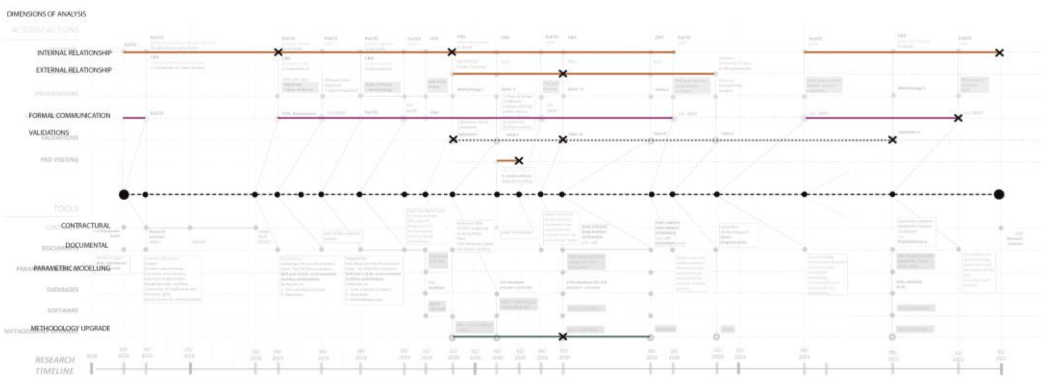

Figure 90. the creative process, and the designer's role.

[177] For further details see paragraph *1.1.3 The "machine"*.
[178] J. De Martin, Università futura, Codice edizione, 2017.

Actors were involved with balanced power in the decision-making and validation process. In this regard, if ***democratisation*** occurs in terms of intent and responsibility in the creative process, what is the architect's position? It could be possible to resume the answer with a Renzo Piano statement[179]:

The architect embodies not only an aesthetical responsibility but also a moral and ethical one able to make him part poet and artist, a part builder, sociologist and anthropologist.

These dimensions are intertwined to such an extent that it is not known where architecture ends and anthropology begins[180].

At this point, it is worth it to conduct a reflection on the changes in the creative process and the designer's role when subjected to the introduction of digital tools and multidisciplinary collaboration.

According to P. Eisenman words[181], the introduction of digital technologies in architecture represents the beginning of a new paradigm in architecture not only because advanced software allows the control and representation of complex forms but also and especially because they ***change the temporal and spatial modalities*** into the whole design process. In particular, digital technologies introduce some ***new dynamics***: they make use of multiple variables and parameters, they introduce the concept of real-time and simultaneity, they modify the relationship between project conception and execution[182], they create new hybrid configurations and can replicate form generative mechanism.

At the beginning of the nineties, P. Eisenman (*Vision Unfolding*, 1992), J. Frazer (*An Evolutionary Architecture*, 1995) and G. Lynn (*Animate Form*, 1999) opened the first new research paths to include digital technologies as central strategies to generate form. However, if initially the employment of informatics technologies was limited to extending traditional processes and methods, now recent approaches, through the use of the ***algorithmic process***, are pushing for results beyond representation[183]. Digital procedures ***amplify*** our senses and perception ability to extend ourselves (McLuhan, 2015)[184].

Design is gradually moving from a sculptural object to a mathematical object, from an object-oriented scope ***to a new ontology*** grounded on social and

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[179] R. Piano, La Responsabilità dell'architetto. Conversazione con Renzo Cassigoli, Passigli, Firenze, 2002, pp.34-35.

[180] R. Piano, Che cos'è l'architettura, cit. DVD.

[181] P. Eisenman, *Oltre lo sguardo. L'architettura nell'epoca dei media elettronici/Vision's unfolding: architecture in the era of electronic media*, "Domus", n. 734, 1992.

[182] Think to the CAM (Computer-Aided Manufacturing) technologies, for example.

[183] See *Chapter 2. Parametric design and ecological challenge* for further information.

[184] Particularly suggestive is the McLuhan original title "The medium is the message".

environmental issues (Schumacher, 2011). Digital technologies favour the overcoming of the idea of architecture as an artefact and push for the conception of architecture as ***a relational system*** intended as interchange and mediation place between different systems (Causarano, 2017) as the result of culture, and technology and space weaving. In light of what has been said, the designer's work gradually focuses on the formal outcome of the process.

A designer's interest opens to multidisciplinary intents and relationships. The increasing complexity of the architecture mission is gradually keeping distance from the idea of the architect as an artist, the architect as a genius (Armando & Durbiano, 2017). What is emerging today is a growing democracy in the creative opera conception, whose gestation is the outcome of the relationship between equal figures with equal power. The tendency is provoked by the necessity of expressing sophisticated messages and devising increasingly complex means of communication that don't allow the solitary *artist-author* to conceive his work closed in the laboratory. The artistic object, such as the architectural, avoids the sculptural object-oriented aim to become a means able to incorporate, transmit, and elaborate ***messages***. It is clear that embodying such scope and ability empowerment requires an opening toward multidisciplinarity in terms of knowledge and competencies. The object loses the single authorship to acquire multiple authorship and becomes the output of a complex process of interchange and negotiation.

In conclusion, information-related technologies contribute not only to the fold of the design process but also to the designer's role in the creative process. Information technologies provide means to amplify perception and representation modalities that go beyond the object and incorporate relations and messages toward establishing a relational ontology grounded on environmental and social purposes. On the other hand, they shift the architectural research toward the process dimension and a democratic and multidisciplinary approach to the creative method. The architectural production has to, finally, include the wave of ecological and environmental social issues and include ecological awareness and information revolution intersection in its aesthetic and philosophical vision.

5.2 Reading the transformative tool power

The section is dedicated to describing a ***complementary*** part in respect to the previous section. The problematisation approach employed in questioning the research process is here used to ***unveil*** the transformative power that the tool can operate on consolidated design practices. In this sense, the focus this time will be positioned on the ***tangible*** results in terms of ***innovation in consolidated design practices.***

The section maintains a reading plan built on the relationship between "construct" and "interpret" to abandon an authoritative position towards the object studied and, on the contrary, learn *with* and *from* it. The intent does not exhaustively describe a phenomenon through its abstract observation but to trace some considerations from practical experimentation. The collected considerations are here subjected to critical analysis and comparison with bibliography recognition in the field and existing methodologies to map out an account concerning the transformative features of the tool in the consolidated practice.

The section is going to trace the achievements and limits of the process and results in terms of tangible data starting from Politecnico di Torino and CRH collaboration, the adoption of an integrated design process, and the innovative features of the tool with respect to traditional methodologies, the tool limits. The aim is to resume reading the transformative tool power to provide a conclusive overview of the research process, made of successes and limits.

5.2.1 Achievements from the collaboration procedures

The tangible achievements concerning collaboration procedures in the study can be resumed as follow:

For all of the actors: Politecnico di Torino, CRH, Heijmans.

1. The increase in information exchange means reaching a higher quality in the design process and product;
2. The methodology allows information sharing between actors from the preliminary design stages. This represents an increase in information exchange with a consequent passage from the traditional linear process to an integrated one.

For the Politecnico di Torino (education-driven)[185]:

1. The chance to work on real word targets;
2. An opportunity for knowledge and technology transfer;
3. Additional economic funds, access to industrial equipment and licensing or patenting income;
4. Promoting research based on applied science.

For CRH (profit-driven)[186]:

1. Improving holistic methodologies and theoretical backgrounds;
2. Opening perspectives toward pure science;
3. An opportunity for knowledge and technology sharing;
4. Access to laboratories and equipment;
5. Re-skilling of employees;
6. Improved transparency towards clients and shareholders;
7. Improved (data drive) awareness of the environmental impact, which can drive systemic change.

Moreover, the collaboration model and the consequent innovation platforms for evaluation methods help to overcome some issues typical of the traditional design processes, e.g., the incommunicability and the impossibility of creating impact scenarios of processes and products, the difficulties in the relationship between stakeholders during the design process, the difficulties in managing information belonging to multiple and separate documents. Therefore, employing **an integrated design process** (see Figure 91) allows a combination of specialized contributions in real-time and in a single database that connects objects and information. In particular, the dialogue between stakeholders occurred from the early stages of design with a consequent increase in design quality.

[185] From Barnes, T.; Pashby, I.; Gibbons, *A. Effective University–Industry Interaction: A Multi-Case Evaluation of Collaborative R&D Projects*. Eur. Manag. J. 2002, 20, 272–285.
[186] From Rybnicek, R.; Königsgruber, R. *What Makes Industry–University Collaboration Succeed? A Systematic Review of the Literature*. J.Bus. Econ. 2019, 89, 221–250.

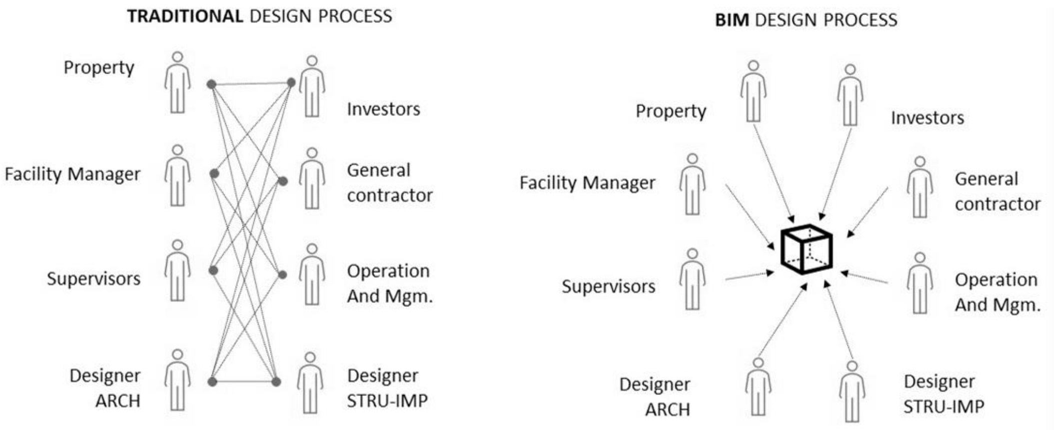

Figure 91. Traditional process and integrated[187].

By considering these premises, the evaluation method for decision making based on the use of digital tools and collaboration between stakeholders allows for gains both on the side of the **process and the product**. In particular, an evaluation method grounded on an integrated design process, as the methodology showed, allows these main advantages:

- **a.** The increase in the awareness of the stakeholders both about the process (in terms of tools, resources) and the problems to face;
- **b.** The possibility for stakeholders to comprehend the impact (environmental, social, economic and moreover) of the product thanks to the simulation scenario;
- **c.** The increase in better time management and the consequent reduction in the time spent to run the actions and to obtain design results;
- **d.** The improvement in the quality of the product thanks both to simulations and the continued control over the design process.

[187] Image rielaborated from Huan, Y.; Liang, T.; Li, H.; Zhang, C. *A systematic method for assessing progress of achieving sustainable development goals: A case study of 15 countries.* Sci. Total. Environ. 2021, 752, 141875.

5.2.2 Innovation in the flow of the activities

The process that led to the tool definition in its requirements and features is entirely and detailed described in paragraph *4.1.4 Validation phase*[188]. The requirements chosen for the progressive and subsequent validations were: phase of design, software, formats, model, building typology, EPDs phases, EPDs database, categories for simulation, input, output, results, stakeholders and user's actions. Progressively, during the validation phases, the purpose was to refine the choices more and more according to stakeholders' needs and objectives. The final result, which occurred with the third round of validation, was as follow (see Table 17):

Requirements	***Validation III*** *(08/2021)*
Phase of design	Concept Design
Software	Excel (input), Revit + Dynamo (simulation)
Formats	.xls, .rvt, .dyn,
Model	LOD 200
Building Typology	Prototype (residential)
EPDs Phases	**A1-D** (GWP, PENRT, NRSF, RSF)
EPDs Database	Online (Okobaudat, Environdec etc)
Categories for simulation	Walls, floor, stairs
Input	EPDs.xls (EE, EC); Revit Model.rvt LOD 200, script.dyn
Output	EC, EE scenarios
Results	**Charts.rvt + Diagrams.html**
Stakeholders	Building M Provider + Academia
User's actions	(4) 1. Model.rvt LOD 200, 2. Upload EPDs.xls in script.dyn, 3. Run the script 4. Save the .html diagrams

Table 17. Tool 3.0 requirements.

