NATURE-INFORMED ARCHITECTURE (NIA):
LEARNING FROM DEFECTS IN CRYSTALS

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ABSTRACT

NATURE-INFORMED ARCHITECTURE (NIA): LEARNING FROM DEFECTS IN CRYSTALS

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The transformation of design problems, processes, and praxis of construction by continuously increasing data mass is one of the major concerns of this dissertation. In this change, nature is re-emerging as an important source of information in the search for such processes, in which architects become not only their designers but also their programmers and even their supervisors.

This dissertation values defects in nature and abiotic part of it as a source of information in design. While the majority of current nature-based studies are mostly focused on the biotic part of nature with its flawless forms, patterns, and behaviors as a reference, nature also offers various exciting references showing how to deal with defects and encouraging examples in diverse entities of abiotic nature. Therefore, in this thesis, the relation between nature and architecture is revisited focusing on abiotic nature, defects, and the method of learning from them.

The information of defects in nature are found valuable to be learnt from for architecture, not only to adopt the strategies of nature to cope with them, but also to understand the role of defects on the responsive, adaptive and resilient nature of beings. With transferring the information of defects, it is aimed to be find the fitness defects of architecture that will enable us to fit new and challenging environments and technologies.

The resultant approach encapsulating all these constituents, which is called nature-informed architecture (NiA), is proposed. In the scope of NiA, the concepts of data, data literacy, capta, and model are revisited and well-known terms like scale, precision, and accuracy are redefined. Hence, a new metadata model, named transfer learning model (TLM), defining the data transfer from one domain to another is introduced. In this context, crystal formations are studied, a computational model revealing the behaviors observed in crystal formation is developed; then, this model is employed to inform the models created for extended design processes encapsulating form, fabrication and construction specific parameters for additive and modular construction techniques.

Keywords: Nature-informed Architecture, Defects in Nature, Computational Design, Transfer Learning, Crystal Formation

ÖZ

DOĞA BİLGİLİ MİMARLIK (DBM): KRİSTALLERDEKİ KUSURLARDAN ÖĞRENMEK

Kruşa Yemişcioğlu, Müge
Doktora, Yapı Bilimleri, Mimarlık
Tez Yöneticisi: Prof. Dr. Arzu Gönenç Sorguç

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Artan veri kütlesinin yalnızca tasarım problemlerini ve süreçlerini değil, aynı zamanda inşa etme eylemlerini de dönüştürmesi bu tezin ana motivasyonlarından biridir. Bu değişimde doğa önemli bir bilgi kaynağı olarak yeniden ortaya çıkmakta ve bu süreçte mimarların sadece tasarımcı değil aynı zamanda programcı ve hatta süpervizör rolü üstlenmelerini gerektirmektedir.

Bu tez kapsamında, tasarımdaki bilgi kaynağı olarak doğadaki kusurlara ve abiyotik doğaya odaklanılmaktadır. Mevcut doğa temelli çalışmaların büyük bir kısmı, referans olarak kusursuz formları, örüntüleri ve davranışlarıyla çoğunlukla doğanın biyotik kısmına odaklanmaktadır. Öte yandan, doğa abiotik varlıklarla birlikte kusurlar ve kusurlarla nasıl başa çıkılacağını gösteren çeşitli heyecan verici referanslar sunmaktadır. Bu nedenle, bu tezde, doğa ve mimarlık arasındaki ilişki, abiyotik doğaya, kusurlara ve onlardan öğrenme yöntemine odaklanarak yeniden ele alınmaktadır.

Doğadaki kusurlarla ilgili bilgiler, mimarlık için, yalnızca bunlarla başa çıkmakta doğanın stratejilerini benimsemek için değil, aynı zamanda kusurların, varlıkların duyarlı, uyarlanabilir ve dirençli doğası üzerindeki rolünü anlamak için de değerli

bulunmaktadır. Kusurun bilgisinin aktarılmasıyla, yeni ve zorlu ortamlara ve teknolojilere uyum sağlamamızı sağlayacak mimarlık için uyumluluk ölçütünü sağlayan kusurların bulunması hedeflenmektedir.

Bu tezde, Doğa-bilgili Mimarlık (DbM) olarak adlandırılan tüm bu bileşenleri kapsayan bir yaklaşım önerilmiştir. DbM kapsamında veri, veri okuryazarlığı, seçilmiş veri ve model kavramları yeniden gözden geçirilmiş ve ölçek, hassasiyet ve doğruluk gibi iyi bilinen ölçüm kriterleri yeniden tanımlanmıştır. Bu amaçla, bir alandan diğerine veri aktarımını tanımlayan transfer öğrenme modeli (TÖM) adlı yeni bir meta veri modeli tanıtılmıştır. Bu bağlamda kristal oluşumları incelenmiş, kristal oluşumunda gözlenen davranışları gösteren hesaplamalı bir model geliştirilmiştir. Daha sonra bu model, eklemeli ve modüler yapım teknikleri için form, imalat ve yapıya özel parametreleri kapsayan genişletilmiş tasarım süreçleri için oluşturulan modelleri bilgilendirmek için kullanılmıştır.

Anahtar Kelimeler: Doğa Bilgili Mimarlık, Doğadaki Kusurlar, Hesaplamalı Tasarım, Transfer Öğrenme, Kristal Oluşumu

to people who shaped my past, present and future

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INTRODUCTION

Architecture has always been a manifestation of its time integrating state-of-art technologies in its interdisciplinary nature. Architects, engineers and master builders have never framed themselves with available technologies, but rather push the limits and stimulate the discovery of new technologies.

In the 20th and 21st century, the extend of observable information has increased with the invention of electron microscope and James Webb Space Telescope in both directions. Hence, humankind have access to more data about the material, structure, and processes of biotic and abiotic nature. Even though, the accumulated accessible data bring great benefits and potentials, it also poses new challenges to all the disciplines. These challenges can be listed as (1) the complexity of data, (2) the demand for precision requiring new analysis and processing tools, and technologies and (3) new approaches for modelling. As the precision, number and the complexity of this data is increasing, not only handling and analyzing but also designing and modelling data become the new challenge in this quest. Today, these explorations need to be pursued forward via the "data design" understanding including "determination / selection of data, reformulation of the problem, evaluation of method and results, and utilizing or devising appropriate metrics" (Özgenel 2018).

All these advents in technology and abundance of data, radically change the way we design, communicate and construct in architecture. Especially, with the increasing involvement of computational design techniques, machine learning models and robotic construction, alter the design practice and a new holistic way of designing and making/constructing is started to be discussed in the field. Therefore, today architects are no longer only the designer of an artefact, but they are becoming the programmers and/or the supervisors of the intelligent systems.

In this vein, considering current challenges regarding with environmental issues (Zari 2010), and data crunching, analyzing and modeling, the concept of performance become more significant and data-oriented by searching for new means to cope with them. Among them, learning from nature is not a new concept for engineering or architecture and former applications which embrace nature as a source of inspiration, analogy, metaphor, ornament and imitation came in sight in different time periods. Contemporary technology carries also the discussion regarding nature-based design studies to a new stage, introducing nature not only as a model or measure but also as a mentor (Benyus 2002). In this respect, architecture refocused on nature to de-code and re-code the processes in nature to overcome these challenges and to perform a data transfer with data design approach as it is proposed in this thesis.

As nature and the designing process in architecture both exhibits complex behaviors in terms of its material, scale, form and function, the models of them becomes multilayered-models showing multilayered-structure. Conveying information from nature to architecture is considered as a mapping process between these multilayered models in this thesis. Computational technologies provide an invaluable interface in this process to analyze, understand and reinterpret the system, information flow, and process of nature (Erdoğan ve Sorguç 2011). Thus, like many other disciplines, architecture is seeking for a system to map the features found in nature into the objectives of the design process. In this search, especially in the last decades, researchers started to reinvestigate nature-architecture relationship once more focusing on exponentially increasing amount of data related with both animate and inanimate nature in relation with changing objectives of architecture.

In this vein, architecture has already proposed and adopted many terms implying different approaches by means of inspiration, modelling, and measuring as will be studied in the following chapters. On the other hand, in this thesis, all these studies are conceived as transfer of information from one domain to other which is acknowledged as data transfer process among various scales. In this process, data transfer understanding introduces the discussion of *scale* which can be defined with proportion, level of information, and level of complexity. Scale transformation has always been discussed in mathematics and studied by many disciplines in various contexts in sets, graph theory, and in mapping since 19^{th} century. All these studies contribute to today's understanding of complexity and model in general. Hence as this thesis regards studies oriented from nature in architecture as a data transfer and thus mapping, a novel approach to modeling and mapping processes is proposed in the realm of computational design.

It is agreed that the role of computational design (R. Oxman 2008), large data crunching capacity and new construction techniques, and materials, turn architectural models into multi-layered data models comprising several information levels such as form, generation principles, performance, fabrication/production/construction. In achieving such models, computational design brings concepts like "file-to-factory" (B. Kolareviç 2003) and "form-to-formation" (Gönenç Sorguç, Özgenel, et al. 2016) into architectural design process. With this understanding, **model** is more than a manifestation of its form, it becomes an interface that all the information can be analyzed and experimented in towards fabrication which brings the concept of "process design" into the design process.

In this thesis, data design is embraced as a framework enabling us to capture, model and transfer data from one domain to another. This process is referred as an *informing* process. Hence nature is admitted as a supervisor rather than a model or a mentor. Here, it is important to focus on the act of information transfer where models of research fields are being cultivated by models of nature. Here it is proposed to refer such studies as ***Nature-informed studies*** in order to reveal the act of data transfer in a broader way rather than popular terms being used to define the information transfer from nature to other disciplines. The further discussions related with Nature-informed studies in terms of re-defining the references in nature, exploring the target and designing a new model to inform the problem area are examined in depth in the following sections of this study.

1.1 Problem Definition

The main challenge in nature-informed studies is the complexity of nature, and to transfer this complex information into other domains. When nature-informed architecture (NiA) is considered, both nature and architecture as domains presenting different level of complexities can only be understood through feature extraction and then modeling, for which "data calibration" is essential in this act of transfer.

In the realm of the thesis, ***scale*** which is composed of features belonging to each domain is used to depict the level of complexity. Features define a dimension(s) of a domain by bringing their own data which are transferred (transposed/projected) to each other.

This transfer needs to be explored, defined, and clarified in a structured way based on data of each domain. This clarification process requires 3 main phases: (1) identification of the extend of referred examples in nature (references), (2) defining the objective of the problem in architecture: cause for this search, and (3) need for a model to transfer information.

1.1.1 Reference: What can be the source of information?

The extent of the current nature-informed studies in architecture is mostly limited with the animate nature and learning from the inanimate part of the nature is mostly ignored in the scope of Biomimetic studies by calling it "Geomimicry". It is claimed that adapting living nature's aspects to survive and thrive on Earth is the only valuable strategy, although water, stars, air, and rocks are counted as important substances of "nature" life (Dorfman 2016) (Biomimicry Institute 2013). On the other hand, the work of Philip Ball shows that the emergence, growth, and evolution of abiotic beings have great potentials to examine, analyze, predict, and generate the built environment as much as biotic nature (Ball 1999). Recent researches on abiotic nature shows that there is still need for new studies to reveal those potentials in many disciplines including architecture.

In most of the studies regarding nature-architecture relationship, proper generative processes or their outcomes are taken as references. However, nature is the outmost complex system showing dynamic stability which is neither fixed in time, nor an assemblage (D'Holback 1868). Systems in nature have always open to change, and resilient towards discontinuities/defects, yet it is always finding a new path to proceed. Since these paths can be considered as deformations, defects, discontinuity or disorder, the response and *continuum* of the being are instructive for architecture. In order to comprehend the relations and to be informed from them, understanding the behavior of such complex systems is a must which can be accomplished through modeling (F. A. von Hayek 1967) and pattern prediction (F. von Hayek 1974). As Wahl (2016) suggests; *"In many ways a system is less a 'thing' than a pattern of relationships and interactions – a pattern of organization of constituting elements."*. It is possible to demonstrate the relation between pattern and defect with a morphology of a tree trunk, discontinuity of defects in crystal formations and even in healing mechanism of human skin. Therefore, conceiving nature free from its defects leading us to miss many opportunities to comprehend the true performance of nature.

1.1.2 Target: What is Architecture Seeking for

Literature shows us that most of the nature-informed studies focused on performance. Today, the new tools allow architects, designers and all the actors of the built environment to measure the performance in all means, therefore performance started to become a quantitative issue as well (Kolarevic 2004) (B. Kolareviç 2003). Besides, it becomes critical to improve and evaluate "environmental performance" of buildings since environmental problems such as depletion of the resources, deterioration of ecological balance / climate change (Zari 2010) become more severe. Thus, architects as the main actor of the built environment have to confront with such demands as well.

As these problems are increasing in global level, architecture re-investigate its relation with nature through built and unbuilt environment more frequently. Inevitably, optimizing building performance come to fore, and architects and researchers gravitate towards nature to learn again. Today, it is possible to see many examples of performance and informed problem areas in architecture. Only some of these examples are given in the following table.

Table 1.1 Some of the examples showing the common required performances and informed layers in architecture

Sought Performance	**Informed layer in Architecture**	**Example (Reference)**
Acoustic Performance	material	(Wang, et al. 2016)
Behavior	structure	(Vailati, et al. 2018)
Behavior	form	(Erdine 2013)
Behavior	facade	(Badarnah and Knaack, Bionic breathing skin for buildings. 2007)
adaptation	optimization	(Casciati and Elia 2017)
Energy performance	Efficiency	(Fecheyr-Lippens and Bhiwapurkar 2017)
Growth	facade	(Tabari, Kalantari and Ahmadi 2017)
Lifecycle	Lifecycle	(Yin, et al. 2013)
Material	Biomaterial	(Yang, Yoon and Lee 2018)
Morphology	Façade performance	(Badarnah, Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation 2017)
Self-healing	Material	(Qureshi, Kanellopoulos and Al-Tabbaa 2018)
Structural performance	structural performance	(Wang, et al. 2018)
System	infrastructure	(Apul 2010)

Table 1 exemplifies number of studies illustrating how nature is incorporated in design for the required performance. Study of current literature shows what is searched in nature and examples referred in nature is diverse. Yet, it is possible to categorize these studies to learn (1) to generate, (2) to recover/heal, (3) to predict behaviors.

In today's architecture, generative design is not only a form-finding method but also is a critical asset in design and optimization of structures providing novel solutions for building systems (structural, HVAC, circulation etc.) or building parts (facades, roofs, layouts etc.). In parallel with technologies and increase in the available environmental data, computational design becomes more operative but also a complex process of the digital age and still a challenge in architectural design.

Another important issue that architects should concern is the existing building stock, and their rehabilitation of them against natural disasters, aging, and their improvement for use of resources. Prolonging the life of buildings, providing a safe environment, maintaining the integrity of the building is a responsibility of architects and should be concerned even in the early phases of the design. At this point, turning back to defects in nature, understanding their causes and learning from how nature deals with them are valuable sources of information for architecture to recover/heal the faults.

Generation is taken place not only in buildings but in urban level as well. An urban environment is a complex continuum with interwoven, dynamic relations and balances acquiring detailed analysis and sophisticated models. Methods like shape grammars, cellular automata and in recent years highly used machine learning algorithms are frequently used in urban development and planning which also implicitly or explicitly using data from nature or mimics nature.

Computational design processes as a whole introduce a new level of precision into the design process. Similarly, advents in construction technologies improve the construction accuracy and BIM becomes an interplay between design and construction. Despite all these efforts, there are still incompatibilities among design and construction processes which deteriorate the efficiency of the whole process and the expected quality of the artefact. In order to overcome such problems, design process should also include construction processes, strategies and critical stages of fabrication/production.

In consideration of the issues outlined above, this thesis explores following contemporary problems, namely, path finding for robotic additive manufacturing which are employed more and more in various scales, design and development of various building units/modules having different symmetries and a robust tile design process in regular and irregular boundaries even in the existence of defects.

In solving these problems, not only nature is re-visited, but various **synchronized/holistic generative design** methods are explored.

1.1.3 Act of Information Transfer

Finding proper relations in learning from nature is clearly related with the potentials of selected reference which highly determines the success of learning process. Not only the reference, but also retrieving information from the collected data, the act of transfer among domains, the medium of this transfer together with a proper model(ling) are vital in such studies.

It is seen that studies focusing on nature-architecture relationship show similarities in their strategies, how they approach the problems and the way they model. But it is also seen that there is still need for further investigation to improve how information from nature can be internalized in relation with subjects of interests. Today, nature-driven architectural designs mostly manifest themselves in mechanical systems like ventilation, and façades, materials, components or remain in small-scale applications like pavilions. Though, performance of nature requires to be conceived as a whole defined by the performance of constituents and as a system, embracing animate and inanimate nature together. Thus, we need to have a holistic model defining the reference, data, process and target to transfer data from nature to architecture.

Consequently, as this thesis focuses on what architecture is seeking in nature, which processes is to be followed to transfer this information and what are the new frontiers to be studied, the whole process defined here named as ***Nature-informed***

Architecture (NiA) which is proposed as an overarching term approaching bio-informed and geo-informed strategies. This new understanding requires a new approach concerning not only the act of *information transfer* and *mapping* as the main acts, but also how we determine the reference, problem, models and correlations playing a crucial role in this process.

1.2 Hypothesis and Research Questions

In the context of nature-informed studies, the emerging technologies and the availability of the massive amount of data in all scales related with nature including biotic/abiotic and perfect/defectious features will change the act of learning from nature as well as design and construction processes in architecture. This hypothesis is scrutinized through following research questions:

Q1. How inanimate nature and defectious behaviors in nature be incorporated with architectural problems as sources of information?

Q2. How the data transfer between nature and architecture be realized to transfer the information retrieved from nature in terms data selection, relations and role of model?

Q3. How the design processes and construction process will be designed/generated together? What can we learn from crystal formations in this problem?

Q4. What will be the role of architects in this process? Will they serve as programmer or supervisor in addition to be the designer?

1.3 Scope and Objectives

The contemporary literature shows that the biomimetic studies cover a wide range of subjects referring different scales, levels of complexities and implementations. In this thesis, envisaging earlier mentioned challenges of architecture, a new approach called nature-informed architecture is introduced extending the source of this information transfer to include abiotic beings as well as biotic ones with their flawless and defectious behaviors with a model named transfer-learning model to execute the act of learning. Although contemporary literature shows that there are many researches focused on biomimetics and biomimicry which are focused on biotic part of the nature, this research aims to explore the potentials of both flawless and defected growth behavior of abiotic nature for architecture by proposing to develop a system, its tools and the interface. As an implementation of the proposed framework, a case study on crystal formations with various exemplary scales is conducted.

The main objectives of this study for the previously mentioned problems are:

- to examine the potentials of the defectious behaviors and beings in abiotic nature to inform the novel construction techniques.
- to study crystal formation as a source of information with their flawless and defectious behaviors regarding its potentials in architecture.
- to dwell proper data sets based on defined problem areas and selected references of crystal formations to achieve data model(s) enabling information transfer as mapping.
- to portray the new position of architects in nature-informed studies.

1.4 Methodology

In the scope of this thesis, first, existing studies are examined with narrative and systematic critical literature reviews. In these reviews, literature is revisited under the term *NiA*, referring to studies transferring data from both biotic and abiotic nature into the architectural domain. The outcomes of these studies are represented with tables and flow diagrams that reveals data transformation in existing studies. Then, this data transfer process is examined by means of data, capta, modelling, similitude and transformation which will form the meta-data model that enable us to achieve the transfer. This model is called transfer learning model (TLM) in this study in reference to machine learning applications. Moreover, as one of the significant propositions of this study, the answer of this question is investigated: “In which extend architecture can learn from nature? Is it limited to the biotic, animated, or living part of nature?”. It is seen that inanimate nature is instructive as animate nature and proposing a holistic model is crucial as defects are valuable sources to understand the reaction against the forces, abnormalities and extremes in nature. As one of them, crystal formation which can be found both in animate and inanimate nature is preferred to be studied considering its nature to be modular, ordered/disordered, adaptive and resilient. Also, considering the available data on crystal formations, as a subject, crystals have great potential to serve as a precedent to evaluate the validity of the proposed approach and its model.

Furthermore, crystal formation process is modelled in different scales namely nano, micro, meso, and macro which reveal themselves in unitcells, lattice structures, behaviors, defects and habits. Then, the mathematical models retrieved from these various scales are used to inform different scales in architecture from design to construction phases in many dimensions like performance, aesthetics, planning and automation. The developed models based on TLM are presented and evaluated based on data/information transfer performance and also the success of the final outcome(s). The methodology followed in this thesis is shown in Figure 1.1.