The validation phases and the related tool final version definition were aimed at skipping and solving some of the most common problems related to traditional methodologies aimed at environmental impact scenarios creation. According to this premise, the major weaknesses belonging to consolidated workflows were identified with the scope to shape a tool to incorporate new solutions and necessary achievements in the field. Here is the list of the achievements reached, the structural limits and some suggestions for next tool development.

[188] For the detailed description of the chronological development of the tool.

The tool reached the achievements here listed[189]:

a. There is **no need for high-medium skills in LCA** analysis; the EPDs database employment allows a simplified and precise environmental impact calculation.
b. There is **no need for LCA software**; the environmental calculation is run with a script able to merge digital model quantities and the EPDs database.
c. The environmental impact and LCA analysis are usually conducted during the late phase of the design. The current tool allows the scenarios calculation during the **conceptual design** stage when the influence on design choices is great and the costs of changes are low.
d. The tool simulation in the conceptual design stage can well respond to **public politics** toward environmental impact simulation in the preliminary design stages[190].

Structural limits:

1. The current **slow implementation of EPDs databases**. Industries are starting to equip themselves with an environmental impact database, but the transition is undergoing.
2. At the moment, there is the need to manually fill the EPDs values into an excel format to link the database with the script[191]. Due to the lack of complete implementation of the EPDs database and the definition of a common standard, it is necessary to employ a personal template to link the environmental data with the script.

Next objectives[192] and recommendations:

a) Devise a Revit plug-in to create a user-friendly interface;
b) Automate the EPDs database upload;
c) Move from the building scale to the city (toward a higher scale);
d) Move from the building to single material analysis (toward a smaller scale).

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[189] *Chapter 3. Building the playground* introduced the detailed definition of the implications, scope and goals of the digital tool.
[190] For example, the Ministerial Decree n. 312 of 2 August 2021 containing amendments to Ministerial Decree no. 560 of 1 December 2017 ("BIM Decree" or "Baratono Decree") for the progressive introduction of information management methods and tools for construction and infrastructure by the Public Demand.
[191] Read *Chapter 4. Devising a tool for planning decision*, section *4.1 The assembly work* for the complete description.
[192] See *6.Concluding remarks* for further description.

The result analysis is also carried beyond the simple identification of strengths and weaknesses to trace technical progress in terms of technologies, time and general resources. The chart (see Table 25) highlights the comparison between traditional flow and digital tools when employed in performing the task of environmental impact scenarios creation. The aim is to identify some categories of comparison (software, skills, time, result restitution, phase of design) to highlight the tool's potential in performing the scenarios activity.

	Traditional Flow	**Digital tool**
a.Software needed	BIM modelling + LCA software	BIM Modeling + script
b.Skills	BIM (basic-medium) + LCA	BIM (basic-medium)
c.Time for simulation	About 2 hours	About 15 min
d.Results restitution	.pdf charts	.pdf chart + .html diagrams
e.Phase of design	Developed/Technical	Conceptual

Table 25. Comparison between the traditional and the new workflow.

The tool employment significantly favours a most rapid environmental impact analysis performance by allowing users with no technical skills in LCA analysis to obtain the most efficient and communicative impact scenarios. The strength of the methodology lies precisely in its wide and user-friendly employment. However, the user should be aware of the process and the results to obtain.

In conclusion, the chapter intended to introduce a critical discussion on two levels of analysis, the process and the results. As the narration suggested, the research path was subjected to strong experimentation and possibilities that led to a not predictable result. Therefore, the intent was not to describe a phenomenon exhaustively but to immerse ourselves in the experimentation by tracing a knowledge account anchored in the context of the practical activity. During and after the process, I retraced the operative stages, achievements, errors and attempts, aware of being narrating a particular story, a process made of attempts, changed views, and diverse theories answers to certain conditions. How could be the next achievement? In which terms the tool could reach a higher performative power?

The last and following section aims to narrate some considerations concerning the end of the research path and highlight some limitations of the methodology and possible future development.

Chapter 6.

Concluding remarks

The thesis purpose was to enquiry the intersection between ecological awareness and information revolution related technologies in contributing to the foundation of a new philosophical vision on architecture and in triggering innovation and transformation in consolidated design practice. The research purpose was addressed by different reading plans developed in the dissertation in the following three sections: *Theoretical background and implications, The laboratory experience, Observatory on the experiment*. The third and current section closes with the observatory aimed at creating an account of knowledge through personal practical and observative involvement in the process. The observatory illustrates the performative characteristics of the tool in itself and comparison with traditional methods, its transformative power in the design process and its influence on the designer's role and the creative process. The narration was correlated with critical reflections on the research's theoretical and practical output in contributing to ecological debate in the fold of the information revolution. The section widely addressed the critical discussion and observations of the process and resulted in their theoretical and practical challenges, and now some recommendations for future next development have to be traced in addition to tricks to overcome the main obstacles and difficulties.

The intricate complexity of ecological dynamics and their relationship with human actions and production require innovative and advanced solutions far from traditional processes. Addressing the increasing issue's complexity means equipping ourselves with new tools and implies changing in minds in terms of awareness, consolidated actions, and ways of collaboration. In other words, it means to make more complex tools and methods.

By taking into account the difficulties in addressing the task, the section illustrates some limits that occurred in the methodology and tool definition in terms of process and results. The factors that influence the appearance of some limits in the research work are various and with different entities, from structural to circumstantial. It has to be reminded of the circumstantial causes, especially the necessity to develop the research into an established time lap that limits are fixed from contracts and not from needs. Moreover, the research objectives were defined following multidisciplinary actors' needs and interests; therefore, the result was an object of negotiation in terms of means, time and space. Between the structural circumstances, instead, it is possible to recall limited equipment in terms of technologies at disposition, market dynamics concerning digital tools diffusion for environmental impact calculation and the undergoing implementation of ecological awareness in the field (for example, the EPDs database are nowadays under development and without a common standard).

However, structural and circumstantial limitations must not be considered negative, but they represent the common situation of work and research that often can lead to unexpected and creative solutions. The section will describe and highlight two main "limits" of the methodology and tool development that could represent the starting point for future discussions and advancement in the field: expanding the tool application from the building scale to the city and recognising the limits and fallacious intent belonging to models that pretend to describe a phenomenon exhaustively.

The discourse is addressed by highlighting implications and crucial speculations about the topic to introduce critical reflections on them. The intent is to open a debate that could hopefully become the ground for future experimentation.

6.1 Recognise the limits of an all-compassing model

The first consideration introduces the necessity to redistribute the power we gave to technique and technological means. To establish a balanced relationship with technique, humans have to grasp its essence, which consists not in dominating reality but in embodying a means to unveil it. The technique is a means by which disclosing reality[193], a consideration that could seem banal apparently, encloses the deep power in reordering the hierarchical relationship between humans and machines instead. Parametric and computational logic do not substitute human creativity but have the potential to enhance it and provide tools for exploring fields otherwise inaccessible (Terzidis, 2003). What remains to the designer? The faculty interprets input and output to which attributing a meaning[194].

Secondly, parametric and computational tools can restitute an accurate forecast model concerning situations and behaviours. Still, they embody a certain kind of indeterminacy that must be clearly taken into account. Parametric and

[193] Heidegger thought narrated in *Per un'etica del progetto* by R. Causarano, Timia, 2017.
[194] Read paragraph *5.1.3 Multidisciplinary collaboration and the designer's role* for further details.

scripting procedures seem well-fitting with the scope of responding to complex targets (such as the ecological one) due to their potential in managing a huge amount of real-time data and performing simulation and data elaboration. Scenario creation embodies a great power in simulating the behaviour and future conditions; however, they incorporate a certain level of indeterminateness. Digital means are efficient in data elaboration consisting of measurable scenarios, but they are not completely effective in managing social dynamics. Human, as well as natural facts, can not be exhaustively explained by employing mathematical functions. Scenarios, therefore, can restitute a certain kind of accuracy, high on many occasions, but at the moment, they are not able to incorporate unexpected events especially related to social conditions. Relying on simulation can be dependable in terms of a technical object. Still, the user has to take into account the limits of a model that can't be all-encompassing and develop an ethical responsibility toward the digital means and its results.

Thirdly, the limits occurred by the impossibility of devising an all-encompassing model do not lie only in forecast previsions but in the impossibility to take into account all of the dynamics and purposes. This time, however, the "fault" does not belong to the tool's technical limitations but to the man's fallacious thought. Humans often consider technology as the overall solver tool and pretend by it the performance that they would never ask of other entities. Humans must stop the claim to dispose of a tool able to solve anything to consider it valuable or "good". In order to provide an example, the tool developed in the current research thesis was driven, in its input and output, by defined and precise necessity and implications[195] that shaped the tool form and results. Therefore, the tool was "tailor-made" to respond to a certain kind of situation, planning decisions at a micro-scale and elaborating a specific type of data, a carbon emission database. The resulting tool was not prepacked, but it was the result of articulated experimentation on parametric and algorithmic design conducted with the involvement of multidisciplinary stakeholders[196]. A difficult and laborious process led to a certain kind of result: a digital tool for planning decisions regarding Embodied Carbon and Energy in the conceptual design stage. By taking into account the premises, asking the tool to be performative in a different kind of situation and dataset is fallacious.

In conclusion, humans must abandon the determinist view that they built over the technological means and regain possession of a position of supremacy and control over this in addition to reconsidering their claim toward technology as the overall solver means. Acquiring this kind of awareness can establish, on the one hand, a more balanced relationship between humans and technology but,

[195] Read the net of implications at paragraph *2.1.1 A wave of environmental and social issues.*
[196] See *Chapter 3. Building the playground* for further details.

especially, take a step beyond the false opposition outlined between man/machine and, in a broader view, between culture/technique (Simondon, 2021). The cause of alienation and dissatisfied feelings toward technique in the contemporary world resides in the lack of comprehension of the machine and its essence and, moreover, in confining it between mere technical objects outside the values that include culture.

6.2 Expanding the scale: from the building to the city

The second important consideration to be highlighted concerns the limits of the tool and their possible resolution as the ground for future research. However, the paragraph does not intend to trace the limitations on the technical side[197] but open a wide discussion on methods and applications in the ecological and design discourse.

During the three years of research, the thesis's intent is gradually matured and shifted from sustainable to ecological applications. The necessity of incorporating ecological awareness into the design practice was introduced in *Chapter 1. Parametric design and ecological awareness*. At different scales of intervention, it described how design is called to reach sustainable development objectives by carefully balancing the dialectic between natural and artificial to establish a new alliance between humans and nature. In these terms, architecture's aim became to express a philosophical and aesthetic vision by embodying ecological awareness and innovation in the fold of the informatics revolution (Wines, 2000). The methodology developed into the research path openly aims to reach this target, but the intentions could be more implemented with the next development. In fact, the digital tool finds itself currently transitioning between sustainable and ecological procedures if, clearly, it tends to the second objective cited. Surely, at the moment, it represents an effective vehicle to create and enhance awareness about the climate change target, but the way the informatics revolution related technologies are employed could be further implemented to include an autopoietic mechanism and agent-based modelling[198]. Integrating such advanced technologies allows favouring the reach of much more complex ecological objectives and expands the tool's scale action from the building to the city. Sophisticated computational modelling advantage the interaction beyond the building barriers and permits the interaction with human and non-human entities, external inputs of

[197] See paragraph *5.2 Reading the transfornative tool power*.