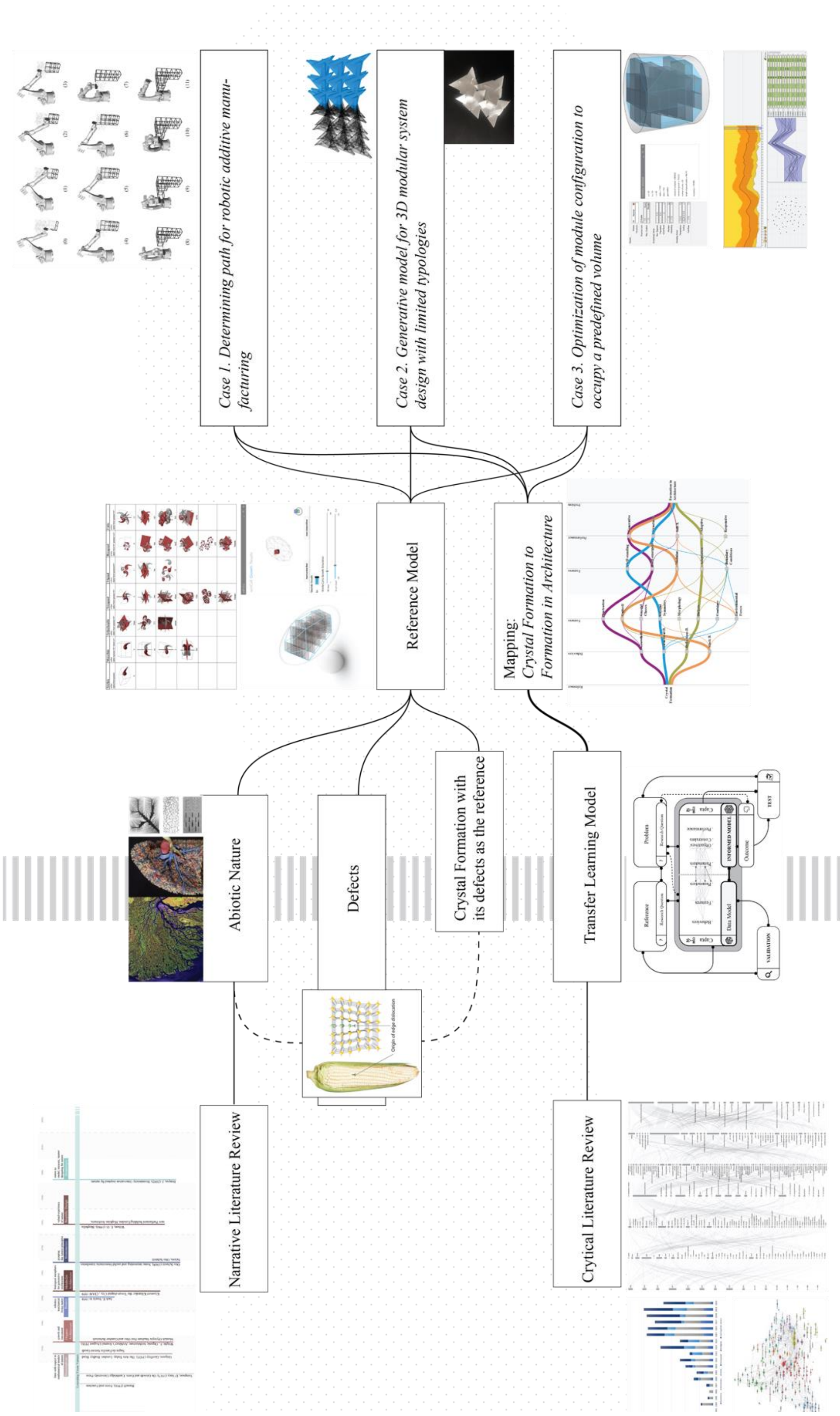

Figure 1.1. Methodology of the thesis

1.5 Significance and Contributions

Nature-informed architecture (NiA) is a holistic approach providing a novel point of view to the field introducing abiotic nature and defectious behaviors as a part of reference domain, providing a model as a template. The implication, new ideas and a transfer learning model (TLM) are proposed based on narrative and critical literature reviews and discussions on scale, dimension and model.

Initially, as it is proposed in this thesis, today, the role of architects is expanding not only to cover skillsets like programming but also to embrace the knowledge and methodologies of various disciplines to understand, decode and transfer the information into their own field. Along with this transformation, the design and construction processes designed by architects are required to be considered as a whole rather than two separate timespans. In this vein, NiA as an approach putting forward the act of informing rather than abstraction as in most of the common approaches proposes, reinforces multidisciplinary teams working on transdisciplinary areas in architecture. Moreover, along with TLM, NiA comprises this process end to end aiming a holistic approach not only for learning from nature, but also for any information transfer targeted among different domains.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this dissertation, the term *Nature-informed* study is proposed as a general term which encapsulates frequently used terms and strategies like learning-from-nature, bionics, biomimetics, biomimicry, geomimetics and geomimicry to describe studies originated/learnt from nature. As this thesis emphasis the act of learning from a broader perspective, what *Nature-informed* implies is the act of information transfer from one domain to another by defining the relations through captured data, data models, and it is an informing process in which nature acts as a supervisor.

Throughout the history of architecture, inanimate and animate nature is always scrutinized to understand form, structure, material, responsiveness and more, to find better solutions to shelter ourselves and/or to improve our built environments free from defects which are “failure or shortcoming in the building’s function, performance, statutory or user requirements” (Pheng and Wee 2001) (Nielsen, Hansen and Aagaard 2006). On the other hand, defects are important source of information to understand the response of the artefacts, their weaknesses in strength in materials, structures and systems (Prameela and Weihs 2020) to the environmental forces. The same argument is valid for defects and failures in nature and how nature deals with them. On the other hand, majority of the studies and their subjects of concerns, show that defects and failures in nature are not included in the field of architecture even though they deserve to take more attention.

History of nature inspired studies is very long and it is possible to see that in many innovations, nature in broadest sense is either explicitly or implicitly referred. The works of Goethe: “Metamorphosis of Plants” (1790), E.S.Russell: “Form and

Function" (1916), Sir D'Arcy Thompson: "On Growth and Form" and R.H.Francé: "Plants as Inventors" (1920) can be accepted as the early examples of nature in informed studies in contemporary sense. All these studies have shown the potentials of life examining growth, metamorphosis and behavior. Among these studies, Growth and Form particularly draw attention with its mathematical models and it was a new approach to evolution with a new reference understanding, inspiring several researchers, designers and artists (Thompson 1917).

In the study of Thompson, natural forms, geometrical and mathematical analysis and resemblances with each other are examined, and he proposes a morphogenetic approach to Cartesian coordinate system, thereby the idea of transformable/deformable coordinates (Figure 2.1) which even today, is a back bone of freeform modelling approaches. These examples and his detailed studies did not only influence researches working on mathematical and algorithmic development of forms, but also lead the research of morphogenesis in today's biomimetic studies. His approach of mapping the information from one creature to another with the help of a transformed grid system is very similar to contemporary form finding in computation through various reference systems. In this sense, he has a very important role in both biomimetic and computational design studies in today's architecture.

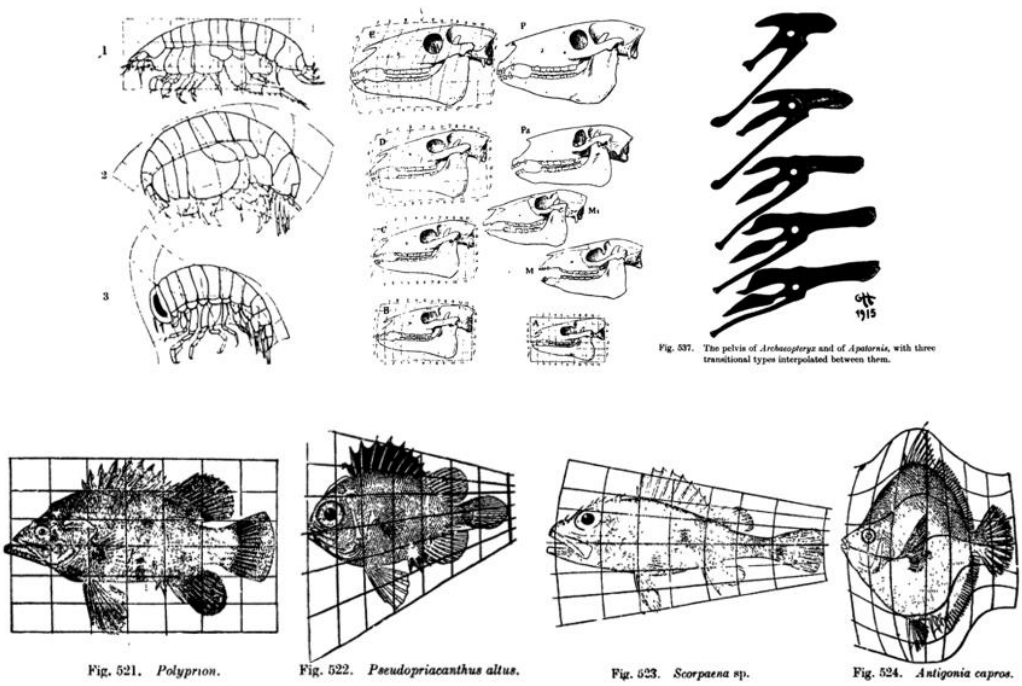

Figure 2.1. Examples from "On Growth and Form" (Thompson 1917)

This quest is much more critical than before not because of increasing number of environmental problems, economic and political instabilities, depletion of resources, but also opportunities provided by technological advancements. Nature, today, is not only visited as a model, measure, or mentor (Benyus, 2002) but also it turns to be a supervisor in our designs with the help of new tools, media, and computational power, in the last two decades.

Nature-architecture relationship has reached to a new phase especially in the 21st century as architecture should respond more demands and performance becomes one of major and intriguing challenges in any design. In the realm of nature informed studies, introduction of advancing technologies, collaboration with other disciplines and being able to retrieve information in many different scales alter the contemporary modelling understanding in any discipline and in architecture as well. Today, any model either related with architecture or beings in nature is furnished with multi-layered information not only related with form, material, structure, processes but also with patterns which are possible to be decoded/recoded with high data handling capacities of today.

In this chapter, current literature is revisited how nature-architecture relationship evolves in the course of time, in the lenses of nature-informed idea. This study not only gives a picture of nature-architecture relationship but also shifts in understanding of scale which is proposed as a measure dimensionality and level of complexity in relation of incorporated data/information. Initially, a brief narrative literature review is conducted revealing the breakthroughs in the history of Nature-informed Studies. Then, the results of systematic review are presented to portray the tendency of the field towards most common strategies. Moreover, the state-of-art examples, strategies and taxonomies are examined to show the strengths, weaknesses and potentials of the field. Finally, the role of architecture in this process is revisited in terms of the targeted problem area as the motivation of this study.

2.2 Nature-Architecture Relationship

> *…Nature herself is a prodigious 'inventor' and has already produced through natural selection all kinds of devices, structures and materials.*
>
> *(Steadman 2008)*

From the beginning of time, humankind have always been in search of solutions in nature for its survival. Architecture mediates this relation either protecting man from nature or showing ways to live in harmony with nature. Throughout the history, the outcomes of this relation can be found in many ways as in Corinthian column head in Pantheon and as structural systems as the gothic flying buttresses (Figure 2.2).

Figure 2.2. (1) Primitive Hut by Laugier (retrieved from http://primitivehutb5.blogspot.com.tr/ on 15.04.2017), (2) Corinthian capital from the Pantheon (retrieved from http://blog.marcantonioarchitects.com/byzantine-simplicity/ on 15.04.2017), (3) Cross Section of Cathedral of Notre-Dame (retrieved from http://www.pitt.edu/~medart/menufrance/pndmain.html on 15.04.2017.

In “The Ten Books of Architecture”, Vitruvius indicates nature as the ultimate source of architecture in many scales and forms (Vitruvius 1914). In the last century BC, he mentions the importance of;

- *referring structures of nature to learn how to benefit from natural materials,*
- *observation of animals to comprehend the forces in nature,*
- *acknowledging nature as the assessment medium for any architectural design,*
- *referring nature via plants, animals and human bodies to understand the significance of proportion and symmetry i.e., for the column proportions growth of the trees should be examined*

This approach of Vitruvius had a great influence on architecture for many centuries, not only in historical artefacts but also in contemporary ones. Many architects in searching for their design strategies, look back to nature to understand the origins of space like Gottfried Semper who defined the elements of architecture as *hearth*, *roof*, *enclosure*, and *mound* and refer nature to learn materials should be used according to laws of nature (Semper 1851).

In history, among the pioneers who approached nature as a source of information, Leonardo da Vinci, and Gaudi stand out in the field. Leonardo da Vinci (1452-1519) is considered as the forerunner of nature inspired innovation with his methods and inventions which are still taking attention of all designers seeking for innovation (Jabbari, et al. 2014). His studies in "Codex on the Flight of Birds" (Figure 2.3) in 1505/1506 can be accepted as the first nature-informed study in the field. In that study, Leonardo observed movements of bird wings to understand kinetics of flight, to model its physics. He then reflected what he learnt to design his own flying machine. His approach in this study can be simply summarized as exploration, modelling, and design as most of the design processes of today. Also, his effort on understanding aerodynamics by exploring birds in different scales is still outstanding. This can be considered as one of the early biomimetic approaches which can be acknowledged as an act of mapping as proposed in this thesis. His studies on various bird sizes show that he was also concerned about the scale phenomenon, and seeking for ways to convey his knowledge to develop flying machine.

Figure 2.3. Flying analysis of different birds from Codex on the Fligth of Birds by Leonardo da Vinci (retrieved from http://www.leonardoda-vinci.org/Codex-On-The-Flight-Of-Birds-large.html on 23.04.2017) (2) Glider Machine (retrieved from http://www.leonardodavinci.net/flyingmachine.jsp#prettyPhoto on 23.04.2017)

Following Leonardo da Vinci's studies, many inventors encompassed biology as a source of innovation and created as many new designs as analogues of biological beings such as first airplane of Wright brothers, or even simple mechanical devices like the lever and the screw (Headrick 2015).

In architecture, the works of Antoni Gaudi is prominent both with its realization of "the unusual structures and shapes" (Collins 1963), and with his studies on geometry, and nature. Ruled surfaces created in Sagrada Familia is still source of inspiration and curiosity for mathematicians, structural engineers and architects with its structural elegance, curvature control and distribution of the forces (Velimirovic, et al. 2012). His approach towards nature was not only considering it as a model, but also as a measure for the structural design which manifest itself in its hanging structural model. The form finding process of Gaudi is based on the scaled model to analyze the physical behavior of the optimal system by exploring the impact of forces on the scaled model and building itself. This method has also a reflection today like Norman Foster's "New International Airport for Mexico City RIBA" by determining the final form of the shell-like structure with reference to the behavior of the reverse chain model against gravity. Geometries presented in his designs which are "strong, elegant polyhedral models deformed into more organic looking shapes" can also be considered the initial examples of organic architecture (Browne 2008).

Figure 2.4. (1,2) Hanging chain models of Gaudi for Sagrada Familia (http://dataphys.org/list/gaudis-hanging-chain-models/)

Until the 20th century, lessons learnt from nature are implemented into many designs not only in masterpieces, but also in ephemeral structures. As in aforementioned examples, it is seen that nature has been observed, experimented and tackled in many scales that are available for people. This century become fruitful regarding the discussions, artefacts and foundations of the following studies. In the 20th century, on the other hand, the scale of observable information has drastically changed with the invention of electron microscope and Hubble Space Telescope in both directions. Hence, humankind started to have more information about materials, structures, and processes in nature.

> "It has become part of the accepted wisdom to say that the twentieth century was the century of physics and the twenty-first century will be the century of biology." *(Dyson 2007)*

All the advents of technology and information/data quake that several disciplines experience urge them to re-explore nature. While several engineering disciplines take the leading role in biology inspired innovation with bionics, and biomimetics, it is seen that there is a stagnant period of architecture in terms of nature informed studies in relation with modernism and post-modernism. Starting with 1990's, nature informed studies are accelerated in architecture as well and impact of them can be seen in various examples.

When the past two decades of nature informed studies are reviewed, it is seen that there is a remarkable increase in number of biomimetic researches. Richard Bonser's study revealing that between 1985 and 2005, the number of patents worldwide containing the word "biomimetic" or "bio-inspired" increased by a factor of 93 as the growth factor for non-biomimetic patents was 2.7 (Bonser 2006).

With the beginning of 20^{th} century, designers focused on the formation processes of nature to understand its evolution and adapt them to their designs. Understanding those examples is very critical since they are the bases of today's understanding of biomimetic approaches. How learning from nature can be achieved, systematic approaches, and methods have always been concerns for anyone involved in such studies. In that quest, biomimicry become the focus of many movements with different names. In the course of time, nature-informed studies have been named differently in relation with the zeitgeist of the era. These terms also triggered various movements in architecture as exemplified in Figure 2.5. Within this framework, comprehending how the terminology is evolved, how available technologies take part and how the act of modelling is advancing in this shift is important.

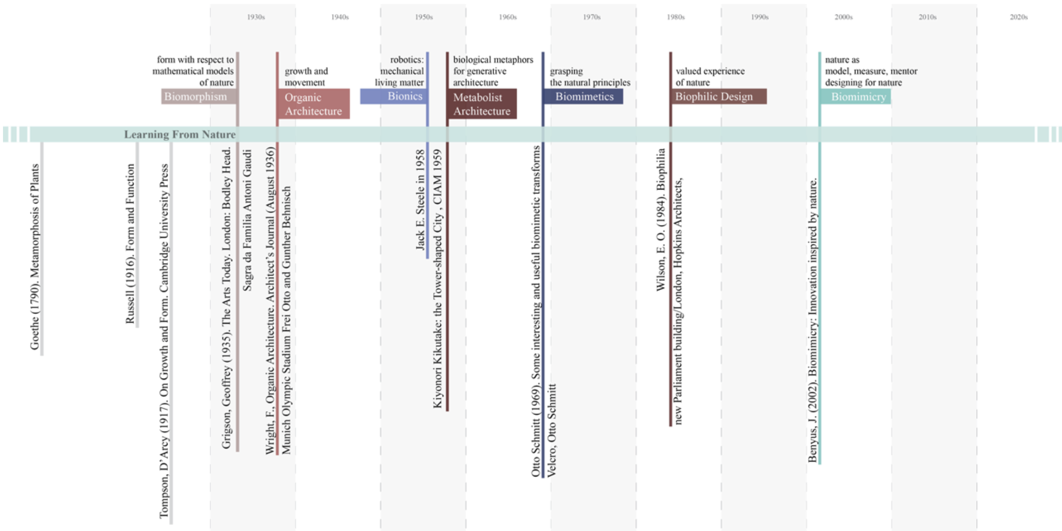

Figure 2.5. Nature-informed Architecture studies and corresponding movements in 20th Century

One of the movements studying structures in nature and their mathematical models in last century is ***Biomorphism*** as named by Grigson (Grigson 1935). This movement influenced famous painters like Yves Tanguy and Roberto Matta and architects like Fariborz Sahba, and Eero Saarinen. The works of Gaudi are also acknowledged among the examples of this movement. However, he is not only the pioneer of Biomorphism, but also is one of the precursors of the organic architecture.

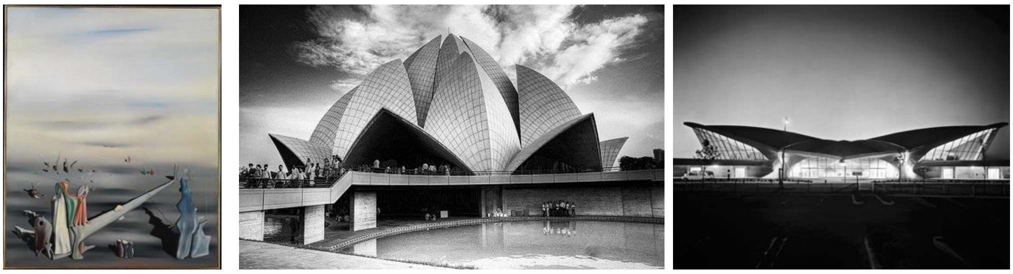

Figure 2.6. (1) The Satin Tuning Fork by Yves Tanguy (retrieved from http://www.metmuseum.org/art/collection/search/490030 on 11.05.2017), (2) Lotus temple by Fariborz Sahba (retrieved from http://www.archdaily.com/158522/ad-classics-lotus-temple-fariborz-sahba on 11.05.2017), (3) TWA Terminal by Eero Saarinen (retrieved from http://www.archdaily.com/66828/ad-classics-twa-terminal-eero-saarinen on 11.05.2017)

Wright refers his design approach as ***organic architecture***, and, suggested a new understanding of building forms by considering growth and movement in nature as an inspiration (Wright 1936). He created his architectural models based on growth phenomenon he experienced in nature. Wright referred to Nature as “The Book of Creations” by adapting the principle of continuity, instead of creating “trimmed” doors, windows, walls and roofs. Thus, he claimed that “form and function are one” instead of “form follows function”. He has reflected this approach to his designs such as Guggenheim Museum reflecting the movement and Imperial Hotel focusing on the wholeness of the slab, roof, wall, window and doors (Figure 2.7).