[198] Agent-based modelling is a computational model to simulate the interaction of autonomous decision-making entities, called agents, to understand the behaviour of a system. See paragraph *1.3.6 The re-tooling of the discipline* for further details.

various nature and the environment in a system of communicative interaction. In this way, architecture itself could become an interface of multi-modal communication[199]. The research attempted in its experimentation to reach the objectives described, but even if it represents a primordial and perfectible attempt to merge ecological awareness and informatics revolution technology, it can represent a ***working prototypal of action*** toward that direction.

Clearly, opening the application toward the city is strategic employment to integrate city governance methodologies and solve some of the limits that an architectural prototype presents. The parametric and computational logic was tailor-made to fit with a conceptual prototype; therefore, increasing the scale of application means keeping into account a net of intricate dynamics related to the city. It means including reflection on the genius loci, the integration with the city fabric, traffic, crowd analysis, social interaction, and moreover, anyway, keeping in mind the limits imposed by the impossibility of shaping an all-encompassing model introduced in the previous paragraph. Therefore, the solution could be selecting one or more fundamental dynamics that interest the city and including them as the thematic layers of analysis of the digital tool. Surely, the mathematical functions would effectively respond to the scale upgrading, and the data elaboration would not be a problem, but the results and the reliability of the scenarios should be subjected to accurate interpretation by adopting an ethical responsibility. The difficulty in ethical employment of an instrument must not represent the limit for which not to make use of it but a stimulus for more conscious employment.

I strongly believe that ecological awareness transition design should not be only grounded on the use of renewable energy and new material. Still, it must be established on the foundation of a new binomial relationship between humans/nature with information technologies' mature and ethical support. Reaching an ecological awareness means, first of all, educating about it. Until today, environmental data and indicators are not comforting nor improving, but we can still respond with a change, which is that of our minds. I am glad and proud to have contributed to the environmental debate with this research, even in minimal part. However, even the sea itself is made up of single drops, and as we know from mother nature, the union of single particles can trigger unexpected evolutionary changes.

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[199] Terms employed by P. Schumacher in *The Autopoiesis of Architecture*, 2012.

References and thematic bibliography

Design theory and practice

Adamson, G. (2007). *Thinking through craft*, Bloomsbury.

Anderson, P., Salomon D. (2010). *The Architecture of Patterns*, Norton & Co Inc.

Armando, A., & Durbiano, G. (2017). *Teoria del progetto architettonico.* Carocci editore.

Aurigi, A. (2015). *Making the Digital City: The early shaping of urban internet space*, Ashgate.

Batty, M. (2013). *Big Data, smart cities and city planning*, Dialogues in Human Geography, 274-279.

Beretta, M. (2002). *Storia materiale della scienza*, Mondadori.

Bria, F., Morozov, E. (2018), *Ripensare la Smart City*, Codice editore.

Burry, M. (2016). Antoni Gaudí and Frei Otto: Essential Precursors to the Parametricism Manifesto. *Architectural Design*, *86*(2), 30–35.

Cache, B. (2011), *Projectiles*, Architectural Association.

Carpo, M. (2011). *The Alphabet and the Algorithm*. MIT Press.

Carpo, M. (2012). *The Digital Turn in Architecture*, 1992—2012. John Wiley & Sons.

Carpo, M. (2017). *The Second Digital Turn: Design Beyond Intelligence*. MIT Press.

Causarano, R. (2017). *Per un'etica del progetto*. Timia.

Corbellini, G. (2006). *Diagrams. Instructions for use*, in "Lotus international", n. 127, 2006, pp. 88-95.

Corbellini, G. (2013). Morassi C., *Ultimo tango a Zagarol*, in "Parametrico Nostrano", LetteraVentidue.

Cuff, D. (1992). *Architecture: The Story of Practice*, MIT Press, Cambridge.

Dei, F. (2012). *Antropologia culturale*. Il mulino.

Eisenman P. (1992). *Vision Unfolding*. Domus.

Eisenman P. (1999). Diagrams Diaries, Universe Pub.

Eisenman P. (2014). Inside Out, Quodlibet.

Eremia, M., Toma, L., Sanduleac, M. (2017). *The Smart City Concept in the 21th Century,* Science Direct, Procedia Engineering, 181.

Ferraris, M. (2018). *Scienza Nuova*. Rosenberg&Sellier.

Foucault, M. (2011). *Storia della follia nell'età classica [1962]*. BUR.

Frazer, J. (1995). *An Evolutionary Architecture*. London, Architectural Association.

Friedman, Y. (2009), *L'architettura della sopravvivenza*, Bollati Boringhieri.

Friedman, Y. (2012), *Alternative energetiche. Breviario dell'autosufficienza locale,* Bollati Boringhieri.

Friedman Y. (2016), *Utopie Realizzabili*, Quodlibet.

Gabetti R. (1977), *Imparare l'architettura*, Allemandi.

Ginzburg C. (1986). *Spie. Radici di un paradigma indiziario* in "Miti, emblemi e spie", Einaudi.

Gomez, P. (2016), *Attunement, Architectural Meaning After the Crisis of Modern Science, MIT Press.*

Gregory, B. (1972). *Verso un'ecologia della mente*. Adelphi.

Gregory, P. (2013). *Teorie di architettura contemporanea*. Carocci Editore.

Hénard E., *The Cities of the future, Royal Institute of British Architects,* Town Planning Conference London, 1910.

Ingold, M. (2019). *Making*. Raffaello Cortina Editore.

Kuhn, T. (2009). *La struttura delle rivoluzioni scientifiche.* Einaudi.

Latour, B. (1987). *La scienza in azione: introduzione alla sociologia della scienza*, Edizioni di Comunità.

Latour, B. (2013). *Cogitamus. Sei lettere sull'umanesimo scientifico*. Il mulino.

Leon Battista Alberti (1485). *De re aedificatoria*.

Luhmann, N. (1995). *Social Systems*. Stanford University Press.

Mancuso, S. (2020). *La pianta del mondo*. Laterza.

McLuhan, M. (2015). *Gli strumenti del comunicare*. Il Saggiatore.

Olmo, C. (2013). *Architettura e storia. Paradigmi della discontinuità*, Donzelli.

Purini, F. (2008). *Architettura virale.* Lotus 133 (2008) - Viral Architecture. https://www.editorialelotus.it/web/item.php?id=132

Rainer, Z. (2019). *Gaudì. The complete works.* Taschen.

Ratti, C. (2017), *How ubiquitous computing is bringing robotics to places you'd never supect* in Kries M., Hello, Robot. Design between Human and Machine, Vitra Design Museum Publications, Berlin.

RIBA (2020). *Plan of Work.* Available online: www.ribaj.com

Rossi, A. (1966). *L'architettura delle città*, Quodlibet.

Secchi, B. (2015). *La città del ventesimo secolo*, Laterza.

Simondon, G. (2021). *Del modo di esistenza degli oggetti tecnici*. Orthotes.

Digital transition. From sustainability to ecology in design.

Abdullah, H., Kamara, J.M. (2013). *Parametric Design Procedures: a new approach to Generative-Form in the Conceptual Design Phase*, Research Gate.

ACCA. (2017). Guida al BIM. https://www.acca.it/ebook-guida-al-bim

Ahankoob, A., Preece N. (2012). *BIM perspectives on construction waste reduction*, Research Gate.

AIA (2019). *Document E202 Building Information Modeling Protocol Exhibit*, American Institute of Architects: Washington, DC, USA.

Antón, L.Á.; Díaz, J (2014). *Integration of LCA and BIM for Sustainable Construction*. Int. J. Civ. Environ. Eng., 8, 1378-1382.

Antón Alvarez, L., Díaz J. (2014). *Integration of life cycle assessment in a BIM environment*. Science Direct.

ASVIS (2018). *L'agenda Urbana per lo sviluppo sostenibile*.

Autodesk (2021). Dynamo Primer Guide. https://primer.dynamobim.org/

Aurigi, A. (2015). *Making the Digital City: The early shaping of urban internet space*, Ashgate.

Batty, M. (et al.) (2000), Torrens P.M., Visualising the City: Communicating Urban Design to Planners and Decision-Makers, Technical Report Paper 26, Centre for Advanced Spatial Analysis (UCL).

Batty, M. (2013). *Big Data, smart cities and city planning*, Dialogues in Human Geography, 274-279.

Bahu, J.M., Koch, A., Kremers, E., Murshed, S.M. (2013). *Towards a 3D spatial urban energy modelling approach*, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 2013, II-2/W1.

Biljecki, F., Stoter J., Ledoux H., Zlatanova S., Çöltekin A. (2015). *Applications of 3D City Models: State of the Art Review*, ISPRS International Journal of Geo-Information.

Bolton, R. (2018). *Customer experience challenges: Bringing together digital, physical and social realms*, Journal of Service Management, 29(5).

Bork, R. (2014). Dynamic Unfolding and the Conventions of Procedure: Geometric Proportioning Strategies in Gothic Architectural Design. *Architectural Histories*, *2*, 14.

Bria, F., Sagarra ,O., Rodríguez, j., Balcells, P. (2018). D5.6 Deployments of pilots in Barcelona (Decentralized Citizens Owned Data Ecosystem), V.1.0.

Brockwell, S.; Horrocks, R (2020). *BIM, GIS and Smart Cities: Challenges and Opportunities*. Autodesk University: San Rafael, USA. Available online: https://www.autodesk.com/autodeskuniversity/article/BIM-GIS-and-Smart-Cities-Challenges-and-Opportunities-2020, (accessed on 15 August 2021).

Building Smart (2012), *Common BIM Requirements (COBIM)*, v.1.0, Finland.

Burry, M. (2016). Antoni Gaudí and Frei Otto: Essential Precursors to the Parametricism Manifesto. *Architectural Design*, *86*(2), 30–35.

Bunz, M. (2013). *The silent revolution. How digitalisation transform knowledge, work, journalism and politics without making too much noise*, Palgrave Macmillan.

Caputi, M., Odorizzi, P., Stefani, M. (2015). *Il Building Information Modeling,* Hoepli.

Carpo, M. (2011). *The Alphabet and the Algorithm*. MIT Press.

Carpo, M. (2012). *The Digital Turn in Architecture*, 1992—2012. John Wiley & Sons.

Carpo, M. (2016). Parametric notations.The birth of the non-standard. *Parametricism 2.0.* Wiley, London, 86(02).

Carpo, M. (2017). *The Second Digital Turn: Design Beyond Intelligence*. MIT Press.

Causarano, R. (2017). *Per un'etica del progetto*. Timia.

Chen, R. (2011). *The development of 3D city model and its applications in urban planning*, in Proceedings of the 19th International Conference on Geoinformatics, Shanghai, China, pp. 1–5.

Chesbrough, H. W. (2003). The new imperative for creating and profiting from technology. Open innovation.

Ciborra C., Andreu R., Sharing knowledge across boundaries, Journal of Information Technology, 2001.

Ciribini, L. C. (2016). *BIM e digitalizzazione nell'ambiente costruito,* Grafill.

Çolagoklu, B., Yazar, T. (2007). *An innovative design education approach: Computational design teaching for architecture*, Metu Jfa.

Construction Industry Council (2013), *Building Information Model (BIM) Protocol*, London.

Corbellini, G. (2006). *Diagrams. Instructions for use*, in "Lotus international", n. 127, 2006, pp. 88-95.

Corbellini, G. (2013). Morassi C., *Ultimo tango a Zagarol*, in "Parametrico Nostrano", LetteraVentidue.