Figure 2.7. Guggenheim Museum (retrieved from https://www.guggenheim.org/the-frank-lloyd-wright-building), Imperial Hotel, Tokyo (retrieved from https://en.wikipedia.org/wiki/Imperial_Hotel,_Tokyo)

Organic architecture is acknowledged as the ancestor of today’s biomimetic architecture. However, organic architecture examples still refer to nature as a metaphor, although, shifting the natural doctrines from formal to relational. This approach has also seen in the works of Le Corbusier, and Aalto and they are mentioned in the sequel. Thus, the organic architecture is only referred as a part of the development of nature-informed studies in architecture.

In parallel with all these developments, especially with the impact of technology, in the search for modelling the nature, Kiesler brought a new meaning to architecture with the concept of biotechnique in 1939 to designate the correspondence between architecture, biology and technology. He was part of the Buckminster Fuller’s Structural Studies Associations at the time and he used the term to distinguish his thinking from the more direct imitation of biological forms or processes (Braham 2005). Kiesler defines the current understanding of his time about natural and artificial act of building as *"nature builds by cell division with the aim of continuity; man can only build by joining parts together into a unique structure without continuity."* (BRAHAM, HALE ve SADAR 2007). His blob structure named "Endless house" (Figure 2.8) reflects not only his understanding of natural growing structure, but also the impact of nature on his architecture as a measure factor which shapes the final form naturally.

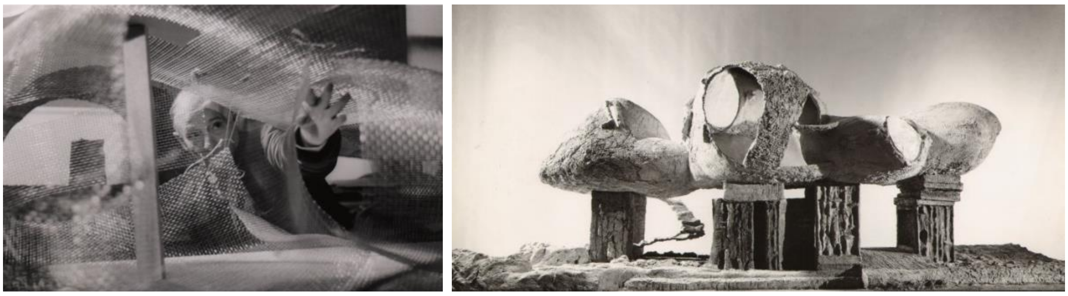

Figure 2.8. (1) Frederick Kiesler working on the wire mesh model for an "Endless House", New York 1959/60, (2) model for an "Endless House", wire frame structure, New York 1959
(retrieved from https://www.berlinerfestspiele.de/ on 23.04.2017)

With Le Corbusier and Alvar Aalto the concept of cell adapted from nature introduced a new position by altering the scale of nature inspiring the models in architectural design practice. The ancestors of the modernist movement, Le Corbusier and Alvar Aalto both emphasized the importance of references from nature and existence of architecture in it. As Le Corbusier highlighted that smallest cell (individual unit of housing) is vital to determine the health of the whole, Aalto focused on the methods of both biology and culture which are to construct "cell by cell" with reference to processes of nature (Menin ve Samuel 2003).

In the works of architects like Alvar Aalto, Kenzo Tange and Le Corbusier, nature appeared in organic analogies (Giedion 1980) which is believed that, this traditional 'organic analogy' forms the foundation of the contemporary 'new organic architecture' founded on 'ecological analogy' and 'metaphor' (Steadman 2008). Although the distinction between organic and geometric seems to address the biomimesis in architecture, different formal expressions of the architects such as

Wright and Aalto show that form explorations are not obligatory for bio-inspired design approaches.

In 1960s, a new trend emerged in the modeling of nature and search of a new system in architecture. This movement called as ***Metabolist Architecture*** is initially introduced in CIAM (1959) claiming that the design of a city can be achieved analogous to human body. Later this approach is mostly adopted and developed in Japan. Proposed system aims to understand the complexity of adaptation of nature in architecture at different scales such as building and urban design. Later on, Kenzō Tange who is one of the attendees of Otterlo meeting of CIAM 1959, presented "Tower-shaped City" and "Sky House" as the initial steps of the movement and the shift "from functionalism to structuralism" (Lin 2010). As Kiyonori Kikutake designed "tower-shaped city" and "Sky City", Ocean City, Space City, Nakagin Capsule Tower, Kenzo Tange contributed to the movement with Tokyo Bay Plan, Yamanashi Press and Broadcaster Centre, Shizuoka Press and Broadcasting Tower, plan of the Skopje city center projects (Figure 2.9). As both pioneers represented with their designs, Metabolist architects adapted biological metaphors in order to create generative architecture with customized cells and adaptable temporary configurations (Schalk 2014).

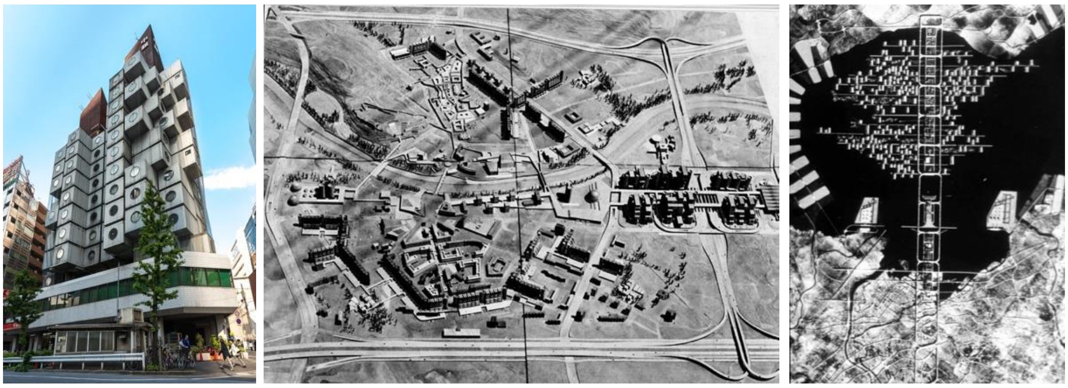

Figure 2.9. (1) Kurokawa, Nakagin Capsule Tower erected in the Ginza district of Tokyo in 1972, retrieved from https://en.wikipedia.org/wiki/Metabolism_(architecture) on 18.09.2016. (2)Tange, Competition entry model for master plan of the Skopje city centre, 1965 (Lozanovksa 2012), (3) Tange,Tokyo Bay Plan retrieved from https://www.studyblue.com/notes/note/n/montreal-1967/deck/13194926 on 18.09.2016.

The functionalist approach of Japanese movement which is a process-based approach had a great influence after World War II and during the post-modernist period, architects tended towards nature and its unique solutions. In this period engineers and architects like Fred Severud and Frei Otto, Richard Buckminster Fuller are distinguished with their "natural structures" and developed such structures since 1950 (Pohl ve Nachtigall 2015). With the advents in construction technology, lightweight nature-like structures (also called 'logical') came into practice.

Among those pioneers, Frei Otto comes to the front with its experiments on the optimal form (Yunis 2015). It is possible to consider Frei Otto in different ways since among other architects, he is the one approaching to nature as a source of measure. Some of the examples Frei Otto can be seen in Figure 2.10.

Figure 2.10. (1)Munich Olympic Stadium / Frei Otto and Gunther Behnisch retrieved from http://www.archdaily.com/109136/ad-classics-munich-olympic-stadium-frei-otto-gunther-behnisch on 18.09.2016. (2) Frei Otto, Hanging Model for Regierungszentrum KOCOMMAS (Kings Office, Council of Ministers and Majilis Al Shura), retrieved from https://tr.pinterest.com/pin/553450241683813212/ on 18.09.2016

In the 60's, in parallel to the new approaches in architecture modelling, there was another conversion in engineering tackling with the bionic approach. In this quest, engineering has tried to take a fact from nature directly and convey into the model hence modeling has gained a new importance. The word ***bionic*** was coined by Jack E. Steele in 1958 formulated in the field of engineering in attempting to study the echolocation of bats to develop radar technology (Pohl and Nachtigall 2015). When he used the term, it has a different meaning than current use; the meaning that he proposed was closer to biomimetics than today's bionics. Today bionic has a narrower definition: "*robotics and replacement or enhancement of living matter, tissue, body parts and organs with mechanical versions*" and biomimetics has appeared as equivalent to the original meaning of bionic and is commonly used (Gruber, Biomimetics in Architecture [Architekturbionik] 2011).

In parallel with all these technological developments, Otto Schmitt called the first electrical circuit he designed in 1934, modeling neural impulse systems of squids, as biomimetic and he introduced the concept of ***"Biomimetics"***. From this point on, similar studies in the world have begun to be evaluated from a different perspective. Then it is acknowledged as a new research field in many disciplines which are seeking for innovative solutions. Pohl & Nachtigall describes biomimetics as:

> … the mere imitation of nature, neither in material and functional nor in creative regard, rather the grasping of natural principles to aid in the comprehension of analogous, technological questions, which could then be solved by the applications of optimized technologies. (Pohl and Nachtigall 2015).

In addition to biomimetic design approach introduced by Schmitt and the success of this approach in the field of engineering draw the attention of architects. Approaching nature as an information source in biomimetic studies has redefined nature's place in architecture. In this context, it is important to distinguish the approaches defined by bio-inspired and biomimetic in architecture in order to clarify how nature informed architectural design evolves in course of time. Gruber stated this differentiation as such:

> "While bioinspiration may be limited to a morphological analogy, biomimetics makes use of functional analogies, processes, mechanisms, strategies or information derived from living organisms." (Gruber, Biomimetics in Architecture [Architekturbionik] 2011)

As architecture is attempting to develop information transfer strategies to learn from nature like other disciplines, on the other hand, in 1984, the concept of ***Biophilic Design*** is emerged with the Biophilia hypothesis of Edward O. Wilson. He defined Biophilia as "*the innate tendency [in human beings] to focus on life and lifelike process."* (Wilson 1984). In architecture, the fundamental objective of biophilic design is defined by Kellert as "*to elicit a positive, valued experience of nature in the human built environment*" (Kellert 2005). Despite of its influence on creating awareness towards nature, biophilic design mostly tied with human welfare, like better health, reduced stress, improved emotional well-being, enhanced productivity, and increased problem solving and creativity. Although biophilia has a great contribution in the relation between nature and architecture, the outcomes of this experience-based approach do not provide any information for the targeted data transfer

In 1998, a new approach ***"Biomimicry"*** which is come up by combining "bios" (life) and "mimesis" (imitation) suggested by Jeanine Benyus. She proposed the idea of biomimicry as a solution of today's problems of ecology, economy, material and sustainability (Benyus, Biomimicry: Innovation Inspired by Nature 2002). She proposed not only learning from nature, but also ***designing for nature*** as the only way to become a part of the nature truly. In her belief, Postmodern relativism of 19^{th} and 20^{th} century give researchers a ground to re-consider the nature and our existence as Bruno Latour's view that "everything is the measure of everything else" can also be considered as one of the sources of Benyus's biomimicry understanding (Dicks 2015).

As she was addressing life itself as a source of development, she proposes three key issues for any information transfer from nature; taking nature as a "model", "measure" and "mentor" and approaching nature as a whole (holistic). Moreover, Benyus classified biomimetic approaches in three categories as mimicking natural form, process, and ecosystems (Benyus, Biomimicry Primer 2014). Although her classification belongs to the late 20^{th} century, what she proposed has always been acknowledged in architecture for centuries.

Benyus's approach of Biomimicry is still significant in the scope of this study. The way she describes nature as a model, measure and mentor opens up new ways of relating different concepts like scaled-to-scaleless, a broadened view on form-to-formation and more, in shifting the conception of model to a new level.

Biomimicry in any discipline is accompanied by the state-of-art technology of its era, making challenging the adaptation of it into any discipline. Architecture which is always related with nature is not an exception. Gruber & Jeronimidis state the difficulties of adopting Biomimicry in the field of architecture as follows:

> "Architecture is developed in different layers and has to meet often contradictory requirements that make information transfer difficult. Too many possibilities and levels of information are interconnected to identify simple straightforward questions and answers. In addition, other challenges have to be met for the adoption of principles from biology in architecture and there is still a difficulty in the gathering of information." (Gruber ve Jeronimidis, Has biomimetics arrived in architecture? 2012)

Yet with the advents in technology, and referred discoveries and innovations in biology and engineering, architecture has paced up including biological references in multiple layers more than before.

Mimetics approach is still an unsettled discussion among architects. According to Neil Leach, the idea of *Mimesis* in architecture should be considered more than "making a copy of", thus it is more an interpretative approach for which model becomes significant. Since engagement of architecture with the built environment is an ongoing process of adaptation, *Mimesis* establishes a form of adaptive mimicry (Leach 2003). Hence, instead of conceiving nature as a metaphor for architecture in terms of spatial organization or formal representation, architects started to reach life as a source of information for efficiency which is the main principle in nature.

As Leach proposes a holistic approach referring to nature for an inspiration in all aspects of nature with the definition of *Mimesis*, Zari, on the other hand, classifies the types of references according to its biological level and architectural domain in five dimensions. Three layers of biomimicry (Organism, Behaviour, Ecosystem) are examined in five possible dimension which are “Form”, “Material”, “Construction”, “Process” and “Function” as Zari classified in Figure 2.11 (Zari 2010). In this study, biology inspired buildings are classified according to the biological domain’s scale and scale of the range that includes the building features informed by nature itself.

Level of Biomimicry		*Example - A building that mimics termites:*
Organism level (Mimicry of a specific organism)	*form*	The building looks like a termite.
	material	The building is made from the same material as a termite; a material that mimics termite exoskeleton / skin for example.
	construction	The building is made in the same way as a termite; it goes through various growth cycles for example.
	process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example.
	function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example.
Behaviour level (Mimicry of how an organism behaves or relates to its larger context)	*form*	The building looks like it was made by a termite; a replica of a termite mound for example.
	material	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example.
	construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example.
	process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or it mimics how termites work together.
	function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example (fig. 6). It may also function in the same way that a termite mound does in a larger context.
Ecosystem level (Mimicry of an ecosystem)	*form*	The building looks like an ecosystem (a termite would live in).
	material	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example.
	construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example.
	process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example.
	function	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilising the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen cycles etc in a similar way to an ecosystem for example.

Figure 2.11. A Framework for the Application of Biomimicry (Zari 2010)

In the classification of Zari, biological scale that is foreseen to cover the living beings inspiring architectural objects has three levels, starting from the living creature itself. Knippers et.al. on the other hand, states that levels of biology that can be a source for biomimetic studies in architecture are molecules, organelles, cells, tissues, organs, and living beings.

In parallel to the Zari's study, in Bionic studies there is a similar approach by classifying influence of nature on Materials bionic as; "Function bionic materials", "Structure bionic materials, "The color and texture, pattern bionic materials", "Chemical composition bionic materials" (Huang, Wu and Zhi 2011). In these studies, while Huang et al. considers the final product to define this process, Zari takes the scale of the nature into account to develop the matrix mentioned above.

However, considering the biological scale stated in the basic biology literature, today's observable scale is much wider which we can observe these scales in different examples like pavilions, partially (and rarely fully) in buildings, in many engineering designs, and in new material development studies. All these studies show that there is still need to understand scale issue which is closely connected with complexity and system understanding as well as accessible collected data of nature and current objectives of architecture.

On the other hand, classifying reference being, behavior or system as alleged by of Zari and Huang et al, is not only contradicts with the all-inclusive approach of Benyus, or Vitrivius's understanding of building as a whole, but also is criticized by contemporary studies of Menges, Oxman and Knippers etc. The common 21st century approach of biomimetic studies in architecture states that as the organs, skin, living being or swarm cannot be discussed individually, and in life material, structure, form and process are not considered independently, it is not possible to compartmentalize the building features while dealing with the biomimetic studies in architecture. In this regard, the approach of biology become significant to comprehend the biological dimension as a whole. Oxman expresses this idea as such;

> *The way we view our environment, and interact within it, is ultimately dependent on the lens through which we choose to see it. Choosing is no innocent act. A material scientist will generally explore the physical composition of matter through the lens of properties. A biologist, however, looks at the world not through the lens of properties, but rather through the lens of function. Both live in the same reality, but experience it altogether*

differently, and therefore act upon it in a singular way. If they could see both views simultaneously, they would link properties and behaviors.

(N. Oxman 2016)

Yet, this holistic approach mostly does not involve abiotic nature as a source, although there are number of studies applying geomimetics approaches (Seifert, Carlson and Moldowan 1981), (Pierini, Foresti ve Fracasso 2010), (Alves 2019). As an example of few exceptional studies, in the paper of Speck et.al., the role of abiotic nature is acknowledged as geo-driven development and included as a part of nature-derived development by defining it as "*technical solutions having non-living concept generator*" (Figure 2.12) (Speck, et al. 2017).

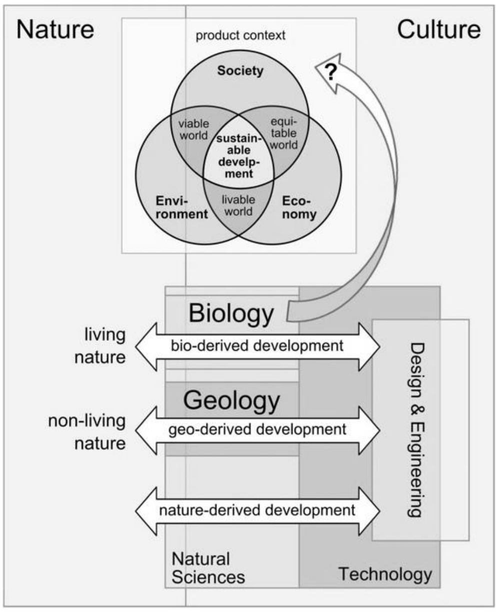

Figure 2.12. Nature derived development (Speck, et al. 2017)

Along with the growing body of contemporary Nature-informed studies and research projects, the need to find a more systematic approach both to classify, and to determine the methodologies, and processes is increasing radically. In parallel with this turn, architecture re-evaluate its position in this process to associate architectural scale and natural scale together with an extended multi-disciplinary modeling approach this time with a much stronger understanding of data and data design as well.

2.3 Approaches and Strategies

Many nature-informed studies can be conceived as mapping however, when their processes are studied, data transfer from nature mostly occurs in an implicit or in a fuzzy way such as in Velcro (Figure 2.13) which is accepted as the first biomimetic study.

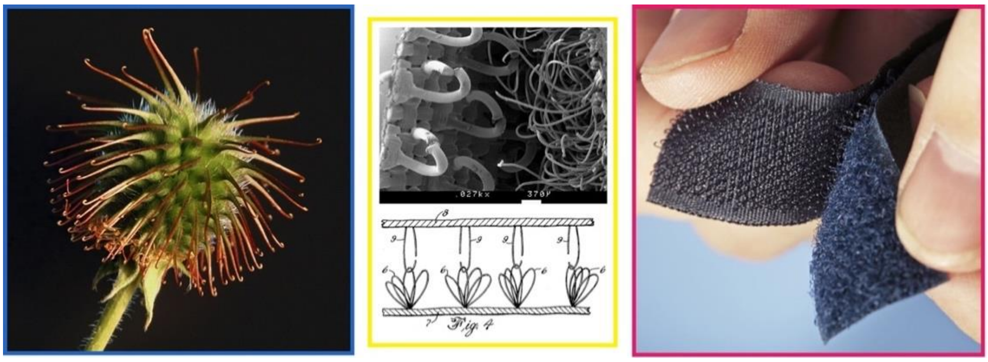

Figure 2.13. Velcro: an example of mapping process from reference and problem

As other studies, in the case of Velcro, there is a model constructed based on the hooks of the burrs. This model is constructed for a specific problem that is bonding two objects. The success of the solution from a simple plant to widely used product lays in the model where information transfer is achieved. The critical role of model can be seen in all the examples of nature informed studies too. Models and modelling processes are also evolving in accordance with all advances in technology and computation. Hence there is still a need to further investigate on what the model is in general and how it serves in nature-informed architecture.

> *A model, by definition, is always an abstraction of reality. Building a model means reducing the infinite complexity of the real world to a level where it can be described with manageable effort. What is obvious in the workshop of a model builder sometimes gets forgotten when almost infinite digital storage space is at hand: a perfect model does not contain as much information as possible, but as little as necessary to describe the properties of an object unambiguously. Any extra bit would be meaningless for the given purpose*

and only impede comprehensibility. … While modelling starts with gathering data, it is far more important to then throw away everything that turns out to be superficial. This task requires quite some (human!) intelligence, because it involves finding patterns and defining general cases. (Scheurer ve Stehling 2011)

Sorguç and Selçuk (2013) define this process as any model including less data for the mapping process will be neither wrong, nor imprecise and any model including more data than necessary will be over complex. Then, the question of "what should be the precision of abstraction during modelling?" appears. Thus, they propose a computational cycle for the modelling process that includes observation, development of mathematical model, analysis, synthesis with a feedback mechanism (Figure 2.14). The real model defined in this process is the codomain representing the levels of architecture which adapt the information from nature. In this process, it is essential to note that to have a computational model, the role of algorithmic thinking is as important as the role of human and machine intelligence.