CRH (2020), Expanding the horizons of sustainable progress, Sustainability Report, CRH: Dublin. Available online: https://www.crh.com/media/3697/crh-2020-sustainability-report.pdf, (Accessed on: 15 August 2021).

Cudzik, J., Radziszewski, K. (2019). *Parametric design in architectural education*, World Transactions on Engineering and Technology Education, Research Gate, Vol.17, No.4.

Del Giudice, M., Patti, E. (2014). *BIM and GIS for district modelling*, Research Gate.

Del Giudice, M., & Osello, A. (2021). *Handbook of Research on Developing Smart Cities Based on Digital Twins*.

DM 560/2017 (2017). https://www.mit.gov.it/normativa/decreto-ministeriale-numero-560-del-01122017

DM 312/2021 (2021). https://www.01building.it/bim/dm-312-2021-digitalizzazione-costruzioni/

Domus. (2012). Frei Otto. Thinking in Models. Access online: https://www.domusweb.it/en/news/2016/11/10/frei_otto_thinking_in_models.html

Easterling, K. (2019). *Lo spazio in cui ci muoviamo*. Treccani.

EEA (2022). *EU Emissions trading system.* https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1

EIA (2019). *Annual Energy outlook*. https://www.eia.gov/outlooks/aeo/

Eisenman P. (2014). Inside Out, Quodlibet.

Eleftheriadis S. (et al.) (2017). *Life cycle energy efficiency in building structures*. Science Direct.

ENSLIC (2010). *Guidelines for LCA calculation in early design phases*.
EPD – *La Dichiarazione Ambientale di Prodotto*. Available online: https://www.epditaly.it/epd-2/ (accessed on 12 July 2021).

Eremia, M., Toma, L., Sanduleac, M. (2017). *The Smart City Concept in the 21th Century,* Science Direct, Procedia Engineering, 181.

ETS, *Sistema per lo scambio delle quote di emissione dell'UE (ETS UE).* Available online: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_it (accessed on 15 August 2021)

EUBIM Task Group (2016). *Handbook for the Introduction of Building Information Modelling* by the European Public Sector. Available online: http://www.eubim.eu/downloads/EU_BIM_Task_Group_Handbook_FINAL.PDF

Feng, F. (2018). *Parametric Design, Design and Analysis of Complex Structures*, Science Direct.

Ferraris, M. (2018). *Scienza Nuova*. Rosenberg&Sellier.

Fiordimela, C. (2016). Frei Otto, pensare in modelli. *Giornale dell'Architettura*. https://ilgiornaledellarchitettura.com/2016/12/15/frei-otto-pensare-in-modelli/

Floridi L. (2011). *The philosophy of information*, Oxford University Press.

Floridi, L. (2014). *La quarta rivoluzione. Come l'infosfera sta cambiando il mondo.* Raffaello Cortina Editore.

Frazer, J. (1995). *An Evolutionary Architecture*. London, Architectural Association.

Frazer, J. (2016). Parametric Computation. History and Future. *Parametricism 2.0. Wiley, London*, *86* (02).

Giaveno, S. (2021). *Smart City and Digital Twins: Definitions, Methodologies, and Applications* in Handbook of Research on Developing Smart Cities Based on Digital Twin. IGI-GLOBAL.

Giaveno, S., Osello, A., Garufi, D., Santamaria Razo D. (2021). *Embodied Carbon and Embodied Energy Scenarios in the Built Environment. Computational Design Meets EPDs*. Sustainability, 13 (21).

Gibson, J. (2014). *L'approccio ecologico alla percezione visiva*, Mimesis.

Gregory, B. (1972). *Verso un'ecologia della mente*. Adelphi.

Gregory, P. (2013). *Teorie di architettura contemporanea*. Carocci Editore.

Gröger, G. (et al.) (2019). *OGC City Geography Markup Language* (Citygml) Encoding Standard v2. 0. OGC Doc, Open Geospatial Consortium: USA, 2012. Available from: http://www.opengeospatial.org/standards/citygml

Hao, W., Yisha, P., Xiaochun, L. (2019). *Integration of BIM and GIS in sustainable built environment: a review and bibliometric analysis*, Elsevier, Automation in Construction, 103.

Harari, Y.N. (2018), *21 Lessons for the 21st Century*, Spiegel & Grau, New York.

Hénard E., *The Cities of the future, Royal Institute of British Architects,* Town Planning Conference London, 1910.

Hollberg, A. (2016). *Parametric Life Cycle Assessment. Introducing a time-efficient method for environmental building design optimisation.* Research Gate.

Hollberg, A. (et al.) (2021). *Review of Visualising LCA Results in the Design Process of Buildings*. Build. Environ.

Huan, Y.; Liang, T.; Li, H.; Zhang (2021). *C. A systematic method for assessing progress of achieving sustainable development goals: A case study of 15 countries.* Sci. Total. Environ. 752.

Ilozor, D., & Kelly, D. (2012). Building Information Modeling and Integrated Project Delivery in the Commercial Construction Industry: A Conceptual Study. *Journal of Engineering, Project, and Production Management*, *2*.

Ingold, M. (2019). *Making*. Raffaello Cortina Editore.

Jabi, W. (2013). *Parametric Design for Architecture*. Laurence King Publishing.

Jacobson, I. (1992). *Object-Oriented Software Engineering: A Use Case Driven Approach*, Addison-Wesley.

Jenkins, H. (2006), Convergence culture: Where old and new media collide, NYU press.

Kaden, R., Kolbe, T.H. (2014). *Simulation-based total energy demand estimation of buildings using semantic 3D city models*, Int. J. 3-D Inf. Model, 3, 35–53.

Kolarevic, B. (2003). *Architecture in the Digital Age. Design and Manufacturing*, London and New York: Routledge.

Kortlander, M., Spierings, J., Demeyer, T. (2019). D5.5 *Deployment of Pilots in Amsterdam*, (Decentralized Citizens Owned Data Ecosystem), v.1.0, 31.

Kreiner, H. (et al.) (2015). A new systemic approach to improve the sustainability performance. Research Gate.

Kuhn, T. (2009). *La struttura delle rivoluzioni scientifiche.* Einaudi.

Kurakula, V. (2017). *A GIS-Based Approach for 3D Noise Modelling Using 3D City Model*s, Master's Thesis, International Institute for Geo-information Science and Earth Observation, Enschede, The Netherlands.

Kylili A., Vaiciunas J. (2015). *Integration of Building Information Modelling and Life Cycle Assessment*. Research Gate.

Lavagna M. (2018). *Life cycle assessment in edilizia*, Hoepli.

Lee, Y. (2000). The sustainability of university–industry research collaboration. Springer. The Journal of Technology Transfer 25, 111–133.

Lee, S., Tae, S., Roh, S., & Kim, T. (2015). Green Template for Life Cycle Assessment of Buildings Based on Building Information Modeling: Focus on Embodied Environmental Impact. *Sustainability*, *7*(12), 16498–16512.

LETI (2021). *Embodied Carbon Primer* (. https://b80d7a04-1c28-45e2-b904-e0715cface93.filesusr.com/ugd/252d09_8ceffcbcafdb43cf8a19ab9af5073b92.pdf

Li, C., Yangluxi, L. (2019). *Parametric design process basing on building physical performance.*

Liu, Z. (et al.) (2015). *A BIM-aided construction waste minimisation framework.* Science Direct.

Liu, X. (et al.) (2017). *A state-of-the-art review on the integration of building information modelling (BIM) and geographic information system (GIS)*, ISPRS International Journal of Geo-Information.

Luhmann, N. (1995). *Social Systems*. Stanford University Press.

Lynn, G. (1990). *Animate Form*. Princeton Architectural Press.

Lynn, G. (2013), *Archaeology of the Digital*. The MIT Press.

Ma, Z., Ren, Y. (2017). *Integrated applications of BIM and GIS: an overview*, Procedia Engineering, Science Direct.

Mah, D. (et al.) (2015). *House construction CO2 footprint quantification.* Research Gate.
Menges, A., & Ahlquist, S. (2011). *Computational Design Thinking.* Wiley, London.

Migayrou, F. (2013), *Architectures Non-Standard,* Centre Pompidou press.

Mohanty, S. P., Choppali, U., & Kougianos, E. (2016). *Everything you wanted to know about smart cities.* Research Gate.

Mori, T. (2004). *Immateriale/Ultramateriale Architettura*, progetto e materiali, Postmedia.

Morton, T. (2018). *Iperoggetti*, Nero.

Morton, T. (2019). *Come un'ombra dal futuro*. Aboca edizioni.

Morton, T. (2021). *Ecologia oscura*. Luiss University Press.

Najjar, M. (et al.) (2017). Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building. *Journal of Building Engineering*, *14*, 115–126.

Negroponte, N. (1970). *Soft Architecture Machines*, MIT Press.

Novembri, G.; Rossini, F.; Fioravanti, A. (2018). *Improving the integration between BIMs and agent-based simulations: The Swarm Building Modeling – SBM.* In eWork and eBusiness in Architecture, Engineering and Construction; CRC Press: Boca Raton, USA; pp. 123–126.

OECD (2015). Indicators in Italy. Italy | READ online (oecd-ilibrary.org). Accessed 15/08/2021.

ONU, Agenda 2030, (2015). Accessed 7 luglio 2021, da https://unric.org/it/wp-content/uploads/sites/3/2019/11/Agenda-2030-Onu-italia.pdf

ONU, UNSDG Linee Guida, (2015). Accessed 7 luglio 2021, da https://unric.org/it/wp-content/uploads/sites/3/2019/11/SDG-linee-guida.pdf.

Osello, A. (2015), BIM, GIS, AR per il facility management, Dario Flaccovio Editore.

Osello, A., Ugliotti, F. (2017). *BIM: verso il catasto del futuro*. Cangemi Editore.

Peng, C. (2016). Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. *Journal of Cleaner Production*, *112*, 453–465. https://doi.org/10.1016/j.jclepro.2015.08.078

Pinch,T. J. (1993). *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology,* Cambridge MIT Press, Cambridge, pp. 17-50.

Purini, F. (2008). *Architettura virale.* Lotus 133 (2008) - Viral Architecture. https://www.editorialelotus.it/web/item.php?id=132

Röck M. (et al.) (2018). *LCA and BIM: Visualisation of environmental potentials in building.*

Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Integrated Assessment and Visualization of Building Elements' Embodied Impacts for Design Guidance in Early Stages. *Procedia CIRP*, *69*, 218–223.

Roncaglia, G. (2010). *La quarta rivoluzione*, Laterza.

Ross, L. (2010). *Virtual 3D City Models in Urban Land Management—Technologies and Applications*, Ph.D. Thesis, Technische Universität Berlin, Germany.

Sacchi, L., & Unali, M. (2003). *Architettura e cultura digitale*. Skira.

Saggio, A. (2010). *Architettura e modernità. Dal Bauhaus alla rivoluzione informatica.* Carocci Editore.

Salgin, B., Akgun A. (2017). *Construction waste reduction through BIM-Based site management approach.* Research Gate.

Salzano, A. (et al.) (2015). *Il BIM a supporto della progettazione sostenibile.*

Sarkis, H. (2017). *Architettura, ricerca e utopia* in Domus, vol. 1011, supp. Innovation, Editoriale Domus s.p.a., pp. 8-15

Schumacher, P. (2008). *Parametricism as Style. Parametricist Manifesto.* Dark Side Club1 , 11th Architecture Biennale, Venice 2008.

Schumacher, P. (2009). *Parametricism. A New Global Style for Architecture and Urban Design.* AD Architectural Design-Digital Cities, Vol 79, No 4. London.

Schumacher, P. (2011). *The Societal Function of Architecture*. Wolf D. Prix & Kristy Balliet.