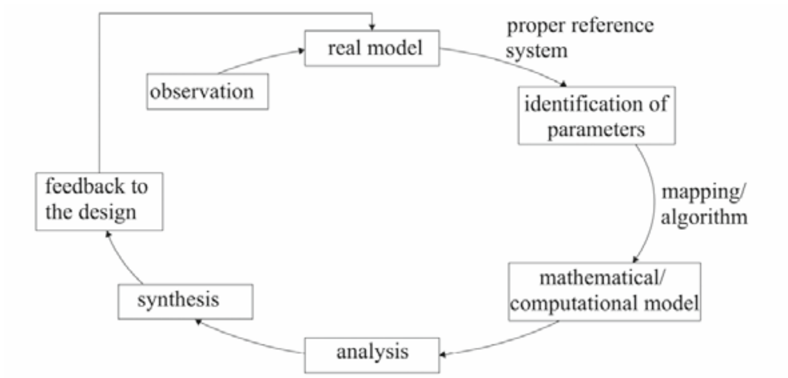

Figure 2.14. Simplified computation cycle for learning/experiencing by modeling retrieved from (Gönenç Sorguç ve Arslan Selçuk, Computational Models in Architecture: Understanding Multi- Dimensionality and Mapping 2013)

Creating a relevant model is already accredited in current strategies proposed by well-known researchers. Although these strategies define the process in two distinct paths; as one of them exploring nature to have some inspiration, the other one looks into nature to solve its specific problem. This distinction is emphasized by Knippers and Speck (Figure 2.15), Vattam, Gebeshuber, Baumeister, Oxman with different terminologies (Table 2.1). In the phases of both of the paths, there is an abstraction step where the observed part of nature is aimed to be modeled to solve the problem in the target domain. Yet the act of modeling is not explicitly defined in any of these strategies.

Table 2.1. Main approaches towards biomimetic studies

(Speck, et al. 2006)	Top-down	Bottom-up
(Vattam 2007)	Problem-based	Solution-based
(Gebeshuber 2008)	Biomimetics by analogy	Biomimetics by induction
(Baumeister 2012)	Challenge to Biology	Biology to Design
(N. Oxman 2016)	Templating Biology for Design	Templating Design for Biology

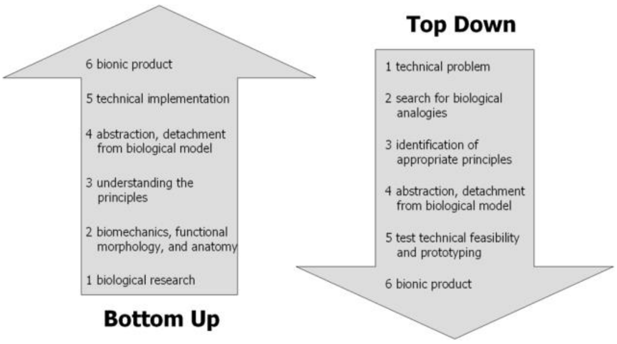

Figure 2.15. Process sequences in biomimetic research by Knippers and Speck (2012). (a) Bottom-up process, (b) Top-down process of biomimetics

These approaches are associated in a single generic integrative design process diagram with their relations in the work of Dörstelmann et.al. (Dörstelmann, et al. 2014) (Figure 2.16). As this study shows the interconnected structure of bioinspired approaches in architecture, it also shows the potential of it on the different dimensions of architecture in its interdisciplinary nature. Today it is possible to find correspondence of all of the scenarios indicated in the diagram, however, regarding the multilayer complex structure of both nature and architecture, it is not possible to linearize the process as shown below.

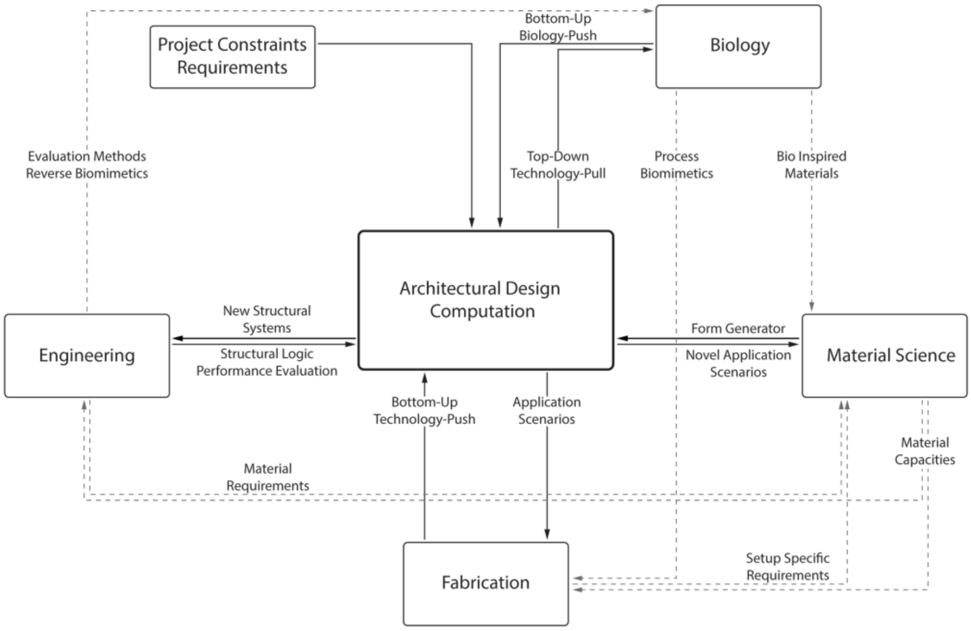

Figure 2.16. Generic integrative design process diagram (Dörstelmann, et al. 2014)

Today, advancement of technologies enables us to handle data in terms of quantity and complexity with large data crunching capacities. Yet, adopting natural beings as a source of multilayer data and processing this data to transform architecture still requires a new kind of approach in terms of information transfer. In this quest, the following part of this chapter is designed both to show the current tendencies in terms of natural references, aims, strategies and to present a future projection for upcoming approaches, strategies models and methods.

2.4 Systematic Review of Literature

This section is designed to examine the recent nature-informed architecture literature focusing on design and construction of buildings. In this respect, a twofold analysis is designed; systematic semantic survey and critical review.

The first part is dedicated to a systematic semantic survey to illustrate the association between mostly acknowledged terms/strategies and their approaches, focal points, and targeted performances. It is constructed to include the most common or acknowledged strategies that current nature-informed studies follow or refer in their publications in a comprehensive picture, not only to decode strategies but also to reveal the coherencies and discrepancies among them. Today, it is seen that these terms are mostly being used interchangeably or sometimes together, despite they are for different purposes, having approaches and methodologies. It is also intended to show the change in the preferred terminology in the last two decades of, solutions looked for and observed references in nature. An integrated dataset referring all these terms is constructed accordingly, they are semantically analyzed, and results are presented with different charts, and following discussions.

The second part of the study is conducted with a template that is designed as a result of the outcome of the first part. Within this framework, the studies exemplifying the information transfer are studied and deciphered to provide a broad picture of the field with mostly studied relations as well as neglected ones.

2.4.1 Semantic Survey on Literature

The proposed research is initiated by searching the following keywords: "learning from nature", biomimetic(s), biomimicry, bionic(s), bioinspired (bio-inspired), bio(-)digital, and biomimesis in Web of Science[1] database. List of keywords are retrieved as raw data and presented with the relationships between keyword aiming to reveal the correlations among keywords, focal points of studies, and outliers which are subjects mentioned rarely.

As a result of initial search based on the keywords, there have been 84005 publications exist in the WOS database. In these findings, it is seen that the publications in Material Science Interdisciplinary category is constitutes the largest part with 15205 studies (18.1%). Moreover, studies categorized under architecture make up the 0.17% of the total research in the field which is extremely low compared to other fields. This analysis raises questions which may be explained by multi-layered complexity of architecture, e.g. structural, special, cultural, environmental, etc., the differences in scales of interest from nano- to macro-, and architecture's inspirational attitude towards nature.

Furthermore, to refine the initial findings in order to retrieve building-related studies, the results are filtered with "*Architecture*", "*Construction & Building Technology*", and "*Engineering, Civil*" categories. As a result, the data related with 533 articles are obtained, and 397 of them including information about the author(s), title, abstract, keyword are used for further analysis. The process of data selection and related outcomes are presented with a flow chart in the Figure 2.17.

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[1] https://apps.webofknowledge.com/ (accessed on 04.08.2020)

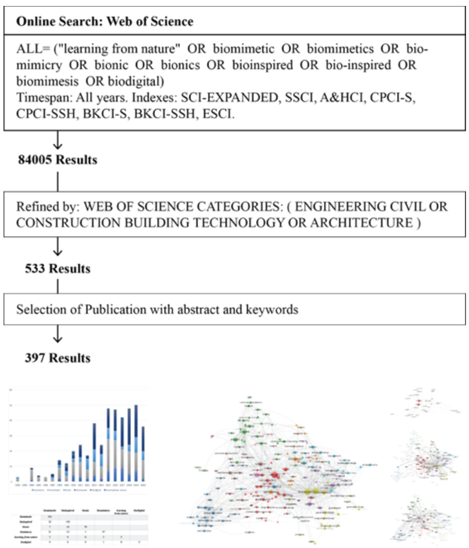


Figure 2.17. Data selection and analysis of the semantic survey (Last update:06.08.2020)

In the first phase of the semantic survey, the resultant raw data of the search is used to generate a trend chart in a time-frame and a keyword network map. Chart given in Figure 15 indicates changing tendencies over time, showing the evolution of terms and nature-informed studies in the last 20 years in architecture, construction and civil engineering literature and the increasing trend and demand of nature-informed studies in these selected fields starting from the early 2000s (Figure 2.18).

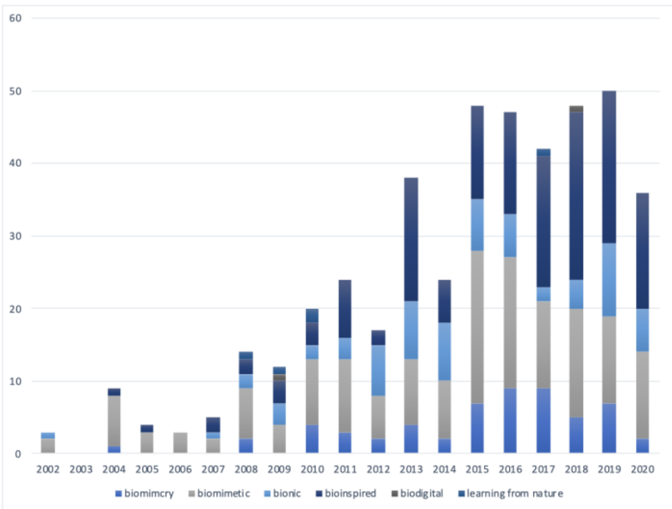


Figure 2.18: Number of articles in which the provided keywords found in the specified areas (Last update:06.08.2020)

It is also noticed that in some of the studies the names of the different approaches are used together or improperly. The coexistence of these keywords in titles, in keywords, and in abstract sections is presented in Table 2.2, which shows the dual usage of these terms. It is even encountered publications referring three or four of them in their keywords. This situation can be stated as a source of confusion about the usage of terms, their motivations, and strategies, despite their main purposes (motivations) and strategies are different from each other. This confusion is also apparent in the following part of this review.

Table 2.2. Correlation Matrix of the keywords

	biomimetic	**bioinspired**	**bionic**	**biomimicry**	**learning from nature**	**biodigital**
biomimetic	161	32	7	21	3	-
bioinspired	32	150	16	13	-	-
bionic	7	16	70	1	-	-
biomimcry	21	13	1	57	2	1
learning from nature	3	-	-	2	5	-
biodigital	-	-	-	1	-	2

The tremendous number of possible references in nature that can be learnt and similarly number of potential applications makes very hard to represent how they can be related. Therefore, the relations between the aspects of studies are aimed to be explored with a network diagram based on the keywords of the publications using Vosviewer (https://www.vosviewer.com). The network diagram presented in Figure 2.19 is not easily legible and yet shows the complexity of the nature informed studies and its intriguing interaction with various subjects.

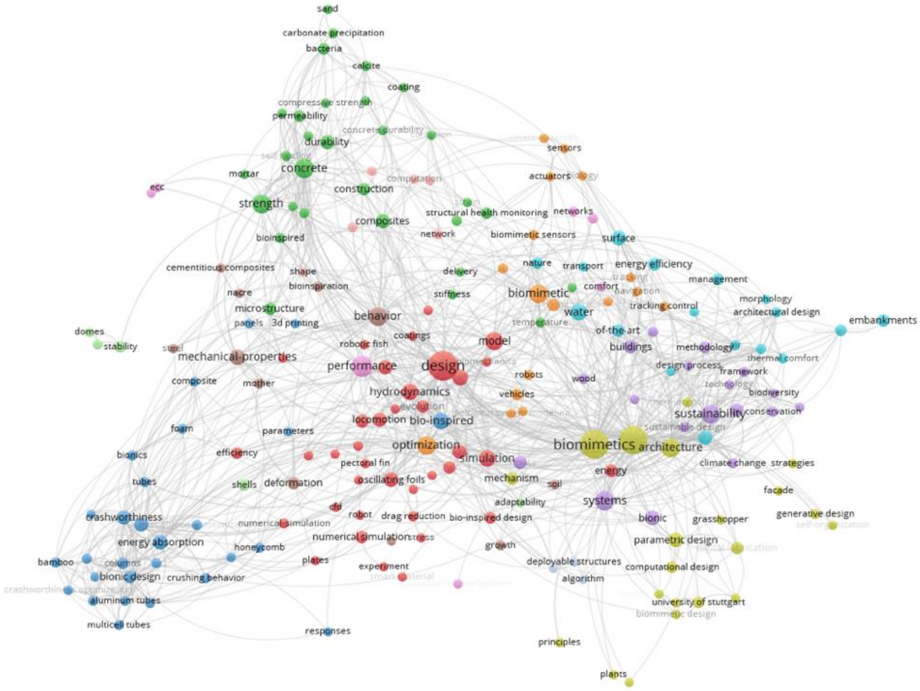


Figure 2.19. Network Graph: Initial findings showing the relationship among keywords (Last update:06.08.2020).

Then, network diagram in Figure 2.19 is refined by pruning to show repeated /recursive relations to identify the major connections/associations and main subject areas in Figure 2.20.

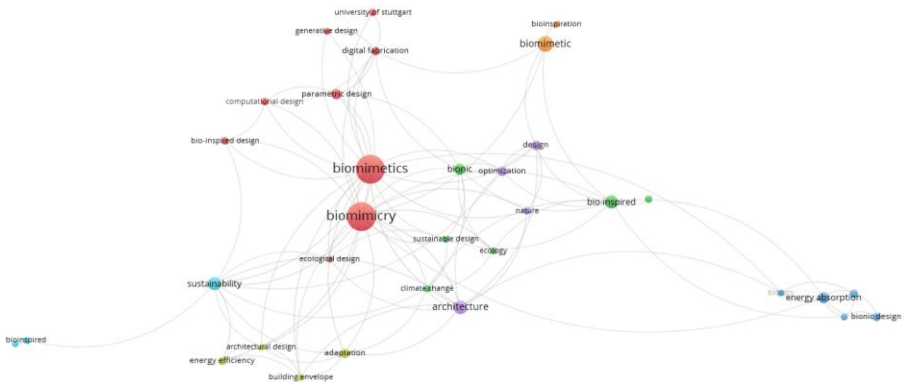


Figure 2.20. Network graph showing the mostly encountered relations (at least 4 times) in the studies. (Last update:06.08.2020).

In this diagram, it is seen that the concept of design has always been the focal point of building studies, even dealing with the performative and constructional aspects as it can be expected in the field of architecture. Another point taking attention is the amount of computation related keywords i.e., computation(al), parameter(parametric), algorithm(algorithmic). When the studies are assessed from this perspective, it can be concluded that the complexity of nature, the amount of available data, the need for interdisciplinary approaches necessitates computational models.

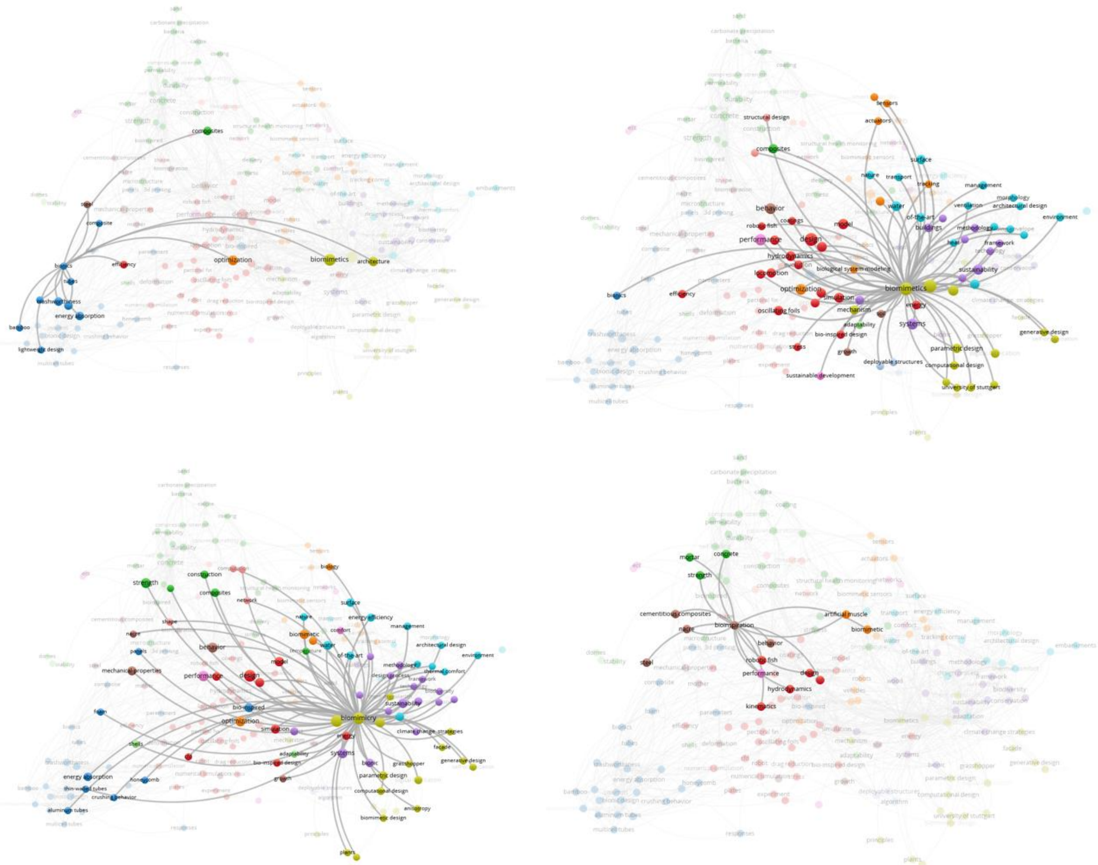


Figure 2.21. Network Diagrams showing the relationships between mostly referred strategies and their foci (Last update:06.08.2020).

Although terminology preferences in the studies are different from each other like bionics, biomimetics, biomimicry, it is seen that each presented study in the publications refers to a similar set of references found in nature for similar targeted performances. As targeted performance can be studied in clusters as environmental, thermal, structural performances, the behaviors of the reference being vary as morphological, growth, structural, system etc.

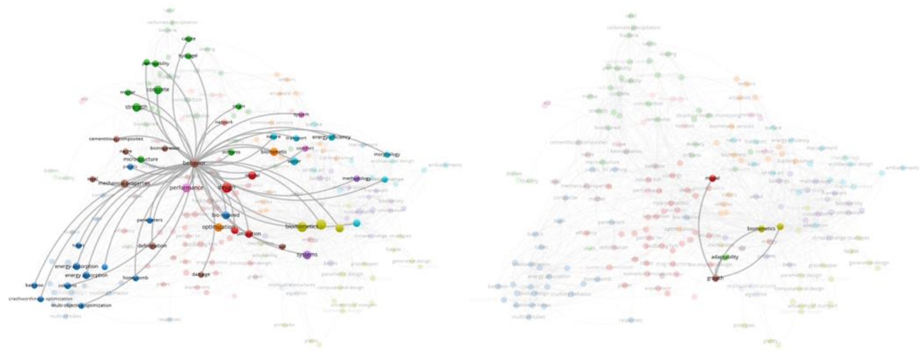


Figure 2.22. Position of behavior and growth among the current studies (Last update:06.08.2020)

In these studies, the interest towards behavior stands out with its relation with many aspects in nature and architecture such as adaptation, energy usage, morphology, structural and mechanical features and more. Therefore, definition of behavior in these studies are found to be one of the significant acts. It is also seen that among many other behaviors, growth phenomenon is not covered as others although it exists in both nature and architecture in various scales.

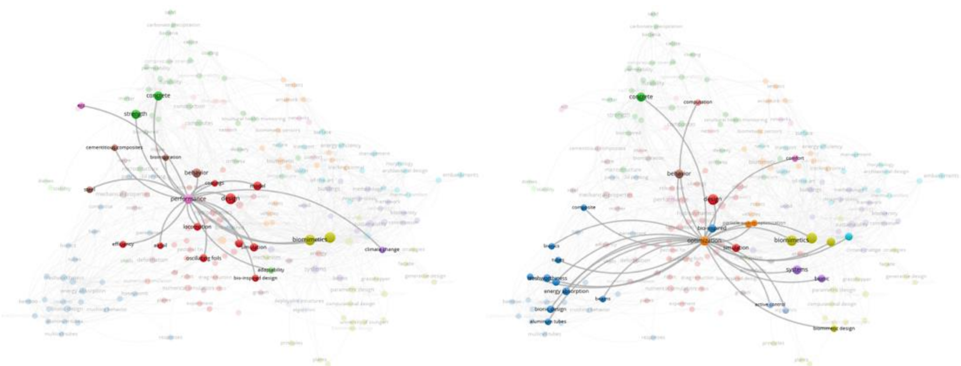


Figure 2.23. Position of performance and optimization among the current studies (Last update:06.08.2020).

Among the studies covered in this survey, the concept of performance and optimization are clearly noticeable either by occurring as keywords alone or with performance related keywords such as structure, environment, thermal, ecological, adaptation. It is an expected result since architecture have always referred nature for better performance and tried to learn from performance related principles. In this context, performance-based criteria can be counted as one of the features that nature-informed studies are seeking for.

As a result of all aforementioned discussions, it is possible to define the information transfer from the reference found in nature to a problem area defined in architecture with the following steps:

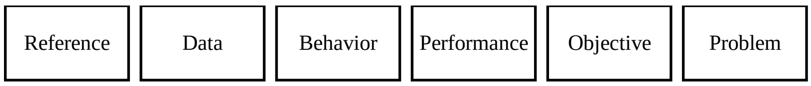


Figure 2.24. Steps of problem definition between reference and problem

1. Reference: the sample selected to be referred to be informed
2. Data(R): Features of the reference defining the behavior of the reference being
3. Behavior(R): the behavior of the natural being within the observed context
4. Performance(P): Expected performance from the outcome of this transfer
5. Objective(P): Objective and constraints of the problem
6. Problem: that study is seeking a solution for

These steps are called dimensions in this thesis considering the transformation of data throughout the process. As the transferred and transformed data can vary among different studies, the main dimensions defining and also classifying them determines the phases of this mapping process. Therefore, the dimensions retrieved as a result of this study is found valuable to define the dimension to be used to deconstruct existing studies as well as to construct a new model. So, an in-depth analysis is designed to be conducted based on this framework to portray the current tendencies in terms of selected references, collected data, observed behaviors of the reference and the targeted performance with the objectives.

2.4.2 Systematic Critical Review of Literature

In this part of the study, systematic critical review (Siddaway 2014) is conducted to explore the data flow from the reference in nature to a specific problem related with built environment. For this review, papers are decoded according to the steps proposed in the previous chapter and presented in a flow diagram showing the continuous relations among steps. Applying this framework on existing studies is important not only to substantiate the newly developing template for data transfer but also to show the existing and the potential paths. At this point, it is important to note that the empty areas (undrawn paths) are as important as the existing ones because they have the potential to lead a new research. Therefore, the studies presented in the first part are examined and among the data of 397 paper indexed in WOS, 102 paper is found eligible to feed the dataset with proposed steps: (1) reference, (2) data, (3) behavior, (4) performance, (5) objective, (6) problem and also bibliographic information like year, used term and publication category. These papers are decoded in a spreadsheet in the given template as presented in the Figure 2.25 and this dataset is used to generate the flow diagram as in Figure 2.26.

Author	Title	Year	Term	a/biotic	Reference	Feature	Observed Behavior/Process	Targeted Performance	Objective	Problem	Category
Le, TV; Ghazlan, A; Ngo, TD	3D Printing and Numerical Modelling of Conch-Inspired Lamellar Structures	2020	biomimetic; bioinspired	biotic	shell	arrangement	lamella	structural performance	lower deflection; less crack	structural design	Engineering, Civil; Engineering, Mechanical
Wang, LX; Du, WF; He, PF; Yang, MJ	Topology Optimization and 3D Printing of Three-Branch Joints in Treelike Structures	2020	bionic	biotic	tree	branch; pattern	growth; morphology; l-system	structural performance; optimization	topology optimization	structural design; component design; topology	Construction & Building Technology; Engineering, Civil
Sun, YY; Wang, S; Wang, ZG	Effect of adhesive interlayers on protective performance of bio-inspired building ceramic covering	2020	bioinspired	biotic	shell; nacre	microstructure	impact resistance	ballistic performance	impact resistance	protective covering; coating	Construction & Building Technology; Engineering, Civil
Bielefeldt, BR; Reich, GW; Beran, PS; Hartl, DJ	Development and validation of a genetic L-System programming framework for topology optimization of multifunctional structures	2019	bioinspired	biotic	tree	branch; pattern	growth; morphology; l-system	structural performance; optimization	multifunctional structures; generative design	tool development; structural design	Computer Science, Interdisciplinary Applications; Engineering, Civil
Rosewitz, JA; Choshali, HA; Rahbar, N	Bioinspired design of architected cement-polymer composites	2019	bioinspired	biotic	shell; nacre	morphology	protection; conservation	structural performance; material performance	composite material; strength	material development	Construction & Building Technology; Materials Science, Composites
Khosromanesh, R; Asefi, M	Form-finding mechanism derived from plant movement in response to environmental conditions for building envelopes	2019	bioinspired	biotic	plant	movement	deformability; responsiveness	environmental performance; kinetic performance	form generation; optimization	envelope	Construction & Building Technology; Green & Sustainable Science & Technology; Energy & Fuels
Sheikh, WT; Asghar, Q	Adaptive biomimetic facades: Enhancing energy efficiency of highly glazed buildings	2019	biomimetic	biotic	plant; leaf	movement	track sun path; adaptive	reduce energy consumption	reduce solar heat gain; reduce energy consumption	envelope	Architecture

Figure 2.25. Some of the decoded studies based on the proposed steps

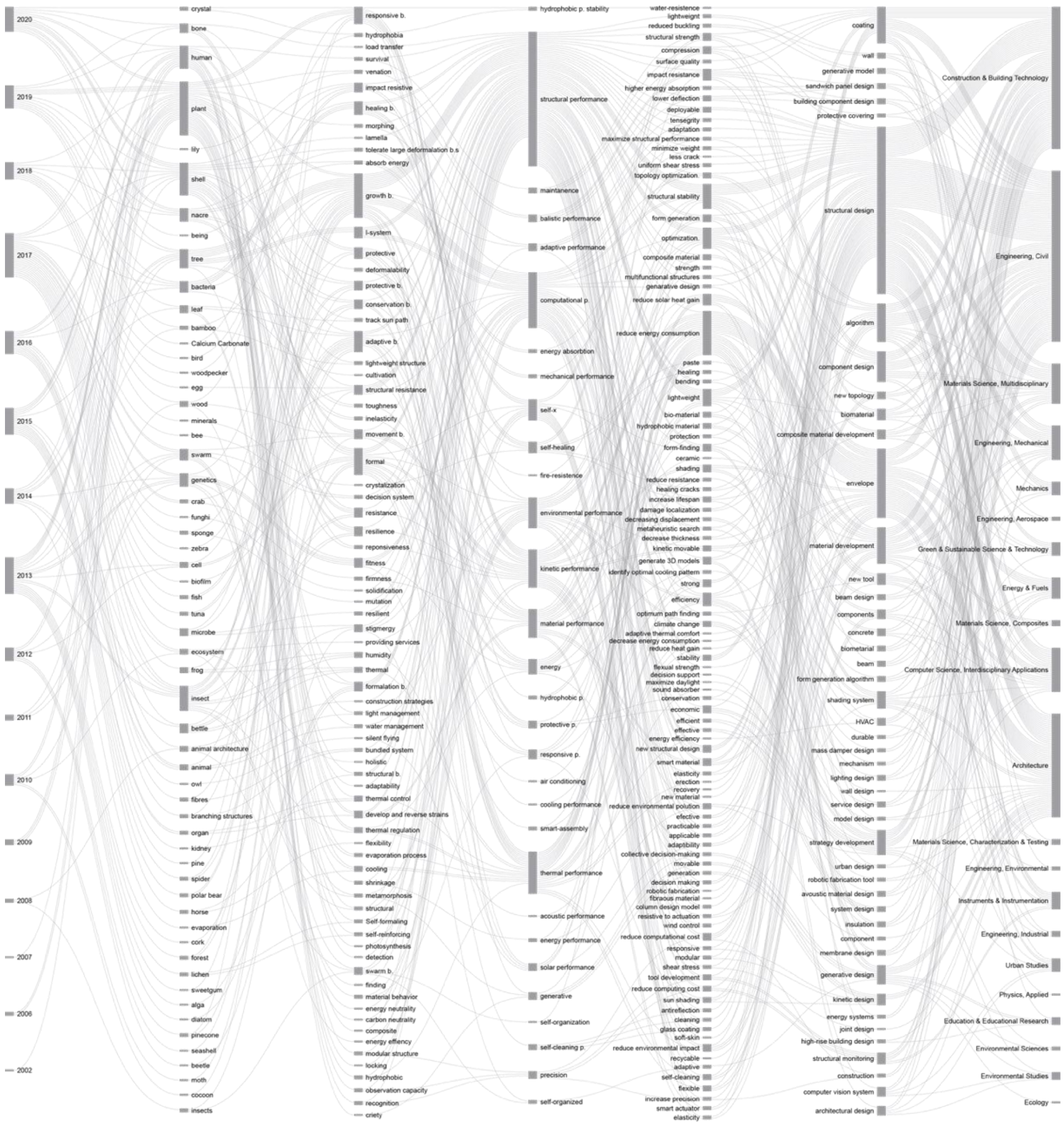


Figure 2.26. Flow chart showing the data transfer from reference to the problem

The initial comprehensive flow chart shows us;

- how rich this research field is
- different types of problems referring the same references and various references addressed by the same problem
- that there is a considerable number of studies are focusing on the same type of references or same problems in different scales
- multidisciplinarity of the field despite the results have been filtered with building related subjects

Yet, it is seen that there is a need for a more focused analysis based on the reference and problem separately with their decoded dimensions and the mapping between them also requires an intense study considering the similarities and differences at the same time. Therefore, following explorations are designed to breakdown each step of the deciphering process to reveal the tendencies and also biases with some examples of mostly studied areas found in the publications.

2.4.2.1 Reference: Features (Data) and Behaviors

Initially, the presented references are defined with its constituent parts as reference itself, features chosen to be studied (or collected the data from), and observed behaviors. The generated flow diagram presenting the examined dimensions of reference can be seen in Figure 2.27. In this decoding process, it is seen that the attention in the publications is mostly given on the outcome (building, artefact, algorithm etc.), rather that the actors of transfer process as well as the act of transfer itself. Therefore, some references were not indicated in detail in these studies which can be observed in the flowchart.

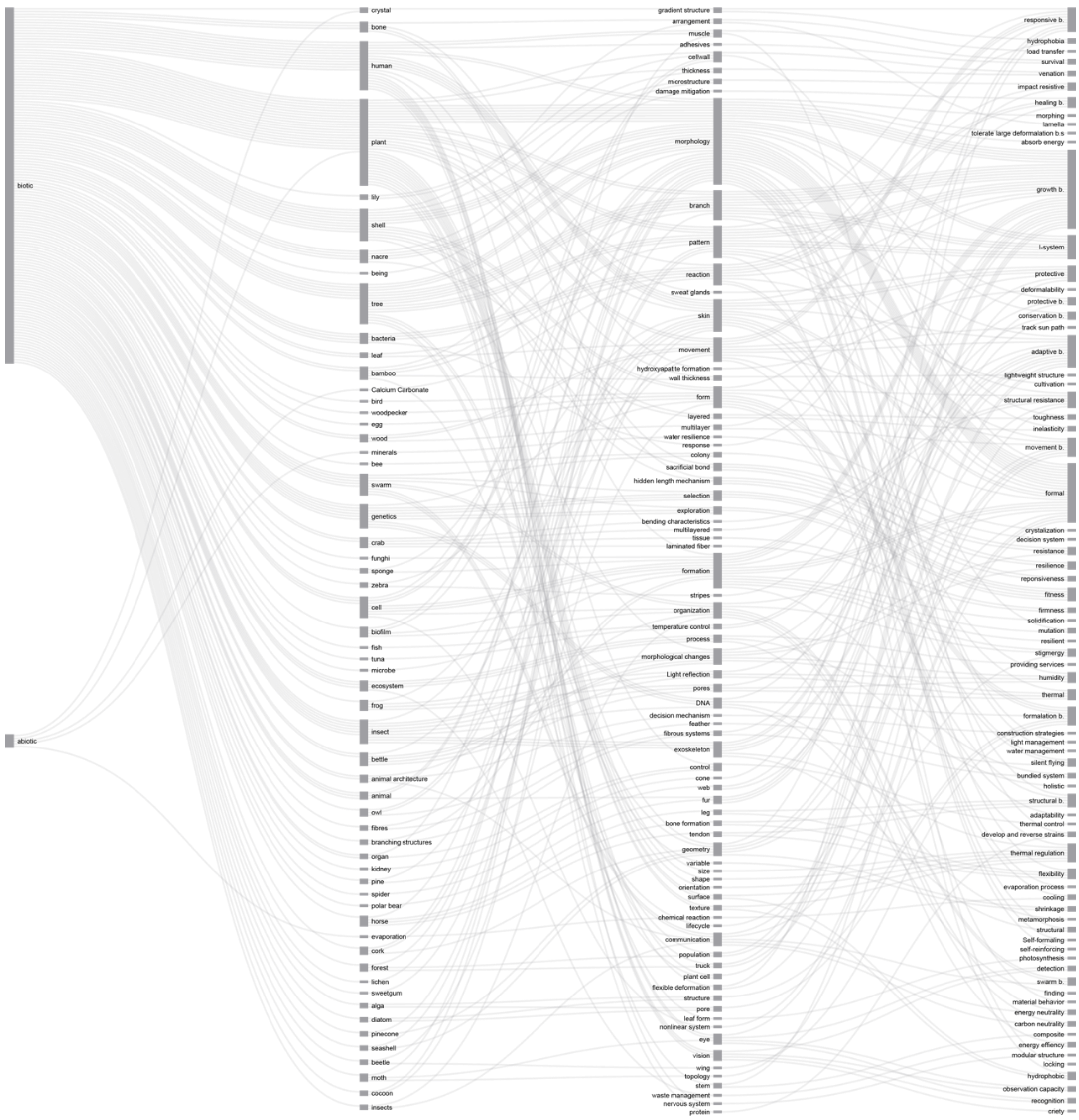


Figure 2.27. Reference: Features and Behaviors

According to the general frame drawn by the proposed flow diagram, samples chosen from nature are mostly biotic ones. There are only few publications sharing their study on crystal structure, environment of plants (as a habitat), minerals and phase transitions as a reference of information transfer. Yet, in most of them, these references are accompanied by biotic ones. Therefore, abiotic samples seem to be neglected/disregarded in nature-informed studies in architecture even though architecture can also be listed as a part of abiotic nature.

Moreover, considering the main foci of the selected publications, selected beings to be learnt from are vary widely as plants, animals, humans, insects and bacteria with their features like cells, leaves, genetics, swarms, shells, skeleton. Additionally, the behaviors observed in these beings and their features also show a lot of variety namely growth, morphological, responsive, environmental (thermal, energy, humidity) and structural behaviors. However, it is important to note that, as the publications are analyzed based in the given template, a confusion is discovered such that behaviors of the reference beings are being defined by the terminology of the target domain in significant number of studies. Although this act seems to provide a ground to provide a relation between domains, it constitutes a risk to conceal the true behavior.

2.4.2.2 Target: Performance, Objectives, Problem and Field

It is inevitable to make the inference that nature has took attention of architecture with performance-based aspects and architecture mostly adapts these principles along with explorations on form, function and behavior. As the target domain is represented with a problem specific for the field, this problem requires to be defined explicitly to seek for a reference in nature. This definition is including the targeted performance, objectives, constraints and informed research area which is the field that paper is published. The resultant flow diagram is presented in Figure 2.28.

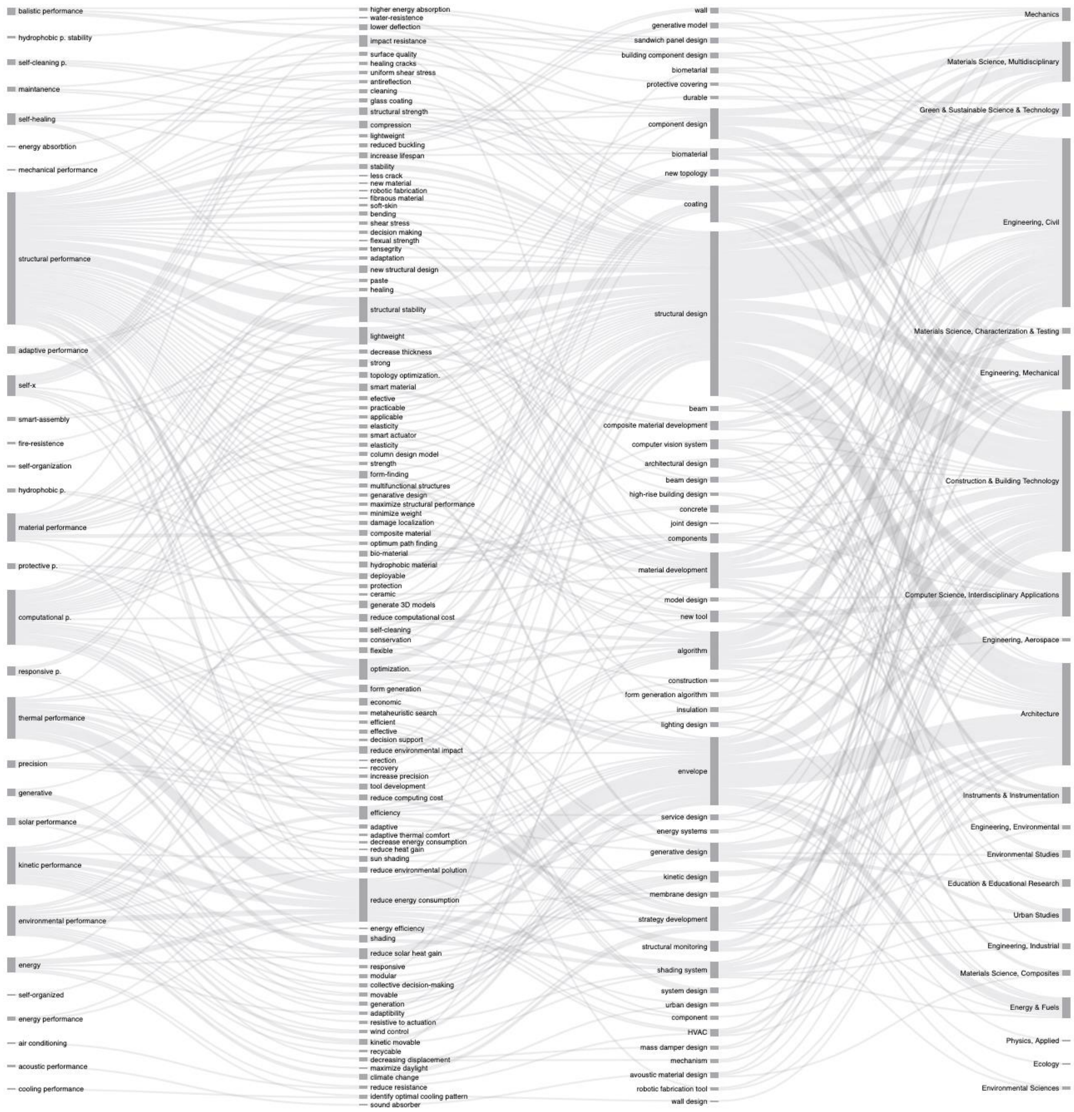


Figure 2.28. Target: Performance, Objectives, Problem and Field

Among many performances stated in these studies, structural performance is become obvious, targeting optimization, efficiency, stability, lightweight and resistance. This rich topic adapts the feature/behaviors/principles of nature into to building structure, components, cement-based development, and material studies which becomes a subject of “Architecture”, “Construction and Building Technology”, “Material Science”, and “Computer Science”.