Schumacher, P. (2011). *The Autopoiesis of Architecture – Extracts: Communication, Societal Function, Semiology*. Available online: https://www.academia.edu/11889782/The_Autopoiesis_of_Architecture_Extracts_Communication_Societal_Function_Semiology

Schumacher, P. (2012). *Architecture's Next Ontological Innovation: Vol. Not Nature – Architectural Manual*. Pratt Institute.

Schumacher, P. (2012). *The Autopoiesis of Architecture, Volume II: A New Agenda for Architecture*. John Wiley & Sons.

Schumacher, P. (2013). *Parametric Semiology – The Design of Information Rich Environments: Vol. Architecture In Formation – On the Nature of Information in Digital Architecture*. Pablo Lorenzo-Eiroa and Aaron Sprecher, Routledge, Taylr and Francis.

Schumacher, P. (2016). *Parametricism 2.0: Rethinking Architecture's Agenda for the 21st Century.* Wiley, London.

Schumacher for Iris Ceramica Group. (2020). *The architects series. Patrick Schumacher Lecture: "Cyber space and the autopoiesis of architecture"* [Interview]. https://www.youtube.com/watch?v=03mcxw4xDYg

Schwab, K. (2016). *La quarta rivoluzione industriale*, Franco Angeli.

Seo, S., Tucker, S., & Newton, P. (2007). Automated Material Selection and Environmental Assessment in the Context of 3D Building Modelling. *Journal of Green Building*, *2*(2), 51–61.

Shepherd, D. (2015). *The BIM Management Handbook*, NBS, Newcastle.

Shin, Y., & Cho, K. (2015). BIM Application to Select Appropriate Design Alternative with Consideration of LCA and LCCA. *Mathematical Problems in Engineering*, *2015*, 1–14.

Singapore Municipality (2013). *BIM Guide*, version 2.0.

Sormani, D. (2016). *Il Tecnopark russo di Studio Hadid*. Abitare.

Soust-Verdaguer, B. (et al.) (2017). Critical Review of BIM-Based LCA methods to buildings.

Spyropoulos, T. (2016). *Behavioural Complexity: Constructing Frameworks for Human-Machine Ecologies*. Architectural Design, 86(2), 36–43.

Statsbygg BIM Manual (2013), version 1.2.1, Oslo.

Sutherland, I. E. (1960). *Sketchpad: A man-machine graphical communication system*. 149.

Terzidis, K. (2003). *Expressive Form: A Conceptual Approach to Computational Design*. Routledge.

Treccani. (2021). *algoritmo in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/algoritmo

Treccani. (2021). *autopoièṡi in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/autopoiesi

Treccani. (2021). *CAD in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/cad

Treccani. (2021). *ontològico in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/ontologico

Treccani. (2021). *script in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/script

Treccani. (2021). *semiologìa in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/semiologia

Treccani. (2022). *protòtipo in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/prototipo

UN. (2015). *UN, The Paris Agreement, 2015*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

UN (2015), Assemblea Generale, A/RES/70/1 Trasformare il nostro mondo: l'Agenda 2030 per lo Sviluppo Sostenibile.

UN. (2018). *UN Secretary-General's Strategy on New Technologies*. https://www.un.org/en/newtechnologies/

UNI 11337 1-7 (2018). Accessed 16/01/2022. http://store.uni.com/catalogo/uni-11337-7-2018?josso_back_to=http://store.uni.com/josso-security-check.php&josso_cmd=login_optional&josso_partnerapp_host=store.uni.com

UNI EN 15804 (2019) *Dichiarazioni ambientali di prodotto.* Available online; https://www.certifico.com/costruzioni/370-news-costruzioni/9658-uni-en-15804-2019-dichiarazioniambientali-di-prodotto, (accessed on 15 August 2021).

UNSDg. (2021). *Goal 13: Take urgent action to combat climate change and its impacts*. United Nations Sustainable Development. Accessed 22 dicembre 2021, da https://www.un.org/sustainabledevelopment/climate-change/

Van Brummelen, J. (2019). *Procedural Generation*. MIT.edu. http://www.mit.edu/~jessicav/6.S198/Blog_Post/ProceduralGeneration.html

Vassileva, I., Dahlquist, E., Campillo, J. (2016). *The citizens' role in energy smart city development*, Energy Procedia, 88.

Vitruvio. (15 a.C.). *De architectura, III, V, 8, on Ionic colums and architraves.*

Weisberg, D. Patrick Hanratty and MCS (2021) Accessed 20 settembre 2021, http://cadhistory.net/15%20Patrick%20Hanratty%20and%20MCS.pdf

Wines, J. (2000). *Green Architecture*. Taschen.

Wittstock, B. (et al.) (2012). *EeBGuide Project*.

Yamamura, S., Fan, L., Suzuki, Y. (2016). *Assessment of urban energy performance through integration of BIM and GIS for smart city planning*, Science Direct, Elsevier.

Zhiliang, M., Yuan, R. (2019). *Integrated application of BIM-GIS: an overview*, Science Direct, Procedia Engineering, 196.

Zhou, S. (et al.) (2010). Crowd modeling and simulation technologies. *ACM Transactions on Modeling and Computer Simulation*, *20*, 20.

Wines, J. (2010). *Green Architecture*, Taschen.

Wu, H.; He, Z.; Gong, J. (2010). *A virtual globe-based 3D visualisation and interactive framework for public participation in urban planning processes*, Comput. Environ. Urban Syst.

Academy-Industry collaboration model

Ankrah, S. N.; and AL-Tabbaa, O. (2015). *Universities-Industry Collaboration: A Systematic Review.* Research Gate.

Barnes, T.; Pashby, I.; Gibbons, A. (2002). *Effective University-Industry Interaction: A Multi-Case Evaluation of Collaborative R&D Projects*. Eur. Manag. J., 20, 272–285.

Bruneel, J. (et al.) (2010). Investigating the factors that diminish the barriers to university–industry collaboration. Science Direct.

De Fuentes, C., Dutrénitc, G. (2012) *Best channels of Academia–industry interaction for long-term benefit.* Science Direct.

De Martin, J. C. (2017b). *Università futura*. Codice Editore.

Dei, F. (2012). *Antropologia culturale*. Il mulino.

Etzkowitz, H., Leydesdorff, L. (1995). *The Triple Helix*. EASST Review (14).

Michaudel, Q. (et al.) (2015). Academia−Industry Symbiosis in Organic Chemistry. *Accounts of Chemical Research 48* (3), 712-721.

Mitev, N., Venter, W. (2009). Reflexive Evaluation of an Academy–Industry Research Collaboration. Research Gate. Journal of Management Studies 46(5):733 - 754.

Myoken, Y. (2013). The role of geographical proximity in university and industry collaboration: Case study of Japanese companies in the UK. *International Journal of Technology Transfer and Commercialisation*, *12*, 43.

Perkmann, M., Walsh, K. (2017). *University–industry relationships and open innovation.* Research Gate, International Journal of Management Reviews 9(4).

Pique, J. M., Berbegal-Mirabent, J., & Etzkowitz, H. (2018). Triple Helix and the evolution of ecosystems of innovation: The case of Silicon Valley. *Triple Helix*, *5*(1), 11.
Pizziolo, G. (2004). *Dai margini del caos. L'ecologia del progettare*, Alinea.

Ranga, M., & Etzkowitz, H. (2013). Triple Helix Systems: An Analytical Framework for Innovation Policy and Practice in the Knowledge Society. *Industry and Higher Education*, *27*(4), 237–262.

Roberts, J.L. (2017). The Future of Academy – Industry collaboration. Research Gate.

Rybnicek, R., & Königsgruber, R. (2019). What makes industry–university collaboration succeed? A systematic review of the literature. *Journal of Business Economics*, *89*(2), 221–250.

Complete bibliography

Abdullah, H., Kamara, J.M. (2013). *Parametric Design Procedures: a new approach to Generative-Form in the Conceptual Design Phase*, Research Gate.

ACCA. (2017). Guida al BIM. https://www.acca.it/ebook-guida-al-bim

Adamson, G. (2007). *Thinking through craft*, Bloomsbury.

Ahankoob, A., Preece N. (2012). *BIM perspectives on construction waste reduction*, Research Gate.

AIA (2019). *Document E202 Building Information Modeling Protocol Exhibit*, American Institute of Architects: Washington, DC, USA.

Anderson, P., Salomon D. (2010). *The Architecture of Patterns*, Norton & Co Inc.

Ankrah, S. N.; and AL-Tabbaa, O. (2015). *Universities-Industry Collaboration: A Systematic Review.* Research Gate.

Antón, L.Á.; Díaz, J (2014). *Integration of LCA and BIM for Sustainable Construction*. Int. J. Civ. Environ. Eng., 8, 1378-1382.

Antón Alvarez, L., Díaz J. (2014). *Integration of life cycle assessment in a BIM environment*. Science Direct.

Armando, A., & Durbiano, G. (2017). *Teoria del progetto architettonico.* Carocci editore.

ASVIS (2018). *L'agenda Urbana per lo sviluppo sostenibile*.

Autodesk (2021). Dynamo Primer Guide. https://primer.dynamobim.org/

Aurigi, A. (2015). *Making the Digital City: The early shaping of urban internet space*, Ashgate.

Batty, M. (et al.) (2000), Torrens P.M., Visualising the City: Communicating Urban Design to Planners and Decision-Makers, Technical Report Paper 26, Centre for Advanced Spatial Analysis (UCL).

Batty, M. (2013). *Big Data, smart cities and city planning*, Dialogues in Human Geography, 274-279.

Bahu, J.M., Koch, A., Kremers, E., Murshed, S.M. (2013). *Towards a 3D spatial urban energy modelling approach*, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 2013, II-2/W1.

Barnes, T.; Pashby, I.; Gibbons, A. (2002). *Effective University-Industry Interaction: A Multi-Case Evaluation of Collaborative R&D Projects*. Eur. Manag. J., 20, 272–285.

Beretta, M. (2002). *Storia materiale della scienza*, Mondadori.

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). A*pplication of life-cycle assessment to early stage building design for reduced embodied environmental impacts*. Building and Environment, 60, 81–92.

Bianconi, F., Filippucci, M., Buffi, A., & Vitali, L. (2019). *Morphological and visual optimization in stadium design: A digital reinterpretation of Luigi Moretti's stadiums.* Architectural Science Review, 63, 1–16.

Biljecki, F., Stoter J., Ledoux H., Zlatanova S., Çöltekin A. (2015). *Applications of 3D City Models: State of the Art Review*, ISPRS International Journal of Geo-Information.

Bolton, R. (2018). *Customer experience challenges: Bringing together digital, physical and social realms*, Journal of Service Management, 29(5).

Bork, R. (2014). Dynamic Unfolding and the Conventions of Procedure: Geometric Proportioning Strategies in Gothic Architectural Design. *Architectural Histories*, *2*, 14.

Bria, F., Morozov, E. (2018), *Ripensare la Smart City*, Codice editore.

Bria, F., Sagarra ,O., Rodríguez, j., Balcells, P. (2018). D5.6 Deployments of pilots in Barcelona (Decentralized Citizens Owned Data Ecosystem), V.1.0.

Brockwell, S.; Horrocks, R (2020). *BIM, GIS and Smart Cities: Challenges and Opportunities*. Autodesk University: San Rafael, USA. Available online: https://www.autodesk.com/autodeskuniversity/article/BIM-GIS-and-Smart-Cities-Challenges-and-Opportunities-2020, (accessed on 15 August 2021).

Bruneel, J. (et al.) (2010). Investigating the factors that diminish the barriers to university–industry collaboration. Science Direct.

Building Smart (2012), *Common BIM Requirements (COBIM)*, v.1.0, Finland.

Burry, M. (2016). Antoni Gaudí and Frei Otto: Essential Precursors to the Parametricism Manifesto. *Architectural Design*, *86*(2), 30–35.