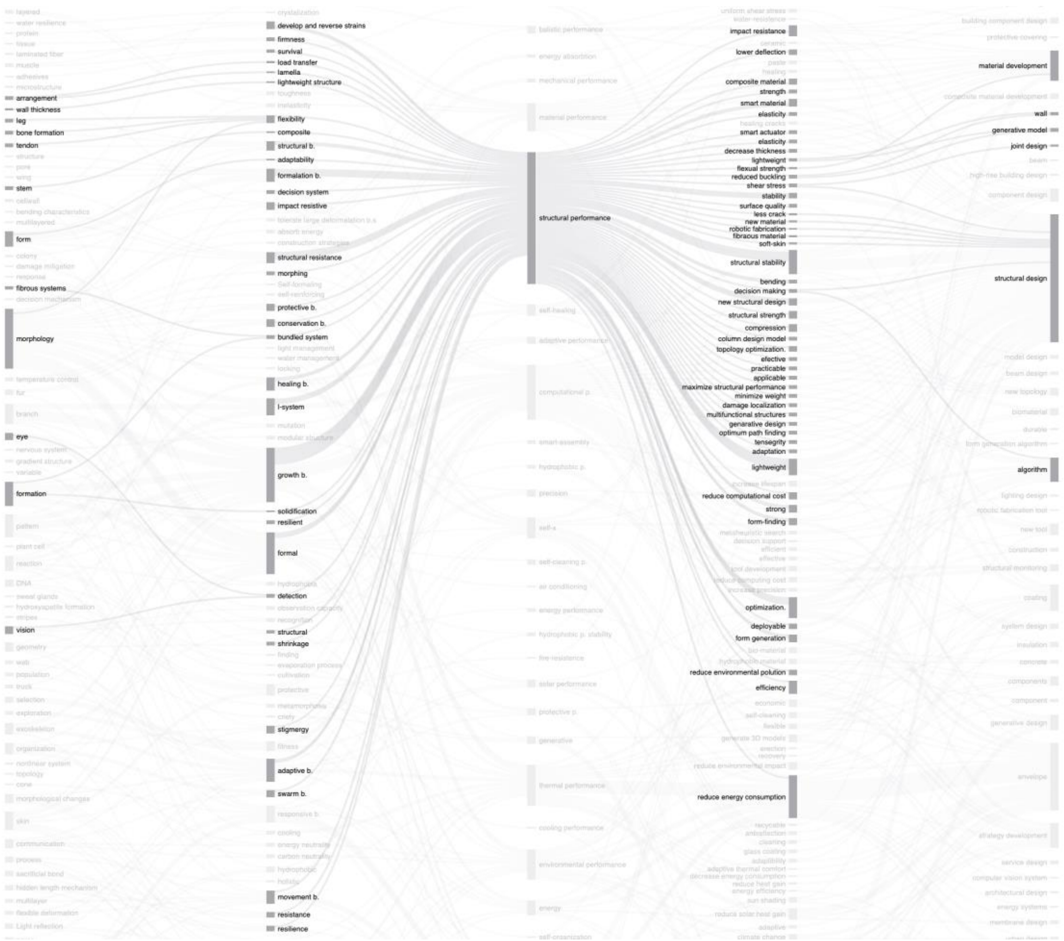


Figure 2.29. The most targeted performance: structural performance

2.4.2.3 Information Transfer: from Behavior to Performance

Relating two different discipline requires a requires a *precise* mapping process among domains having different scales. As this relation can be constructed in many different levels from feature to behavior, in most of the applied fields, this relation is being constructed among behavior of the being and the targeted performance. Therefore, in this part, the existing relations between the observed behavior and the targeted performance is presented Figure 2.30.

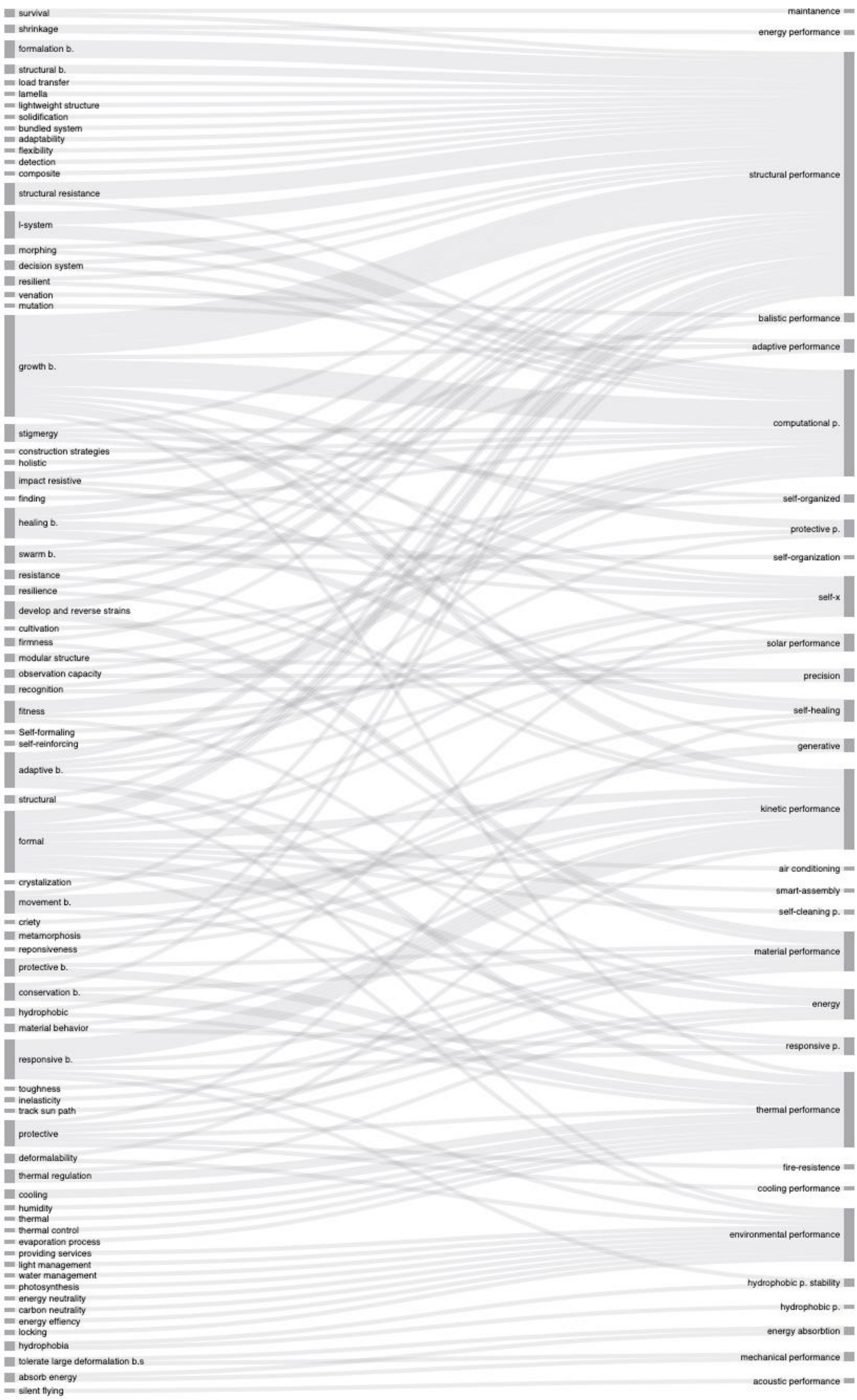


Figure 2.30. Information Transfer: from Behavior to Performance

In this transfer, one of the most important acts here is defining the similarities, correlations, and source of information. The relation to be constructed there works as a catalyst between the datasets of each domain and creates a flow. Yet, in these studies, this relation is mostly referred as an inspiration and the transfer process is not explicitly defined.

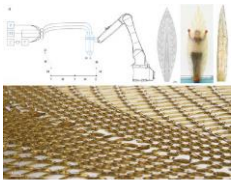
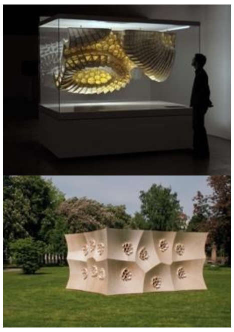
2.4.2.4 Results

It is well-known fact and also literature shows us that today, there is a tremendous amount of research related with learning from nature in different fields from engineering to medicine. Yet, revisiting the literature with the quantitative data and related context has the potential to initiate a new discussion linked to the methodology. The data retrieved by constructing the relations, decoding the studies and categorizing them has a great importance on understanding the current methodologies and drawbacks. In this part of the study, literature is revisited to answer new research questions about the relationship between the mapping process and the different approaches. The data retrieved from the Web of Science database is studied to show the interrelations and discrepancies of approaches, contexts, and concepts, in order to discuss and develop the methodology of the thesis. The outcomes are presented by means of a network map and a flow diagram to reveal the related patterns, existing and potential relational paths. As a result, it is seen that most of the studies have similar paths for learning from natural principles regardless of referred strategy like biomimetic, bioinspired, bionic, biomimicry and geomimetics.

This study also confirms the need for a general methodology defining all the significant phases, and functions not only by studying biotic part of nature, but also the less-explored knowledge of abiotic nature. Also, the devised template which is adopted to examine the current studies proved its validity to define a process from a reference to a problem for nature-informed studies. Therefore, they will be included in the following model development as the phases of this information transfer.

Consequently, it is revealed that in nature-informed studies, the targeted information transfer can only be possible by conceiving nature not only as a model, but also as a supervisor. Considering the existing studies, at first, there are two distinct ways to transfer the knowledge; (1) Implementing the natural material as it is: Biomaterial and (2) Mapping features, behaviors, or models. There are many examples for both approaches, some of them are presented in Table 2.3.

Table 2.3. Some of the examples for biomaterial and mapping studies

Biomaterial		**Mapping (feature, behavior, model)**	
	Silk Pavillion, 2013, MIT Media Lab, retrieved from http://matter.media.mit.edu/environments/details/silk-pavillion#prettyPhoto on 25.08.2016		Tree-shaped columns of Stuttgart Airport, designed by von Gerkan and Marg. Retrieved from http://www.gmp-architekten.com/projects/stuttgart-airport-terminal-3.html on 04.12.2016
	Bio-Plastic Column, MIT (Soldevila, Royo and Oxman 2015)		“HygroScope” and “HydroSkin Pavilion”: Adaptation of hygroscopic behavior to two distinct scales; and environmental conditions
	Hy-Fi, The Organic Mushroom-Brick Tower retrieved from http://www.archdaily.com/521266/hy-fi-the-organic-mushroom-brick-tower-opens-at-moma-s-ps1-courtyard on 25.08.2016		(1) Tunnelling termites are masters at creating air exchange systems to ventilate their mounds (Credit: Bill Bachman / Alamy Stock Photo), (2) Eastgate centre in Harare, Zimbabwe.

For biomaterial approach, architecture found a way of dealing with scale problem in the mapping process referring to nature in 1:1 scale by adopting the physical, mechanical or growth behavior features either by co-fabrication or incorporating organic material itself. As one of the groups working on co-fabrication, the research group in the lead of Neri Oxman introducing a holistic approach is taking attention with approach nature in different scales and transferring not only the inherent information but also the material itself. Among these studies, *Silk Pavilion*, *Silk Pavilion II* and *Bio-Plastic Column* are gained attention with their usage of natural material and material production processes. Both studies approach to nature as a whole; material, form, structure, and construction and producing in the same manner. *Here, it is not possible to discuss the joints as intermediate elements, nor the inner and outer structure.*

A similar approach to natural material use is also seen in Hy-Fi: The Organic Mushroom-Brick Tower which is *the first large scale structure to use this mushroom brick technology adapting growing mushrooms in the form of bricks and using them as regular bricks* (Stott 2014). *Although this research provides an insight of approaching natural material with its all properties, the usage of elements is still conventional.*

Although these studies overcome the scale difference by preserving the very same scale in their implementation, their understanding of nature as a whole is a guide of many other researches looking for such idea. *Learning from nature brought its idea of being the whole. Thus, we can discuss emergence, morphogenesis instead of them.*

On the other hand, there is even a larger number of studies focusing on information transfer through mapping the features or behaviors of the reference being in nature through similarities found between nature and architecture. Among them, learning from the strategies to build a nest which can also be called as animal architecture, formal similarities, and behavioral mimicking examples can be listed as mostly acknowledged ones.

Initially, as one of the pioneering examples, the roof of the Stuttgart Airport Passenger Terminal, Germany (1996) designed by Meinhard von Gerkan is taking attention with its tree like columns transferring the load of the roof to the ground in a hierarchical way. This hierarchy is an outcome of a mimicking process from structural stability to the search for an architectural one. Then, Eastgate Centre designed by Mick Pearce in Harare, Zimbabwe in 1996 is taking attention by modelling the self-cooling mounds of African termites for less energy consumption (Doan 2012). Application of similitude theory in thermodynamics is highly advanced, there should have been more examples like Eastgate Centre based on modelling, analysis, and simulation. The main achievement of Eastgate Center, in the context of this study is referring to an animal architecture constructed in the same challenging context, and adapting the performative features from a smaller scale into the architectural one.

As a result of collaboration of ICD: Institute for Computational Design and Construction and ITKE: Institute of Building Structures and Structural Design, there is a series of studies studying the behavior of natural materials to map this information to larger scale buildings. Among them, HygroScope: Meteorosensitive Morphology (ICD), and "HydroSkin Pavilion" present a method for biomimetic transfer of the hygroscopic actuation of plant cones by means of an integrative, no-tech strategy following biological principles (Reichert, Menges and Correa 2015). In this example, adopting the features and the behavior of natural material to study the responsiveness of a building according to its environment is presented by referring the same phenomenon, the group proposed two projects in two distinct scales responding to different parameters.

In this context, all the examples presented above show that there are several ways to approach nature in different scales. The concept and understanding of scale in this field plays a decisive role in determining the position of nature as model, mentor, and measure and thus the future of nature-informed studies. In this context, scale is embraced not only as a measure, but also the measure of complexity that plays an important role in this transfer.

2.4.2.5 Remarks

This survey shows that nature-informed studies are becoming more and more popular. There are many examples especially in the last two decades dealing with similarities between a reference and a problem. It is seen that all these examples are succeeded to adapt the natural aspects that they have sought by defining the problem with non-dimension parameters, in other words by means of the relation between the force and the form. In this thesis, it is seen that there are two main strategies to adopt and learn from the nature's knowledge with various approaches:

1. Adapting strategies: Biomaterials
    a. Co-fabrication
    b. Incorporating natural material
2. Information transfer scales
    a. Feature
    b. Behavior (multi-feature)
    c. Model

Although there is an abundance of nature-informed architectural studies, current examples adopting the most popular approaches are found limited with their scope, methods and use of data to inform the problem area that this thesis is focusing on: extended design processes encapsulating design, fabrication and construction parameters, constraints and concerns. Therefore, following issues located in the literature are addressed in the following chapter.

2.5 Discussions: Role, Motivation and Goals of Architecture

Despite growing number and variety of studies, it is seen that most of these studies are focusing on biotic part of nature and mostly the flawless behaviors. However, considering architecture as an area in abiotic nature with countless defectious behaviors, abiotic part of nature needs to be acknowledged as well as defects. Here, especially defect formations in nature are taking attention with its formation and handling mechanisms. On the other hand, with increasing amount of data in both nature and architecture and advancements in data management, modeling and simulation, this information transfer needs to be reevaluated and defined in this context. Therefore, in the scope of this thesis, the potentials of abiotic nature and defects, and a new approach to the process of information transfer are found valuable to be studied more in the realm of nature-informed studies.

With the advents in technology, abundance of accessible data, tools and mediums accessible by architecture at one hand, environmental issues like depletion of resources, and natural disasters, new challenges at another hand, have force architects to find new ways of making and designing which have a broad impact on buildings. Today, designing a building is a holistic and interdisciplinary act which uses computational design in generating form to making in every scale which alter the topologies and determine the performance. Performance co-exists with sustainability which started to include not only design but life and after life cycles for which recovery/heal from failure becomes a design concern. Besides the changes that is witnessed in architecture, in larger scale, cities are changing rapidly and prediction of growth (or shrink) phenomenon in urban planning necessitates more dynamic multi-dimensional models. None of these issues can be isolated from each other and they have been always challenges/responses of architects. But starting from 1990s, today, with the second digital turn and beyond, like many other disciplines, architecture is also introduced with the concept of big data providing "data opulence" (Carpo 2017) and forced to find its own way to deal with this bulk and incorporate it in the design.

In the context of the built environment, the concept of Big Data which is a bulk of data (or data deluge) transforms the approach towards the understanding and use of data along with the definitions of model, complexity and the system. As this data can be related with the design or construction process, it can also be used to "map, measure and quantify the intangible – aspects of the human experience" (Karandinou 2019).

In this context, these three essential problems: generation, recovering and predicting have attained a new phase in terms of data- collection, management, modeling and design. In addition to that, in nature-informed studies, data of a natural being/system comes into scene and calibration of the data of both nature and architecture becomes one of the tasks to achieve the targeted information transfer. In this vein, rethinking motivations and goals of architecture in the search of information in nature is crucial not only to define its role in NiA, but also to discover the potentials of natural beings as references.

Firstly, the search for new ways of generation is required to be mentioned in different scales, from building elements to buildings itself, and even in the urban design (Figure 2.31). The facilitator role of computational design tools is vital in the search of new forms, systems and spaces in the last three decades. In this quest, nature is more and more referred as the source of innovation and to develop novel designs.

Figure 2.31. (1) ArboSkin pavilion by ITKE, (2) Libeskind Residences in Milan, (3) Masterplan featuring water cascading down towers of arches Sou Fujimoto (retrieved from https://www.dezeen.com/ on 23.11.2020)

Built environments encompasses existing and newly developed areas, buildings, or regions bringing the sustainability as a critical issue for which existing buildings become a major concern. Improving their performances, prolonging their lives, maintaining and repairing them, preventing defects or repurposing them are the subjects of interest for architects and for other actors of the built-environment. The challenges encountered in old buildings encourage architects to develop new design strategies even in the early phases of the design for new and future buildings. In this sense, nature which provides excellent examples of healing, recovering, regenerating, growing is being referred more and more.

Figure 2.32. (1) Building Raincoat prototype for smart city in Toronto by Sidewalk Labs (retrieved from on 23.11.2020), (2) Demolished building after İzmir Earthquake in 2020 (retrieved from https://www.aa.com.tr/ on 23.11.2020), (3) Cracks in Plaster/Masonry Walls (retrieved from https://www.civilax.com/ on 23.11.2020)

Advents in simulation programs and machine learning applications make **prediction** of behavior of buildings or built-environments, their features and more, a common practice giving feedback to the design and/or planning at any stage of the design process. This makes possible to design more resilient buildings and/or building systems, or planning where strategies to prevent failures, defects, growth patterns are integrated and embedded into them. As one of the examples showing the potential of prediction, Marrakesh project run by José P. Duarte which adopts shape grammar to understand and predict the development of a complex city pattern to develop further strategies (Figure 2.33) can be given (Duarte, Rocha and Ducla-Soares 2007).

Figure 2.33. Partial generation of the Zaouiat Lakhdar based on the shape grammar rules found and adopted by Duarte et.al. (Duarte, Rocha and Ducla-Soares 2007)

The use of advanced computational technologies not only change the buildings but also construction. Today construction is not confined only in site, various industries, several different production technologies, materials from all over the world is involved. CAAD, CAM, BIM, GIS, ML models and more are becoming must in dealing with such new complexities and they are becoming integral part of the practice. It is seen that today design and construction are becoming simultaneous processes due to the continuous feedback between them. This simultaneity brings the problem of synchronization among those two processes. Thus, an adaptable, flexible, agile design models and appropriate construction strategies should be devised. The search for such approaches which are called **extended design** methods is also a concern in this thesis. It is believed that nature can provide a good insight in this search, and thus, architectural applications can be informed in that sense.

In this vein, today, interest on “unsupervised” construction applications on each stage namely site preparation, substructure and superstructure started to be increasing following the research operating in controlled laboratory environments (Melenbrink, Werfel and Menges 2020). As this growing interest can be seen as a result of accessibility of robotic arms, UAVs and automated heavy machinery, it brings number of benefits such as preventing injuries of the workers, and increasing precision and speed of the construction. In this context, the role of architects started to include not only the design of the product but also the design of the generation and construction process. In other words, for the upcoming period, architects are required to be designers, programmers and supervisors of the automated construction processes. Considering this new challenge includes the management of automated machinery, and developing, designing and training the construction ecosystem involving resource management, production, fabrication and assemblage, new approaches are required to be explored. In this sense, nature is a great source of information that already manages complex systems, and processes.

On the other hand, considering the increasing control of designers on both the design and the construction processes, it is not possible to name this process that this thesis is proposing as an unsupervised, instead, it is preferred to be defined as ***under the supervision of nature***. Thus, the data collected from nature transforms/informs/regulates the data of design processes to create an informed process design.

Apropos general problems outlined above; this thesis is focused on the following problem areas that can be informed to develop new models for architecture. These cases focusing on the design and construction processes as a whole are path finding for robotic additive manufacturing, a generative tool enabling designers to design new building blocks based on crystal symmetry and optimization of module parameters to occupy maximum space in a given boundary.

On the search for these problems, the proposed new approach which is called nature-informed architecture, terms defining this approach and proposed process structure is introduced in the next chapter and exemplified with case studies on crystal formation. Crystal formation is believed to be a viable source of information for architecture in many scales to demonstrate both feature and model transfer processes.

CHAPTER 3

POSTULATE

"The form, then, of any portion of matter, whether it be living or dead, and the changes of for which are apparent in its movements and in its growth, may in all case alike be described as due to the action of force. In short, the form of an object is a 'diagram of forces"

(Thompson 1917)

In this thesis, a new holistic approach named Nature-informed Architecture (NiA) is introduced to define the information transfer from nature to architecture including biotic and abiotic nature as a source of reference with their either flawless or defected features and behaviors as a supervisor.