Bunz, M. (2013). *The silent revolution. How digitalisation transform knowledge, work, journalism and politics without making too much noise*, Palgrave Macmillan.

Cache, B. (2011), *Projectiles*, Architectural Association.

Caputi, M., Odorizzi, P., Stefani, M. (2015). *Il Building Information Modeling,* Hoepli.

Carpo, M. (2011). *The Alphabet and the Algorithm*. MIT Press.

Carpo, M. (2012). *The Digital Turn in Architecture*, 1992—2012. John Wiley & Sons.

Carpo, M. (2016). Parametric notations.The birth of the non-standard. *Parametricism 2.0.* Wiley, London, 86(02).

Carpo, M. (2017). *The Second Digital Turn: Design Beyond Intelligence*. MIT Press.

Causarano, R. (2017). *Per un'etica del progetto*. Timia.

Chen, R. (2011). *The development of 3D city model and its applications in urban planning*, in Proceedings of the 19th International Conference on Geoinformatics, Shanghai, China, pp. 1–5.

Chesbrough, H. W. (2003). The new imperative for creating and profiting from technology. Open innovation.

Ciborra C., Andreu R., Sharing knowledge across boundaries, Journal of Information Technology, 2001.

Ciribini, L. C. (2016). *BIM e digitalizzazione nell'ambiente costruito,* Grafill.

Çolagoklu, B., Yazar, T. (2007). *An innovative design education approach: Computational design teaching for architecture*, Metu Jfa.

Construction Industry Council (2013), *Building Information Model (BIM) Protocol*, London.

Corbellini, G. (2006). *Diagrams. Instructions for use*, in "Lotus international", n. 127, 2006, pp. 88-95.

Corbellini, G. (2013). Morassi C., *Ultimo tango a Zagarol*, in "Parametrico Nostrano", LetteraVentidue.

CRH (2020), Expanding the horizons of sustainable progress, Sustainability Report, CRH: Dublin. Available online: https://www.crh.com/media/3697/crh-2020-sustainability-report.pdf, (Accessed on: 15 August 2021).

Cudzik, J., Radziszewski, K. (2019). *Parametric design in architectural education*, World Transactions on Engineering and Technology Education, Research Gate, Vol.17, No.4.

Cuff, D. (1992). *Architecture: The Story of Practice*, MIT Press, Cambridge.

De Fuentes, C., Dutrénitc, G. (2012) *Best channels of Academia–industry interaction for long-term benefit.* Science Direct.

De Martin, J. C. (2017b). *Università futura*. Codice Editore.

Dei, F. (2012). *Antropologia culturale*. Il mulino.

Del Giudice, M., Patti, E. (2014). *BIM and GIS for district modelling*, Research Gate.

Del Giudice, M., & Osello, A. (2021). *Handbook of Research on Developing Smart Cities Based on Digital Twins*.

DM 560/2017 (2017). https://www.mit.gov.it/normativa/decreto-ministeriale-numero-560-del-01122017

DM 312/2021 (2021). https://www.01building.it/bim/dm-312-2021-digitalizzazione-costruzioni/

Domus. (2012). Frei Otto. Thinking in Models. Access online: https://www.domusweb.it/en/news/2016/11/10/frei_otto_thinking_in_models.html

Easterling, K. (2019). *Lo spazio in cui ci muoviamo*. Treccani.

EEA (2022). *EU Emissions trading system.* https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1

EIA (2019). *Annual Energy outlook*. https://www.eia.gov/outlooks/aeo/

Eisenman P. (1992). *Vision Unfolding*. Domus.

Eisenman P. (1999). Diagrams Diaries, Universe Pub.

Eisenman P. (2014). Inside Out, Quodlibet.

Eleftheriadis S. (et al.) (2017). *Life cycle energy efficiency in building structures*. Science Direct.

ENSLIC (2010). *Guidelines for LCA calculation in early design phases*.

EPD – *La Dichiarazione Ambientale di Prodotto*. Available online: https://www.epditaly.it/epd-2/ (accessed on 12 July 2021).

Eremia, M., Toma, L., Sanduleac, M. (2017). *The Smart City Concept in the 21th Century,* Science Direct, Procedia Engineering, 181.

ETS, *Sistema per lo scambio delle quote di emissione dell'UE (ETS UE).* Available online: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_it (accessed on 15 August 2021)

Etzkowitz, H., Leydesdorff, L. (1995). *The Triple Helix*. EASST Review (14).

EUBIM Task Group (2016). *Handbook for the Introduction of Building Information Modelling* by the European Public Sector. Available online: http://www.eubim.eu/downloads/EU_BIM_Task_Group_Handbook_FINAL.PDF

Feng, F. (2018). *Parametric Design, Design and Analysis of Complex Structures*, Science Direct.

Ferraris, M. (2018). *Scienza Nuova*. Rosenberg&Sellier.

Fiordimela, C. (2016). Frei Otto, pensare in modelli. *Giornale dell'Architettura*. https://ilgiornaledellarchitettura.com/2016/12/15/frei-otto-pensare-in-modelli/

Floridi L. (2011). *The philosophy of information*, Oxford University Press.

Floridi, L. (2014). *La quarta rivoluzione. Come l'infosfera sta cambiando il mondo.* Raffaello Cortina Editore.

Foucault, M. (2011). *Storia della follia nell'età classica [1962]*. BUR.

Frazer, J. (1995). *An Evolutionary Architecture*. London, Architectural Association.

Frazer, J. (2016). Parametric Computation. History and Future. *Parametricism 2.0. Wiley, London*, *86* (02).

Friedman, Y. (2009), *L'architettura della sopravvivenza*, Bollati Boringhieri.

Friedman, Y. (2012), *Alternative energetiche. Breviario dell'autosufficienza locale,* Bollati Boringhieri.

Friedman Y. (2016), *Utopie Realizzabili*, Quodlibet.

Gabetti R. (1977), *Imparare l'architettura*, Allemandi.

Giaveno, S. (2021). *Smart City and Digital Twins: Definitions, Methodologies, and Applications* in Handbook of Research on Developing Smart Cities Based on Digital Twin. IGI-GLOBAL.

Giaveno, S., Osello, A., Garufi, D., Santamaria Razo D. (2021). *Embodied Carbon and Embodied Energy Scenarios in the Built Environment. Computational Design Meets EPDs*. Sustainability, 13 (21).

Gibson, J. (2014). *L'approccio ecologico alla percezione visiva*, Mimesis.

Ginzburg C. (1986). *Spie. Radici di un paradigma indiziario* in "Miti, emblemi e spie", Einaudi.

Gomez, P. (2016), *Attunement, Architectural Meaning After the Crisis of Modern Science, MIT Press.*

Gregory, B. (1972). *Verso un'ecologia della mente*. Adelphi.

Gregory, P. (2013). *Teorie di architettura contemporanea*. Carocci Editore.

Gröger, G. (et al.) (2019). *OGC City Geography Markup Language* (Citygml) Encoding Standard v2. 0. OGC Doc, Open Geospatial Consortium: USA, 2012. Available from: http://www.opengeospatial.org/standards/citygml

Hao, W., Yisha, P., Xiaochun, L. (2019). *Integration of BIM and GIS in sustainable built environment: a review and bibliometric analysis*, Elsevier, Automation in Construction, 103.

Harari, Y.N. (2018), *21 Lessons for the 21st Century*, Spiegel & Grau, New York.

Hénard E., *The Cities of the future, Royal Institute of British Architects,* Town Planning Conference London, 1910.

Hollberg, A. (2016). *Parametric Life Cycle Assessment. Introducing a time-efficient method for environmental building design optimisation.* Research Gate.

Hollberg, A. (et al.) (2021). *Review of Visualising LCA Results in the Design Process of Buildings*. Build. Environ.

Huan, Y.; Liang, T.; Li, H.; Zhang (2021). *C. A systematic method for assessing progress of achieving sustainable development goals: A case study of 15 countries.* Sci. Total. Environ. 752.

Ilozor, D., & Kelly, D. (2012). Building Information Modeling and Integrated Project Delivery in the Commercial Construction Industry: A Conceptual Study. *Journal of Engineering, Project, and Production Management*, *2*.

Ingold, M. (2019). *Making*. Raffaello Cortina Editore.

Jabi, W. (2013). *Parametric Design for Architecture*. Laurence King Publishing.

Jacobson, I. (1992). *Object-Oriented Software Engineering: A Use Case Driven Approach*, Addison-Wesley.

Jenkins, H. (2006), Convergence culture: Where old and new media collide, NYU press.

Kaden, R., Kolbe, T.H. (2014). *Simulation-based total energy demand estimation of buildings using semantic 3D city models*, Int. J. 3-D Inf. Model, 3, 35–53.

Kolarevic, B. (2003). *Architecture in the Digital Age. Design and Manufacturing*, London and New York: Routledge.

Kortlander, M., Spierings, J., Demeyer, T. (2019). D5.5 *Deployment of Pilots in Amsterdam*, (Decentralized Citizens Owned Data Ecosystem), v.1.0, 31.

Kreiner, H. (et al.) (2015). A new systemic approach to improve the sustainability performance. Research Gate.

Kuhn, T. (2009). *La struttura delle rivoluzioni scientifiche.* Einaudi.

Kurakula, V. (2017). *A GIS-Based Approach for 3D Noise Modelling Using 3D City Model*s, Master's Thesis, International Institute for Geo-information Science and Earth Observation, Enschede, The Netherlands.

Kylili A., Vaiciunas J. (2015). *Integration of Building Information Modelling and Life Cycle Assessment*. Research Gate.

Latour, B. (1987). *La scienza in azione: introduzione alla sociologia della scienza*, Edizioni di Comunità.

Latour, B. (2013). *Cogitamus. Sei lettere sull'umanesimo scientifico*. Il mulino.

Lavagna M. (2018). *Life cycle assessment in edilizia*, Hoepli.

Lee, Y. (2000). The sustainability of university–industry research collaboration. Springer. The Journal of Technology Transfer 25, 111–133.

Lee, S., Tae, S., Roh, S., & Kim, T. (2015). Green Template for Life Cycle Assessment of Buildings Based on Building Information Modeling: Focus on Embodied Environmental Impact. *Sustainability*, *7*(12), 16498–16512.

Leon Battista Alberti (1485). *De re aedificatoria*.

LETI (2021). *Embodied Carbon Primer* (. https://b80d7a04-1c28-45e2-b904-e0715cface93.filesusr.com/ugd/252d09_8ceffcbcafdb43cf8a19ab9af5073b92.pdf

Li, C., Yangluxi, L. (2019). *Parametric design process basing on building physical performance.*

Liu, Z. (et al.) (2015). *A BIM-aided construction waste minimisation framework.* Science Direct.

Liu, X. (et al.) (2017). *A state-of-the-art review on the integration of building information modelling (BIM) and geographic information system (GIS)*, ISPRS International Journal of Geo-Information.

Luhmann, N. (1995). *Social Systems*. Stanford University Press.

Lynn, G. (1990). *Animate Form*. Princeton Architectural Press.

Lynn, G. (2013), *Archaeology of the Digital*. The MIT Press.

Ma, Z., Ren, Y. (2017). *Integrated applications of BIM and GIS: an overview*, Procedia Engineering, Science Direct.

Mah, D. (et al.) (2015). *House construction CO2 footprint quantification.* Research Gate.

Mancuso, S. (2020). *La pianta del mondo*. Laterza.

McLuhan, M. (2015). *Gli strumenti del comunicare*. Il Saggiatore.

Menges, A., & Ahlquist, S. (2011). *Computational Design Thinking.* Wiley, London.

Michaudel, Q. (et al.) (2015). Academia−Industry Symbiosis in Organic Chemistry. *Accounts of Chemical Research 48* (3), 712-721.

Migayrou, F. (2013), *Architectures Non-Standard,* Centre Pompidou press.

Mitev, N., Venter, W. (2009). Reflexive Evaluation of an Academy–Industry Research Collaboration. Research Gate. Journal of Management Studies 46(5):733 - 754.

Mohanty, S. P., Choppali, U., & Kougianos, E. (2016). *Everything you wanted to know about smart cities.* Research Gate.

Morton, T. (2018). *Iperoggetti*, Nero.

Morton, T. (2019). *Come un'ombra dal futuro*. Aboca edizioni.

Mori, T. (2004). *Immateriale/Ultramateriale Architettura*, progetto e materiali, Postmedia.

Morton, T. (2021). *Ecologia oscura*. Luiss University Press.

Myoken, Y. (2013). The role of geographical proximity in university and industry collaboration: Case study of Japanese companies in the UK. *International Journal of Technology Transfer and Commercialisation*, *12*, 43.

Najjar, M. (et al.) (2017). Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building. *Journal of Building Engineering*, *14*, 115–126.

Negroponte, N. (1970). *Soft Architecture Machines*, MIT Press.

Novembri, G.; Rossini, F.; Fioravanti, A. (2018). *Improving the integration between BIMs and agent-based simulations: The Swarm Building Modeling – SBM.* In eWork and eBusiness in Architecture, Engineering and Construction; CRC Press: Boca Raton, USA; pp. 123–126.

OECD (2015). Indicators in Italy. Italy | READ online (oecd-ilibrary.org). Accessed 15/08/2021.

Olmo, C. (2013). *Architettura e storia. Paradigmi della discontinuità*, Donzelli.

ONU, Agenda 2030, (2015). Accessed 7 luglio 2021, da https://unric.org/it/wp-content/uploads/sites/3/2019/11/Agenda-2030-Onu-italia.pdf

ONU, UNSDG Linee Guida, (2015). Accessed 7 luglio 2021, da https://unric.org/it/wp-content/uploads/sites/3/2019/11/SDG-linee-guida.pdf

Osello, A. (2015), BIM, GIS, AR per il facility management, Dario Flaccovio Editore.

Osello, A., Ugliotti, F. (2017). *BIM: verso il catasto del futuro*. Cangemi Editore.

Peng, C. (2016). Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. *Journal of Cleaner Production*, *112*, 453–465. https://doi.org/10.1016/j.jclepro.2015.08.078

Perkmann, M., Walsh, K. (2017). *University–industry relationships and open innovation.* Research Gate, International Journal of Management Reviews 9(4).

Pinch ,T. J. (1993). *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology,* Cambridge MIT Press, Cambridge, pp. 17-50.

Pique, J. M., Berbegal-Mirabent, J., & Etzkowitz, H. (2018). Triple Helix and the evolution of ecosystems of innovation: The case of Silicon Valley. *Triple Helix*, *5*(1), 11.

Pizziolo, G. (2004). *Dai margini del caos. L'ecologia del progettare*, Alinea.

Purini, F. (2008). *Architettura virale.* Lotus 133 (2008) - Viral Architecture. https://www.editorialelotus.it/web/item.php?id=132

Ranga, M., & Etzkowitz, H. (2013). Triple Helix Systems: An Analytical Framework for Innovation Policy and Practice in the Knowledge Society. *Industry and Higher Education*, *27*(4), 237–262.

Rainer, Z. (2019). *Gaudì. The complete works.* Taschen.

Ratti, C. (2017), *How ubiquitous computing is bringing robotics to places you'd never supect* in Kries M., Hello, Robot. Design between Human and Machine, Vitra Design Museum Publications, Berlin.

RIBA (2020). *Plan of Work.* Available online: www.ribaj.com

Roberts, J.L. (2017). The Future of Academy – Industry collaboration. Research Gate.

Röck M. (et al.) (2018). *LCA and BIM: Visualisation of environmental potentials in building.*

Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Integrated Assessment and Visualization of Building Elements' Embodied Impacts for Design Guidance in Early Stages. *Procedia CIRP*, *69*, 218–223.

Roncaglia, G. (2010). *La quarta rivoluzione*, Laterza.

Ross, L. (2010). *Virtual 3D City Models in Urban Land Management—Technologies and Applications*, Ph.D. Thesis, Technische Universität Berlin, Germany.

Rossi, A. (1966). *L'architettura delle città*, Quodlibet.

Rybnicek, R., & Königsgruber, R. (2019). What makes industry–university collaboration succeed? A systematic review of the literature. *Journal of Business Economics*, *89*(2), 221–250.

Sacchi, L., & Unali, M. (2003). *Architettura e cultura digitale*. Skira.

Saggio, A. (2010). *Architettura e modernità. Dal Bauhaus alla rivoluzione informatica.* Carocci Editore.

Salgin, B., Akgun A. (2017). *Construction waste reduction through BIM-Based site management approach.* Research Gate.
Salzano, A. (et al.) (2015). *Il BIM a supporto della progettazione sostenibile.*

Sarkis, H. (2017). *Architettura, ricerca e utopia* in Domus, vol. 1011, supp. Innovation, Editoriale Domus s.p.a., pp. 8-15

Schumacher, P. (2008). *Parametricism as Style. Parametricist Manifesto.* Dark Side Club1 , 11th Architecture Biennale, Venice 2008.

Schumacher, P. (2009). *Parametricism. A New Global Style for Architecture and Urban Design.* AD Architectural Design-Digital Cities, Vol 79, No 4. London.

Schumacher, P. (2011). *The Societal Function of Architecture*. Wolf D. Prix & Kristy Balliet.

Schumacher, P. (2011). *The Autopoiesis of Architecture – Extracts: Communication, Societal Function, Semiology*. Available online: https://www.academia.edu/11889782/The_Autopoiesis_of_Architecture_Extracts_Communication_Societal_Function_Semiology

Schumacher, P. (2012). *Architecture's Next Ontological Innovation: Vol. Not Nature – Architectural Manual*. Pratt Institute.

Schumacher, P. (2012). *The Autopoiesis of Architecture, Volume II: A New Agenda for Architecture*. John Wiley & Sons.

Schumacher, P. (2013). *Parametric Semiology – The Design of Information Rich Environments: Vol. Architecture In Formation – On the Nature of Information in Digital Architecture*. Pablo Lorenzo-Eiroa and Aaron Sprecher, Routledge, Taylr and Francis.

Schumacher, P. (2016). *Parametricism 2.0: Rethinking Architecture's Agenda for the 21st Century.* Wiley, London.

Schumacher for Iris Ceramica Group. (2020). *The architects series. Patrick Schumacher Lecture: "Cyber space and the autopoiesis of architecture"* [Interview]. https://www.youtube.com/watch?v=03mcxw4xDYg

Schwab, K. (2016). *La quarta rivoluzione industriale*, Franco Angeli.

Secchi, B. (2015). *La città del ventesimo secolo*, Laterza.

Seo, S., Tucker, S., & Newton, P. (2007). Automated Material Selection and Environmental Assessment in the Context of 3D Building Modelling. *Journal of Green Building*, *2*(2), 51–61.

Shepherd, D. (2015). *The BIM Management Handbook*, NBS, Newcastle.

Shin, Y., & Cho, K. (2015). BIM Application to Select Appropriate Design Alternative with Consideration of LCA and LCCA. *Mathematical Problems in Engineering*, *2015*, 1–14.

Simondon, G. (2021). *Del modo di esistenza degli oggetti tecnici*. Orthotes.

Singapore Municipality (2013). *BIM Guide*, version 2.0.

Sormani, D. (2016). *Il Tecnopark russo di Studio Hadid*. Abitare.

Soust-Verdaguer, B. (et al.) (2017). Critical Review of BIM-Based LCA methods to buildings.

Spyropoulos, T. (2016). *Behavioural Complexity: Constructing Frameworks for Human-Machine Ecologies*. Architectural Design, 86(2), 36–43.

Statsbygg BIM Manual (2013), version 1.2.1, Oslo.

Sutherland, I. E. (1960). *Sketchpad: A man-machine graphical communication system*. 149.

Terzidis, K. (2003). *Expressive Form: A Conceptual Approach to Computational Design*. Routledge.

Treccani. (2021). *algoritmo in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/algoritmo

Treccani. (2021). *autopoièṡi in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/autopoiesi

Treccani. (2021). *CAD in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/cad

Treccani. (2021). *ontològico in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/ontologico

Treccani. (2021). *script in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/script

Treccani. (2021). *semiologìa in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/semiologia

Treccani. (2022). *protòtipo in Vocabolario—Treccani*. https://www.treccani.it/vocabolario/prototipo

UN. (2015). *UN, The Paris Agreement, 2015*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

UN (2015), Assemblea Generale, A/RES/70/1 Trasformare il nostro mondo: l'Agenda 2030 per lo Sviluppo Sostenibile.

UN. (2018). *UN Secretary-General's Strategy on New Technologies*. https://www.un.org/en/newtechnologies/

UNI 11337 1-7 (2018). Accessed 16/01/2022. http://store.uni.com/catalogo/uni-11337-7-2018?josso_back_to=http://store.uni.com/josso-security-check.php&josso_cmd=login_optional&josso_partnerapp_host=store.uni.com

UNI EN 15804 (2019) *Dichiarazioni ambientali di prodotto.* Available online; https://www.certifico.com/costruzioni/370-news-costruzioni/9658-uni-en-15804-2019-dichiarazioniambientali-di-prodotto, (accessed on 15 August 2021).

UNSDg. (2021). *Goal 13: Take urgent action to combat climate change and its impacts*. United Nations Sustainable Development. Accessed 22 dicembre 2021, da https://www.un.org/sustainabledevelopment/climate-change/

Van Brummelen, J. (2019). *Procedural Generation*. MIT.edu. http://www.mit.edu/~jessicav/6.S198/Blog_Post/ProceduralGeneration.html

Vassileva, I., Dahlquist, E., Campillo, J. (2016). *The citizens' role in energy smart city development*, Energy Procedia, 88.

Vitruvio. (15 a.C.). *De architectura, III, V, 8, on Ionic colums and architraves.*

Weisberg, D. Patrick Hanratty and MCS (2021) Accessed 20 settembre 2021, http://cadhistory.net/15%20Patrick%20Hanratty%20and%20MCS.pdf

Wines, J. (2000). *Green Architecture*. Taschen.

Wittstock, B. (et al.) (2012). *EeBGuide Project*.

Yamamura, S., Fan, L., Suzuki, Y. (2016). *Assessment of urban energy performance through integration of BIM and GIS for smart city planning*, Science Direct, Elsevier.

Zhiliang, M., Yuan, R. (2019). *Integrated application of BIM-GIS: an overview*, Science Direct, Procedia Engineering, 196.

Zhou, S. (et al.) (2010). Crowd modeling and simulation technologies. *ACM Transactions on Modeling and Computer Simulation*, *20*, 20.

Wu, H.; He, Z.; Gong, J. (2010). *A virtual globe-based 3D visualisation and interactive framework for public participation in urban planning processes*, Comput. Environ. Urban Syst.
Wines, J. (2010). *Green Architecture*, Taschen.

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III.List of abbreviations

BIM: Building Information Modelling
CAD: Computer-Aided Design
EC: Embodied Carbon
EE: Embodied Energy
EPD: Environmental Product Declaration
LCA: Life Cycle Assessment
UNSDg: United Nations Sustainable Development Goals.