Today there is a need for new ways to design in order to generate, recover and predict in a holistic and synchronized way as mentioned in previous chapter. Therefore, in the scope this thesis, some of the answers of these questions are targeted to be searched in nature. Yet current approaches and proposed methods are found insufficient on this search regarding the data deluge of both disciplines.

Hence, considering the abundance and complexity of available data, current technological developments, computational design approaches, the resulting computational models turn out to be more intricate and a new approach towards models and act of modeling becomes a necessity. Therefore, NiA does not solely propose a new comprehensive perspective, but also proposes a new transfer learning model (TLM) with explicitly defined phases through the transfer/transformation of data.

Nature has always played an important role in the development of humankind in different ways. On the other hand, how nature is perceived varies and this variation has been reflected back to its definition. The incorporation of nature in architecture has also shown such alterations in understanding nature. In general, there are four definitions of nature that are mostly acknowledged in the literature:

1. *"The whole of material reality, considered as independent of human activity and history"*
2. *"The whole universe, as it is the place, the source* and the result of material *phenomena (including man or at least man's body)"*
3. *"The specific force at the core of life and change"*
4. *"The essence, inner quality and character, the whole of specific physical properties of an object, live or inert"* *(Ducarme and Couvet 2020)*

In this thesis, nature is acknowledged as a universal entity that does not preclude human activity, and thus architecture. Also, among these definitions, it is believed that approaching nature as a "force at the core of life and change" is crucial to understand features, and behaviors in nature including our own. Therefore, in this thesis, nature is acknowledged as the whole universe whether animate or inanimate including manmade with respect to the forces at the core of the existence.

In nature-informed studies, current approaches mostly mystify nature and they tend to isolate a being, feature or performance as an entity rather than a part of a whole. Especially in many studies, this approach is seen as learning from the best version/moment of a reference found in nature and mostly the biotic part is favored to be referred as a mentor. However, nature needs to be acknowledged in a holistic way. Thus, referring both biotic and abiotic nature with even their defected states are as valuable as others for a number of challenges in many disciplines as well as architecture.

In architecture, among many challenges, there are three major ones leading this study towards a new research: (1) the future of responsiveness, (2) the necessity of resilience and (3) the potential of fitness.

Among these challenges, responsiveness is not a new subject in architecture, on the contrary it has been discussed since late 60s (Negroponte 1970), yet approaching responsiveness along with the environmental forces due to increasing interest on global warming and climate change and more become significant and inevitable for architecture. Today, responsiveness becomes more than the ability of change but a way to preserve/produce energy as a part of an architectural design. In this context, embracing nature's principles (Benyus 2002), and solutions has attained a new meaning along with current data processing tools, and technologies. In this context, the information in nature needs to be covered as a whole system including morphologies, forces, and reactions.

Resilience, on the other hand, is coming in sight as a relatively new subject

> *"Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist."*
>
> (Holling 1973)

In the search for persistence, learning from nature, especially from its responses towards changes is a valuable source to react, adapt, and resist; to be resilient. Therefore, the defects of both biotic and abiotic nature along with ordered/perfect patterns holds a great potential to understand and adopt novel strategies of nature.

Fitness is another relatively new issue for architectural design "the negotiation of several fitness criteria" in multi-criteria systems (Menges 2012) aiming efficiency, performance, adaptiveness and responsiveness (Öztoprak 2018). In biology, fitness is defined "as complex dispositional property of organisms" referring being an inhabitant, survival and reproductive in an environment (Mills and Beatty 1994). The goal of architecture for its creations are not different from it, moreover it is mostly a search for a system capable of producing many entities that will fit various environments. Therefore, the information of how nature succeeds to create beings to fit different environment through adaptation, responsiveness and being able to reproduce can be obtained from the strategies of fitness not only to survive but also to adapt itself.

To sum up, conceiving nature as a whole with its various biotic and abiotic beings and perfect and imperfect features, behaviors and patterns is instructive for architecture on the search for novel ways to create, exist, respond, resist, fit and as a result, to reproduce.

Therefore, this part of the study is dedicated to a two-fold discussion including the potentials of disregarded parts in nature: abiotic nature and defects, and the need for a new extended model approach.

Accordingly, this study aims to bring the neglected/missed potentials of nature e.g. abiotic part and defects forward. Therefore, the first two parts of this chapter are dedicated to the exploration of nature's such neglected/disregarded parts containing valuable information that architecture can benefit of. Defects in this context have an important role in understanding the lifespan of any natural being and the abiotic nature. In the third part of this chapter, model definition is re-examined as an actor of the information transfer process from nature to architecture in relation to data and data modeling. Hence, a novel model is proposed for information transfer from nature to architecture as a transfer learning model (TLM) similar to its definition in machine learning literature which is a model being trained under the supervision of another model. This model, not only provides a template for NiA, acknowledging nature as a supervisor, but also incorporates scale understandings in a broader level, as a measure of complexity, and similitude as a tool enabling targeted data transfer.

3.1 Abiotic Nature

As it is shown, most of the nature-informed studies are focused on biotic part of nature and there are few studies dealing with abiotic nature named as geomimetics or geomimicry. Yet, there are many studies claiming and proving that nature works as a whole and dynamics are not that different in biotic and abiotic nature.

Constructal Law introduced by Adrian Bejan states that nature works with same physical laws both for animate and inanimate nature (Bejan and Zane 2012).

Animate and inanimate nature reacts to forces of their environment in a similar manner which architecture is also seeking for. The exemplary study of Philip Ball shows that abiotic subjects have great potentials that should be examined, and analyzed, to predict and generate the built environment, and biotic and abiotic nature is not that much different from each other, and they form the ecosystem together (Ball 1999). As it is shown in Figure 3.1, systems in biotic and abiotic nature like the generation and growth of geographical formations and our lungs behave similarly depending on natural forces as it is in engineering and architecture. This relation can be explained by Geometric Similarity which is one of the similarity types that can be established between two different scales. These similarities are described with models that provides non-dimensional patterns based on the behavior of the being/design/artifact according to the forces. Thus, the potential of abiotic nature manifests the urge of reconsidering our reference preferences that we are aiming to learn from.

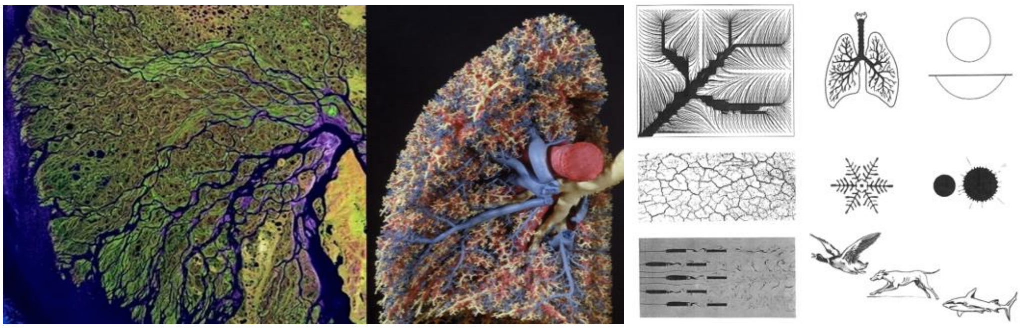


Figure 3.1: (1) Flow systems in action: the delta of the Lena River in northern Siberia (left) and a cast of a human lung (right). (A. Bejan/Doubleday) (2) Design generation in nature: river drainage basins, bronchial trees, round duct cross-sections, and open channel cross-sections, cracks in shrinking solids, dendritic solidification, and splat vs. splash, laminar vs. turbulent flow, and animal locomotion (Bejan and Lorente 2011)

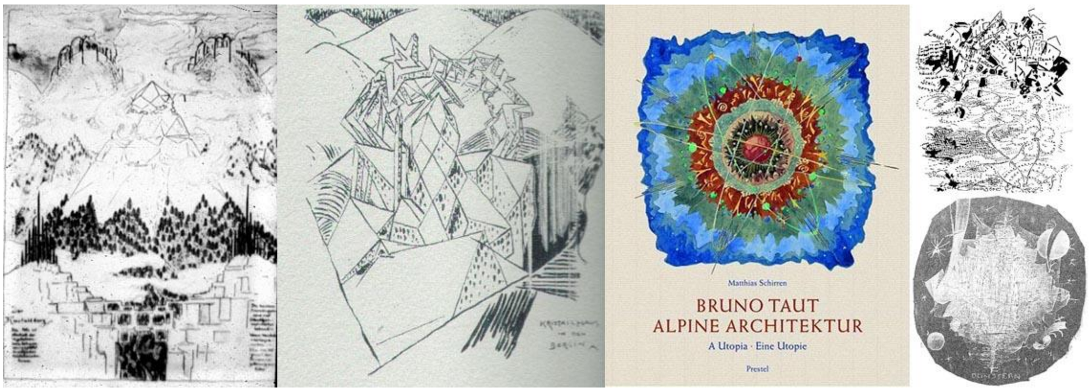


Figure 3.2. Book: Alpine Architecture: A Utopia (retrieved from http://archurbanist.blogspot.com.tr/2008/09/geo-mimicry-2a-beginners-begetters.html on 09.05.2018)

On the other hand, learning from abiotic nature is not a new concept in architecture. Hanging structural model of Antoni Gaudi and book of Bruno Taut describing a utopian city (Figure 3.2) are still the valuable examples showing the potentials of understanding the role of forces on the forms in architecture. In Taut's unrealized drawings and explanations, a new city and architectural approach is proposed based on the geographical formations formed by the natural forces. The drawings created between 1917 and 1920 shows the influence of inanimate nature in his works, also explains the crystal inspiration on Crystal Pavilion (1914) (Gomel ve Weninger 2004). Both the utopian drawings and the pavilion can be seen as the explorations of the influence of environmental forces both on nature and the architecture.

Also, works of Vinci, designs of Nervi, Frederick Kiesler's Endless House (1950) (Sveiven 2011) Soap Experiments of Frei Otto, and structures of Calatrava can be counted as significant examples for learning from inanimate nature. They all succeed to develop novel solutions to cope with the forces of earth, by learning from both living and non-living nature. Among them, especially in Otto's studies, the resemblance between animate and inanimate nature is pointed by the concept *"The "pneu" as an archetype of living nature* and *"net-pneu" with liquid membrane"* (Burkhardt 2016) as seen in Figure 3.3. Today, the continuation of this approach shows itself in tensegrity bridges, formworks etc.

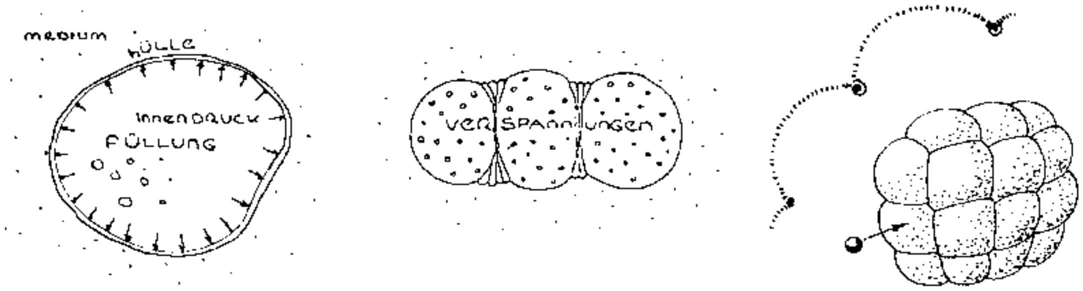


Figure 3.3. The “pneu” as an archetype of living nature (left); “net-pneu” with liquid membrane (Burkhardt 2016).

Many contemporary examples are seemed to be limited with formal approaches like biomorphic ones. However, approaching nature only through living organisms is found to be underestimating the potentials of balance between animate and inanimate nature.

Consequently, this study aims to broaden the extend of nature-informed studies by re-introducing inanimate nature with environmental forces that effect the formation and behavior of the beings to learn from their lessons.

Here inanimate nature is acknowledged as important sources of information with their great potential in architecture. More specifically, unlike biotic nature, the formation mechanisms in abiotic nature are dependent on inherent structures and codes as well as environmental forces rather than properties peculiar to living nature like enzymes, and reactions. Therefore, transferring the behavior of abiotic being to architecture will become more comprehensive.

In the scope of nature-informed architecture (NiA), comprehending the natural system as a whole with biotic and abiotic beings and also its inherited and external relations and its changes over time provides valuable source of information. Therefore, considering the holistic nature of proposed approach, defectious behaviors of both biotic an abiotic nature is also encompassed in the scope of NiA.

3.2 Defects in Nature

In addition to abiotic nature, defects and defectious behaviors existing in both biotic and abiotic nature are often prescinded and are not admitted as a source of information. However, defects which are the changes in the regular features or behaviors of any natural entity as a response to its surrounding forces is one of the fundamental aspects for the ability of being to be adaptable, responsive and resilient. Defects that are seen in nature are mostly observed as interruptions in the existing patterns exhibiting ordered arrangement/behaviors/growth. It is possible to find similar types of defects in both biotic and abiotic nature as shown in Figure 3.4.

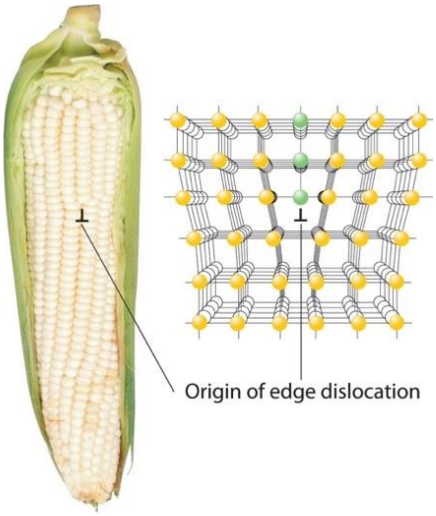


Figure 3.4. Edge Dislocations (Averill and Eldredge 2007)

It is a fact that each of the natural beings is a complex system showing “a complicated mix of ordered and disordered behavior” (Johnson 2009). In understanding these complexities, and growth phenomena, **patterns** in different forms and scales serve as valuable tools to decode and recode information from one domain to another. In nature it is not a surprise to find geometrically well-defined patterns like hexagonal honeycombs, spiral seashells, branching fractals of trees and leafage, molecular distribution and lattice structures of crystals helping to define growth and generation. These patterns can be found in both two and three dimensions in different scales.

The complexity of patterns is not only limited with the ordered behavior of the natural beings, but any disordered behavior that can emerge from the ordered one is a part of the information embedded in the beings, e.g. in its patterns. As it is mentioned before, in this study, nature is aimed to be acknowledged as a whole, and thus, disordered behaviors and the resultant defects are taken into consideration.

Similar to corn example, it is possible to show the relation between pattern and defect in the morphology of a tree trunk as illustrated in *Figure 3.5*. The growth of a tree can be followed by the section of a tree trunk by symmetrical growth rings. Any defect in these ring patterns in relation with the environmental forces caries more valuable information regarding the resilience and survival mechanism of the tree than the regular ring patterns.

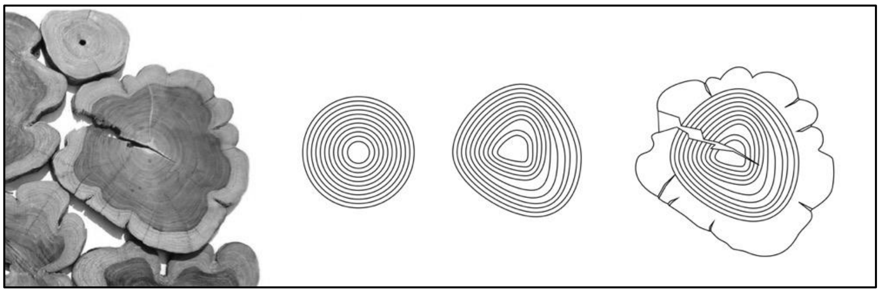


Figure 3.5. The tree trunk morphology from symmetrical configuration towards a defected responsiveness (image is retrieved from https://www.worldwildlife.org/magazine/issues/summer-2014/articles/the-inner-life-of-trees on 05.11.2019 and diagrams are drawn by the author)

Defected behaviors can be observed in various natural beings from animate and inanimate nature such as cells, organs, plants, or crystal formations. It should be noted that the reason of defects may vary, but the results do not always bring undesired outcomes for the being as in the case of cells.

> *The capacity to adapt to changes in the external environment is a defining feature of living systems. Cells can rapidly adapt to familiar changes that are commonly encountered in their native habitat by sensing the parameters of the environment and engaging dedicated regulatory networks to establish adaptive gene expression. However, dedicated*

sensory and regulatory networks become inadequate, or even detrimental, when cells are exposed to unfamiliar environments that are foreign to their evolutionary history. In principle, at least one gene expression state that maximizes the health/fitness of the cell always exists, despite the inability of the native regulatory network to establish such a state. This is true because under any conceivable environment, the *activities of some genes are beneficial, whereas those of others are futile or even actively detrimental. In fact, if the initial fitness defect is not lethal, a population of cells may slowly adapt to an unfamiliar environment through the accumulation of genetic mutations that rewire regulatory networks thereby achieving more optimal gene expression states.*

(Freddolino, Yang and Tavazoie 2017)

As in cells, architecture is also required to define its fitness defect enabling it to adapt its changing environment leading to new morphologies and topologies in the search of optimal solutions. Therefore, in this thesis, patterns belonging to natural beings are addressed with their ordered and disordered features/behaviors i.e. with their defects. In this regard, this study regards patterns as the relations providing natural systems to respond, and transform along with the change in the conditions and forces instead of resist against them. In the realm of this understanding, crystal formations are studied as the resilient examples for which patterns, ordered or defected, exhibit great adaptability to changing conditions and "survive".

3.3 Information Transfer Process for Nature-informed Architecture

In the scope of Nature-informed architecture, the proposed model is constructed based on 3 major concepts: mapping, data and models. ***Data*** which is abundant both in nature and in architecture are referred as domain and codomain, ***mapping*** is the act to enable data transfer and ***model***s are redefined as active figure to be supervised and trained. In the scope of NiA, as it will be explained below, nature is the primary data pool which actually supervise the model in architecture to achieve targets/goals in relation with the given problem.

In this exploration, properties of nature like relations, pattern, symmetry, scale as the essential actors and factors of mapping process and also as the features of data and assessment criteria like **complexity**, **precision** and **accuracy** are discussed and included in the scope of proposed model. Instead of an outcome, model is acknowledged as an **exploration** itself as a structure holding different bodies, sub models together and regulates the process which this thesis is also seeking for. Act of modeling is considered neither linear nor strict. In relation with this understanding, nature-informed architecture studies are defined with data models that is being constructed, transferred and trained. Hence, the definition of model shifted from the constructed to ***predicted/trained/enhanced.***

Therefore, different definitions of aforementioned concepts from various disciplines are included in the process definition of nature-informed studies. In this respect, along with a new model definition for NiA, a novel transfer learning model (TLM) aiming to enable the information transfer from nature to architecture is proposed which will also be exemplified with case studies presented in the following chapters.

3.3.1 Mapping and Data: Nature x Architecture

In nature-informed architectural studies, information that is inherent in the domain (nature) can be mapped into codomain (architecture or artifact) and this process is not always bijective, in other words, in nature-informed studies it is not possible to presume a direct transformation of information from one aspect of nature to the one in architecture. Since ***mapping*** in its broadest sense, is admitted as the method of forming relationships between different domains, nature-informed studies can be regarded as mapping processes relating data of different domains which can only be executed via multi-dimensional models. In this way, the knowledge of nature and architecture can be juxtaposed in different ways in the context of Nature-informed Architecture (NiA).

Subsequently, comprehending and defining the sets that contains data related with each domain become a critical task in this process. Here, in relation with the discussions in 3.1 and 3.2 taking nature as primary data pool, then nature is defined as the universal set (U) in which both reference and target fields are situated in. Following this definition, the set containing a data related with the reference being/entity/group/system is referred as *Domain (D)* and the set holding, and parameters related with objectives, constraints of a given problem is called *Co-Domain (C)* which represents the problem itself.

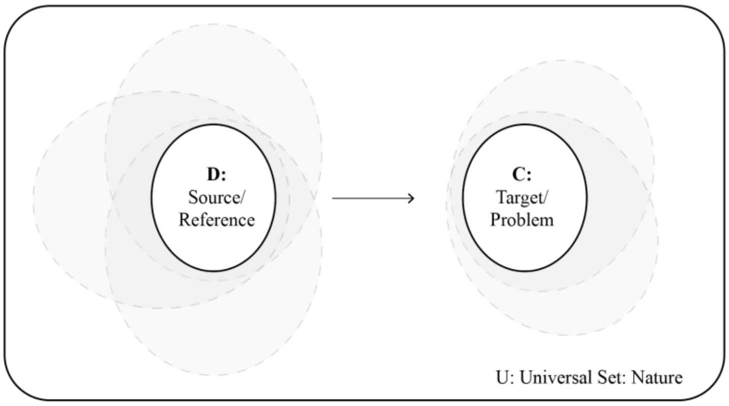


Figure 3.6. Diagram of relationship between source and target (drawn by author)

The collected data defining the source/reference and data of the problem of interest can be related with different research fields. Hence almost all these studies inherit a multi-disciplinary nature. For instance, when crystal growth is considered as the source, data of it can be found in material sciences, physics, or crystallography literature, and similarly structural design as a problem area can be studied by architecture and/or civil engineering and more. Therefore, the definitions of domain and co-domain should not be confined in a specific field, instead it requires to collect and calibrate data from various sources.