Appendix A: BIM and LCA benchmark

cat.	1. AUTHOR // TITLE	2. RESEARCH GROUP	3. TOPIC	4. STRATEGY	5. DATA NEEDED (INPUT	6. TOOLS FOR DATA ANALYSIS
1	Röck M., Hollberg A., Habert G., Passer A. *LCA and BIM: Visualization of environmental potentials in building construction at early stages*	TU Gratz (Austria); ETH Zurich	Support decision making in early design stages with BIM to assess **range of construction options** and their embodied **environmental impacts**	Conceptual BIM Model to evaluate the variety of materials composition + script	**LCA Database** impact per area for building elements [m2BE] **BIM Model** [foundation slab, ex. walls, fllors, roofs, windows, int. partition] **LOD 200** **Script** embodied impact for different construction options: total impact [m2BE]X[GPW/m2BE] area of building element from BIM Model x env impact LCA Database	Excel Database Autodesk Revit Autodesk Dynamo
2	Peng C. *Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling , Elsevier, Journal of Cleaner Production 112, pp. 453-465, 2016.*	School of Architecture, Nanjing, PR China	Estimation of **Co2 emission** during life cycle and to perform quantitative analysis	REVIT + Ecotect to simulate emissions	**LCA Database** LCCO2 in construction (including production)/ operation / demolition **BIM Model** [materials quantities] Simulating performance	Excel Database Autodesk Revit Ecotect
3	Najjar M., Figueiredo K., Palumbo M., Haddad A. *Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical o ffi ce building, Elsevier, Journal of Building Engineering, 14, pp.115-126, 2017.*	Escuela Politecnica Rio De Janeiro	Empower **decision-making processes** in construction sector and achieve sustainable development	BIM + LCA in early design stages. 2 Strategies: 1 Direct access to BIM Model information to calculate LCA performance. 2 Enviromental propeties included in BIM objects. Integration BIM Lenses + LCIA. Impact assessment methods	**ISO 14040 104044 Database** **BIM Model** [Material quantities, local climate] Environmental performance Environmental impacts of materials (lca tool), using: **LCI Dataset**	Excel Database Autodesk Revit Green Building Studio Tally app in Revit + GaBi Database
4	Lee S., Tae S., Roh S., Kim T. *Green Template for Life Cycle Assessment of buildings based on BIM: Focus on embodied environmental impact*	Hanyang University, Korea	**Assessing the impact** of the substances discharged from concrete production process, 6 categories: GWP, ADP, AP, EP, ODP, POCP.	Green BIM Template (GBT)	**LCI Database** of impact factors and major building materials [Ready mixed concrete, steel, glass, concrete block, insulation material, gypsum board] **BIM Model** quantity take-off (units of volume) construction materials **LOD 300**: parametric building elements Library (.rfa) materials/impact	Excel Database Autodesk Revit
5	Mah D., Manrique J., Yu H., Al-Hussein M., Nasseri R. *House construction CO2 footprint quantification: a BIM approach*	Edmonton, Canada	**Carbon emission** Co2 quantification in the current residential construction process.	Database of emissions + BIM Model to quantification Co2 footprint	**Database constrains** [weather, geo location, materials type and size, labour, market conditions, city regulations] **Database Co2** emissions (Kg) for 17 construction stages **BIM Model** [floor plans, finishing materials, elevations, cross-sections, beams/columns, type of heating and ventilations systems] arch. Str. Mep, materials	Excel Database Excel Database Virtual Construction Suite 2008
6	Shin Y., Cho K.	Chosun University, Republic of Korea	To help LCA and LCCA, the study analyses the information needed, evalutes the BIM tools and develps an Excel database	method: 1. literature LCA LCCA, 2. Data required, 3. BIM Model, 4. spread-sheet based framework 5. app case study	Excel **Database** information needed [production, transport, assembly of materials] **BIM Model** [site, structural columns, bearing wall and slab, external skin] + information excel: extract quantity of data. Next_BIM Libraries Energy simulations for different Archicad alternatives	Excel Archicad + Eco Designer
7	Kylili A., Fokaides P. A.	Frederick University, Cyprus Kaunas University of Tech, Lithuania	To estimate the level of sustainability from the early design stages	Integration LCA + BIM	**Database** environmental performance of products [LCI, LCIA] **BIM Model** Cradle-to-gate LCA for enviromental performance	Excel / GaBi Software (VS 6)

RESUME input

1 **BIM Model LOD 200|300**

2 **LCA METHOD**
Goal and Scope
LCA Stages Definition
Life Cycle Inventory

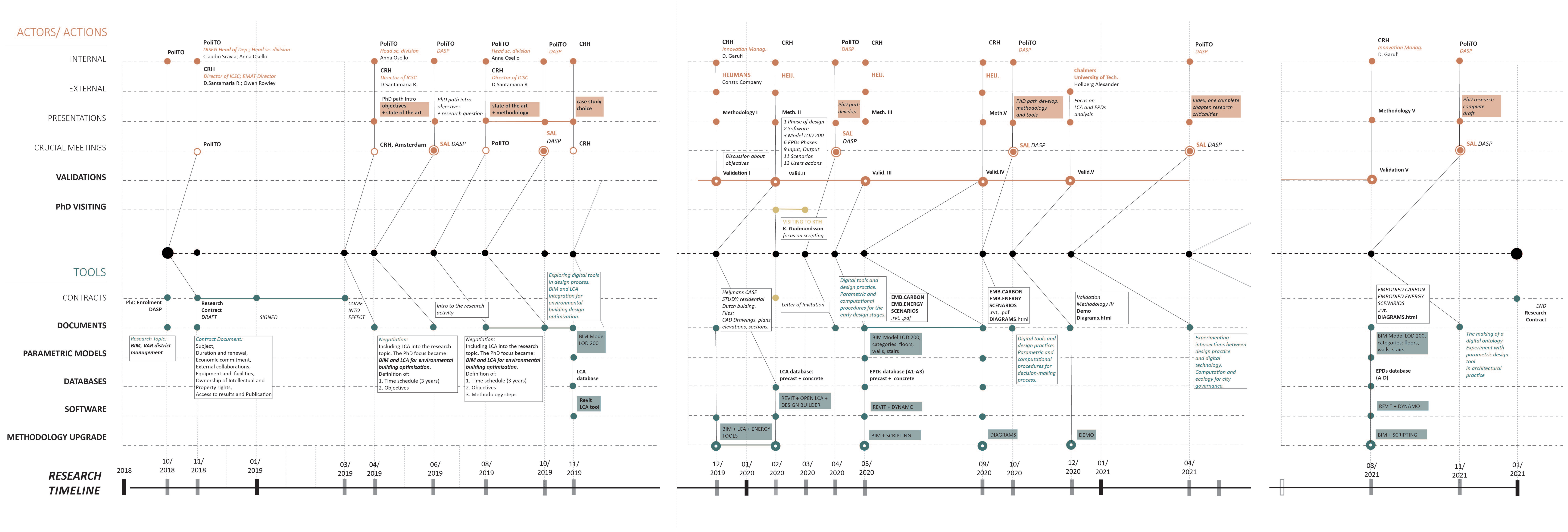
RESUME tools

1 **BIM software**

2 **Software for energy Consuption**

3 **LCA Tool**

Appendix B: mapping process



ACTORS/ ACTIONS
INTERNAL
EXTERNAL
PRESENTATIONS
CRUCIAL MEETINGS
VALIDATIONS
PhD VISITING
TOOLS
CONTRACTS
DOCUMENTS
PARAMETRIC MODELS
DATABASES
SOFTWARE
METHODOLOGY UPGRADE
RESEARCH TIMELINE
PoliTO
PoliTO
DISEG Head of Dep.; Head sc. division
Claudio Scavia; Anna Osello
CRH
Director of ICSC; EMAT Director
D.Santamaria R.; Owen Rowley
PoliTO
PoliTO
Head sc. division
Anna Osello
CRH
Director of ICSC
D.Santamaria R.
PhD path intro
objectives
+ state of the art
CRH, Amsterdam
PoliTO
DASP
PhD path intro
objectives
+ research question
SAL DASP
PoliTO
Head sc. division
Anna Osello
CRH
Director of ICSC
D.Santamaria R.
state of the art
+ methodology
PoliTO
PoliTO
DASP
SAL
DASP
CRH
case study
choice
CRH
PhD Enrolment
DASP
Research
Contract
DRAFT
SIGNED
COME
INTO
EFFECT
Research Topic:
BIM, VAR district
management
Contract Document:
Subject,
Duration and renewal,
Economic commitment,
External collaborations,
Equipment and facilities,
Ownership of Intellectual and
Property rights,
Access to results and Publication
Negotiation:
Including LCA into the research
topic. The PhD focus became:
BIM and LCA for environmental
building optimization.
Definition of:
1. Time schedule (3 years)
2. Objectives
Intro to the research
activity
Negotiation:
Including LCA into the research
topic. The PhD focus became:
BIM and LCA for environmental
building optimization.
Definition of:
1. Time schedule (3 years)
2. Objectives
3. Methodology steps
Exploring digital tools
in design process.
BIM and LCA
integration for
environmental
building design
optimization.
BIM Model
LOD 200
LCA
database
Revit
LCA tool
CRH
Innovation Manag.
D. Garufi
HEIJMANS
Constr. Company
Methodology I
Discussion about
objectives
Validation I
CRH
HEIJ.
Meth. II
1 Phase of design
2 Software
3 Model LOD 200
6 EPDs Phases
9 Input, Output
11 Scenarios
12 Users actions
Valid.II
VISITING TO KTH
K. Gudmundsson
focus on scripting
PoliTO
DASP
PhD path
develop.
SAL
DASP
CRH
HEIJ.
Meth. III
Valid. III
CRH
HEIJ.
Meth.V
Valid.IV
PoliTO
DASP
PhD path develop.
methodology
and tools
SAL DASP
Chalmers
University of Tech.
Hollberg Alexander
Focus on
LCA and EPDs
analysis
Valid.V
PoliTO
DASP
Index, one complete
chapter, research
criticalities
SAL DASP
Heijmans CASE
STUDY: residential
Dutch building.
Files:
CAD Drawings, plans,
elevations, sections.
Letter of Invitation
Digital tools and
design practice.
Parametric and
computational
procedures for the
early design stages.
EMB.CARBON
EMB.ENERGY
SCENARIOS
.rvt, .pdf
LCA database:
precast + concrete
BIM Model LOD 200,
categories: floors,
walls, stairs
EPDs database (A1-A3)
precast + concrete
REVIT + OPEN LCA +
DESIGN BUILDER
REVIT + DYNAMO
BIM + LCA + ENERGY
TOOLS
BIM + SCRIPTING
EMB.CARBON
EMB.ENERGY
SCENARIOS
.rvt, .pdf
DIAGRAMS.html
Digital tools and
design practice:
Parametric and
computational
procedures for
decision-making
process.
DIAGRAMS
Validation
Methodology IV
Demo
Diagrams.html
DEMO
Experimenting
intersections between
design practice
and digital
technology.
Computation and
ecology for city
governance.
CRH
Innovation Manag.
D. Garufi
Methodology V
Validation V
PoliTO
DASP
PhD research
complete
draft
SAL DASP
EMBODIED CARBON
EMBODIED ENERGY
SCENARIOS
.rvt.
DIAGRAMS.html
BIM Model LOD 200,
categories: floors,
walls, stairs
EPDs database
(A-D)
REVIT + DYNAMO
BIM + SCRIPTING
The making of a
digital ontology
Experiment with
parametric design
tool
in architectural
practice
END
Research
Contract
2018
10/ 2018
11/ 2018
01/ 2019
03/ 2019
04/ 2019
06/ 2019
08/ 2019
10/ 2019
11/ 2019
12/ 2019
01/ 2020
02/ 2020
03/ 2020
04/ 2020
05/ 2020
09/ 2020
10/ 2020
12/ 2020
01/ 2021
04/ 2021
08/ 2021
11/ 2021
01/ 2021

Appendix C: interpreting the process

DIMENSIONS OF ANALYSIS