In general, the relation that is being constructed in nature-informed studies takes place between these two subsets which contains captured data of their supersets which are research areas. Constructing these datasets has a great significance for precision and accuracy of the mapping and thus determining the success of the transfer process.

In order to capture the relevant data and construct a meaningful dataset that can inform the problem area in the target domain, information transfer requires to define reference and problem sets carefully and precisely. The notion of ***precision*** *here* is defined in reference with its definition in engineering which is to be neither over simplified, nor over complex, in the way it should be to ensure that they are in comply with each other (Scheurer ve Stehling 2011).

Considering the ***accuracy*** of datasets, defining domains without using proper or specific terminology of its own/original domain, or defining one with the other's terms is a common mistake that is encountered in Nia. This is actually be a disadvantage while searching for fitting references in nature to find similar features among the reference and the target. In other words, each domain needs to be defined and examined with its own terminology revealing the related information of data and its complexity. Only then the scale difference i.e., asymmetry among data sets can be seen and tackled to set relations to be constructed.

It should be noted that in nature-informed studies, the facts collected from domain and ones selected from the problem area are not impromptu, instead they are the intentionally captured data to inform the process satisfying the objectives of the problem under the supervision of the natural reference. These selections are the initial decisions designating not only the information to be transferred but also the precision and the scale of the transformation process. Since nature provides an enormous amount of data, it is a challenge to observe, gather and model the relevant data. In the proposed template, the data retrieved from both sets are called **Capta**. The importance of capturing data stands as a critical phase of information transfer determining the success of process. Determining the capta makes the process data-driven from the very initial stage of the design.

The act of defining Capta is referred in Biomimicry Design Spiral as “Identify” (Benyus, Biomimicry Primer 2014), and included in Bottom-Up process in between “Biological Research” and “Biomechanics, Functionality, and Anatomy” (Knippers ve Speck 2012). However, in this study, defining Capta comes into scene as the first act of the data transfer, defining the reference set (D) and the problem set (C) in a recursive way.

The members of *domain* (*d*) that are found in the reference set (*D*) are the collected raw data. They represent facts/features that can be incorporated in nature-informed studies through models. Their precision should be in accordance with the problem to be informed. The set of data that form the model is represented in a separate set (D’). Similarly, the objectives and constraints (*c*) are defined as the members of problem set (*C*). With these given parameters, it is possible to define the informed parameters (*c’*) and the solution set (*C’*). Defined relation is presented with the following transfer function and the diagram as below.

$$C'(D',C) = \{f(d'_i, c_j) \mid d'_i \in D', c_j \in C\}$$

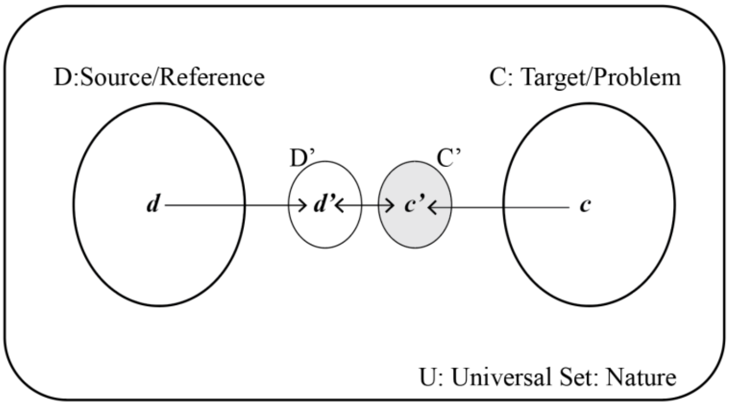


Figure 3.7. Visualization of data mapping between domain and codomain

As it can be followed from the transfer function and the diagram, Capta of both domains are playing important roles to construct a new dataset (C’) which is an informed one under the supervision of nature. Considering both sets (D’ and C’) remains implicit in the strategies of current studies, in the proposed approach, the relations between reference and the designed artifact are defined explicitly with its steps, phases and the constituents.

As it is presented in 2.4.1 Semantic Survey on Literature, the term “data stations” is cooperated with proposed approach to define the datasets that has potential to converge into data paths that enable designer to experience the relationship between reference and the target areas.

In this vein, there is a need for a relation between the parameters defining each domain. Therefore, a set is created with the product of reference and the problem datasets consisting of pairs (or n tuples depending on the subsets and relations) and this relation is explained with the following relation:

$$D' x\ C = \{(t_d, t_c), (b, p) \mid t_d, b \in D', t_c, o \in C\}$$

b: observed behavior of reference
p: targeted performance
t_d*: features of reference*
t_c*: parameters defining objective and the constraints of the problem*

As a result of n-fold Cartesian product proposed above, members of tuples are also datasets containing observed/collected/defined data from each domain and this complex relation can be defined as a n-dimensional relation with included sets. This relation is not only aimed to be constructed among the features, but also in between the models showing the relationships among these features and constitutes the behaviors of the beings.

In this context, first, the definition of model and the concepts stating model are revisited and redefined to reach into the modeling understanding of proposed data transfer process as a part of nature-informed studies. Then, a new transfer learning model (TLM) is proposed where the relations among data and datasets are being explored and the stages of transfer process is explicitly defined based on patterns and relations that can be found in nature as well as in datasets.

3.3.1 Information Transfer Schema

Mapping of features, behaviors and performances has the possibility to occur in different level of complexities (scales), from feature mapping to complex relational mapping. In this context, a new classification is proposed with an ***information transfer schema*** based on how data are incorporated in the introduced mapping process. The mapping processes in this schema can be studied in two categories: ***feature mapping and model mapping***. In the former one, the data retrieved from the features of the reference is tended to be transferred to the features and/or objectives of the problem. This is shown in Figure 3.8

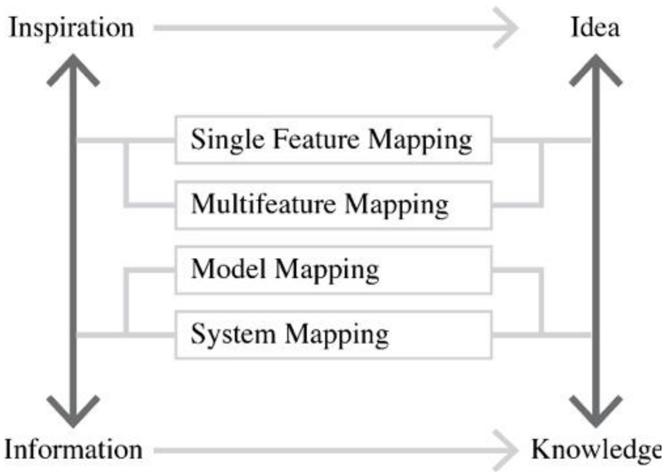


Figure 3.8. Schema proposal based on the data structure to be mapped

Feature Mapping includes single or multiple features to be related. On the other hand, transferring the information included only the features of the reference will has a risk to lack of some information on existing relations among these features.

In the model mapping, features are transferred among domains with their dependencies, coherences, and impacts to each other. Thus, relationships are being constructed between models for the transfer process. Reference domain can include a single model or a system comprised of various models. In this approach, success, precision, level of information in the transfer process is related with the requirements of the problem, captured data in the reference domain and the relation found among them rather than the complexity of the model.

As the transferred features can vary among different studies, the main dimensions defining and also classifying them determines the phases of this mapping process and constitutes an important part in the transfer function that is being introduced in this chapter.

3.3.2 Transfer Learning Model: A New Process Structure

"T an observer B, an object A is a model of an object A to the extent that B can use A* to answer questions that interest him about A." (Minsky 1968)*

Models are defined as constructed, abstract and manageable medium to represent the reality (Scheurer ve Stehling 2011), as an act; "to demonstrate or to show what something is like" (Ackoff, Gupta and Minas 1962), and also as "speculative instruments" having the potential to bring novel hypotheses and speculations (Black, 1962). Considering the importance of models in design both as a part of design process and as the process itself, in the scope of NiA, the model definition is extended encapsulating data capturing, modeling and transferring phases.

In the course of time, models are classified and defined in different ways in architecture and engineering. Initially, they have been categorized as mathematical, analog, qualitative, and engineering. Then this classification is shifted to mathematical, physical (qualitative and quantitative), conceptual models and data models (A. C. Smith 2004). However, today, it is not possible to discern these models with thick lines, on the contrary, the permeability and overlapping of them enhance not only the model as an outcome but the modeling process itself. Besides, the definition of model has already started to gravitate towards a new direction.

Today, models turn to be multi-layered data models encompassing several different information levels such as form, generation principles, fabrication, performance and more. With this understanding, a model is a meta-interface[2] that all the information can be analyzed, experimented in, or generating new ones. Therefore, in the course of nature-informed studies, a novel model is introduced and used for the case studies.

3.3.2.1 Definitions, Actions and Tools

In nature-informed studies, understanding domains is directly related to the ***data*** extracted from these domains which are called capta and the relational models constructed with capta are referred as ***data models***. Data modeling, by definition, is *"a method in which a model represents correlation relationships between one set of data and the other set of data"* (Kim, et al. 2017) to present the included data, the relationships among them, semantics and the constraints (Watt 2014) which coincide with the definition of mapping as proposed in this thesis.

In NiA, considering data literacy of each domain and asymmetry among their data, the definition of model is extended incorporating **data** and its features like **relations**, **pattern**, **symmetry** together with a data model. In this vein, the act of modeling is defined as **mapping** among two datasets as presented in set theory. In this mapping process, **scaling** is proposed as the essential act incorporating **similitude** as a tool to ensure the **symmetry** among these datasets. As defining the model, **complexity**, **precision** and **accuracy** are introduced as the assessment criteria of both the model and the data to be modeled. As a result of these explorations, the resultant model is defined under **data model** as either **rule-based** or **pattern-based model**. This extended definition is represented as a concept diagram in Figure 3.9 and explained below.

[2] Considering each act of analysis, experimentation or generation constituting the modeling process as an interface, models are defined as meta-interfaces managing each part and the whole structure.

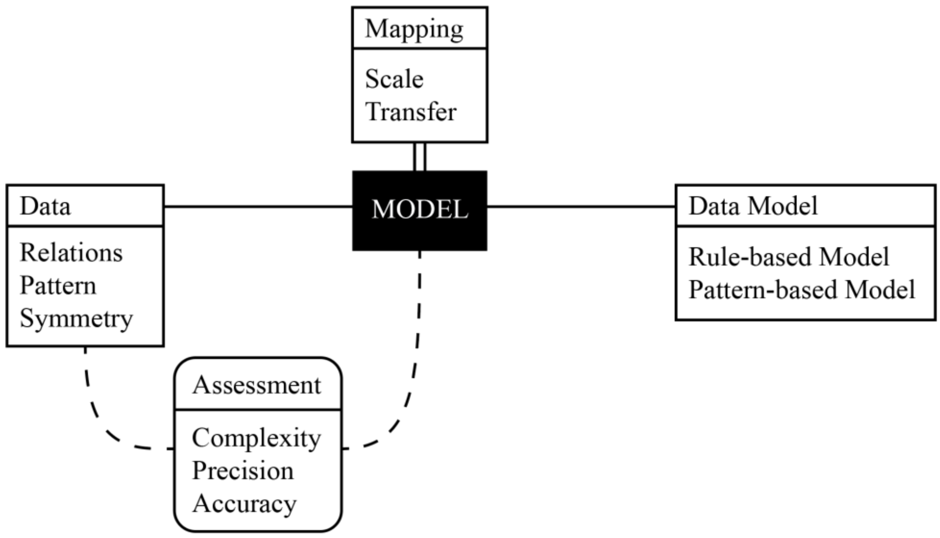


Figure 3.9. Concept diagram of model definition

Not only the information transfer process, but also the outcome of this process is also expected to be a model that is formed according to objectives and constraints of the target domain under the supervision of the reference domain which is nature in this case. This model is not an outcome of a linear process, but rather a ***dynamic entity*** that has a capacity to be ***transformed/trained***.

In this study, the reference model is acknowledged either as a ***rule-based model*** that is constructed with collected data and their relations, or as a ***pattern-based model*** that requires a pattern recognition of features, behavior or system of a reference found in nature or combination of both.

Rule-based models have already been playing an active role in architecture as parametric and generative models. With the abundance of data in architecture both as an input and output, rule-based models become a must for architectural practice. In the scope of NiA, providing rule-based models both for nature which is the reference and for architecture to be trained with the supervision of the reference model.

On the other hand, as Peter Downton defines the relationship between the model and the referent with a shared "pattern of elements and relations" and he associates the notion of ***pattern*** with model and exemplar, these patterns coincide with the information that we are seeking to locate in nature. Moreover, Bateson (1979) refers to the pattern connecting model and the reference as ***meta-pattern***. In the proposed mapping process, meta-pattern is aimed to be formed with the relations between the constituents of natural pattern (behaviors, features, parameters) and the components of the problem area (performances, features, parameters). This approach brings ***pattern-based model*** that entails pattern recognition of the reference and the target. Here, the pattern-based models have great potential to serve as a supervisor and even be used as a reference model of transfer learning application as in machine learning.

Considering the complexity and **asymmetry** of each domain, relating two different models occurs as the most challenging task in nature-informed studies. This challenge is proposed to be handled with few strategies by relating (1) features to objectives, (2) behaviors to targeted performances, and (3) different scales with a non-dimensional approach. Considering the disparity between the scales of reference and target, nature and architecture respectively, in NiA, the proposed model providing a template for information transfer of one domain to the other, eventually addressees the scale phenomenon.

Scale has always recognized as a significant part of architecture in relation with proportion. As Ching (2015) mentioned, architecture has referred to the scale of the inhabitant to design and generate spaces, modules and elements of buildings. Although this approach is as old as humankind, it is still the main concern of architecture; being in a harmony with environment, inhabitant, and in itself. However, today, with developments in the technology and interdisciplinary studies, architecture confronts with another definition of scale. Scale means more than a measure of size or proportion; it refers to the levels of dimension of the information included in both natural and architectural models as a measure of complexity.

In this vein, similitude is proposed in thesis as a tool maintaining the relationship between nature and architecture as domains having different scale, behavior, and complexity. Here, ***Similitude Theory*** allows us to scale form and behavior by reducing the complexity to a bring symmetry into the model and thus mapping process by redefining the scale.

In similitude theory, three similarity criteria are defined as "*geometric similarity*", "*kinematic similarity*" and "*dynamic similarity*" (Zohuri 2015) to achieve similitude. These criteria are acknowledged for nature-informed studies to define the ***modeling*** process. The act of scaling which performs the transfer between domains is an important phase of modeling through defining the rules of transformation. During the scaling process, model becomes less dimension dependent, thus it becomes free of the restriction of physical scale, and it became possible to compare and combine the data sets (Gönenç Sorguç and Arslan Selçuk 2013).

Scaling process requires a precision which is to be neither over simplified, nor over complex, in the way it should be to ensure that they are in comply with each other. Here, the concept of ***precision*** come into scene not only as a drawing or construction accuracy, but also the precision of modeling, and scaling. Thus, the precision of the modeling, and the act of transfer determines the precision of the mapping process. This method has been used in engineering for a long time and it have been employed in applications like planes by modeling fluid flow conditions in hydraulic and aerospace engineering to test the functionality of the model and the prototype. Moreover, in the studies of NASA, this technique is being used for large and "oversize" systems, like tall buildings, dams, bridges, spacecraft, airplanes, and space stations to create similar system called scale(d) model which "replicates the behavior of the actual system (prototype)" (Simitses ve Rezaeepazhand 1992).

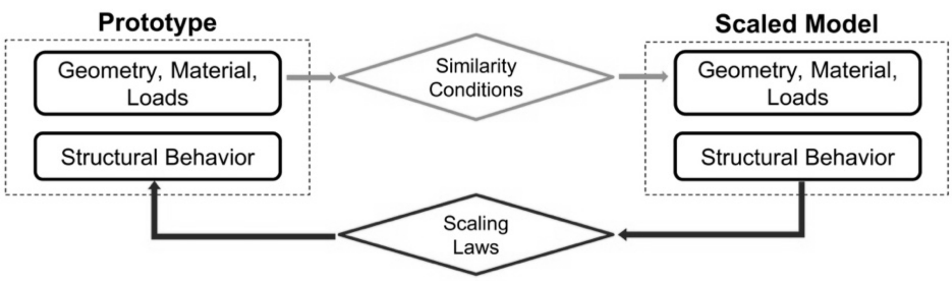


Figure 3.10. Conceptual diagram for prototype and scaled model. (Coutinho 2017)

In the applications of Similitude theory, the act of scaling is taking place according to the "Scaling Laws" which are derived and calculated by reducing the level of dimension of the variables and produces the ***interface*** which is the prototype in scaling studies in engineering as well as in NiA.

It is essential to identify the association between the dimensions and their impact on the behavior, then this information will be eligible to be transferred. Complexity of the model can be controlled via scaling. Hence, in this thesis, architecture resulting from nature-informed studies can also be considered as the ***prototype of nature***.

In the scope of this thesis ***complexity*** is defined, by variables, dimensions and their relationships which can also be explained by *Buckingham's π -theorem* stating the following relation where Y is representing the function, and $X_1, \ldots, X_n$ represent the variables (Buckingham 1914):

$$Y = F(X_1, \ldots, X_n)$$

By determining the variables and specifying the dimensionless group where the function is equal to zero, the dependencies of the variables can be defined and as a result, the information can be modelled by reducing the complexity.

Since it is a procedure that can be followed and measured, the process is named as a ***transfer*** rather than abstraction regarding the act of dimension reduction to have comparable models. In this vein, the transfer process requires to be executed with a modeling approach considering the parameters, variables and dimensions. Well-known example of this approach is the Mach number (M).

Mach number (M) as "the ratio of the speed of a body to the speed of sound in the surrounding medium", is the most known similitude example showing how successfully different domains can be related through non-dimensional parameters i.e., scaling in a broader perspective, analogous to this, in this thesis, it is aimed ***to define how to determine the "Mach number(s) (M)" of nature-informed architecture***.

Consequently, in the scope NiA, model and modeling redefined with the notion of data, and data modeling approaching it as a dynamic entity having the capacity to predict and to be trained/enhanced. Therefore, a new data model transferring the data in n-tuples to generate an informed model. In this transfer process, similitude is proposed as a tool that can be incorporated in the proposed NiA model enabling the scale transfer of various levels of complexities between nature and architecture regardless of where the research is initialized (from natural phenomenon or from a technical problem), or in which extent nature is referred (biotic and/or abiotic).

3.3.2.2 Model Structure

As discussed, and presented in part 3.3.1, the transfer of information among different domains is expressed in relation with set theory and represented with the following diagram (Figure 3.11).

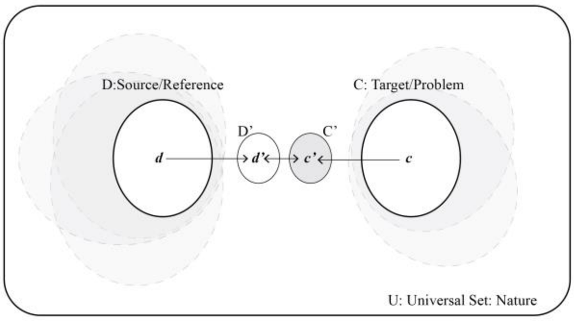


Figure 3.11. Relationship between domain and codomain in the course of information transfer

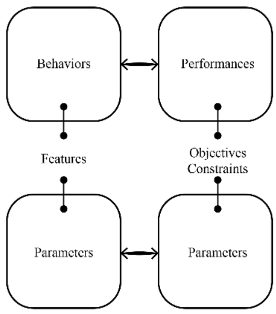
In this way transfer of data from any reference in nature to a targeted problem area becomes possible. The relations to be constructed between different domains is explained with relationships between two distinct datasets. These relationships can be expressed by cross product of two sets as below. As it is seen in this definition, feature(s) and behavior(s) of reference being are associated with objectives and targeted performance of the problem.

$$D'x\ C = \{(t_d, t_c), (b, p) \mid t_d, b \in D', t_c, o \in C\}$$

b: observed behavior of reference
p: targeted performance
t_d*: features of reference*
t_c*: parameters defining objective and the constraints of the problem*

The constructed tuple with behavior and features of domain and performance and objectives of codomain, and parameters of both provides a template for the information transfer based on data models in the light of the discussions related with model, scale and dimension. The relations as tuples is presented in Table 3.1 showing information transfer through the transfer learning model (TLM) which is explained below.

Table 3.1. Diagrams and definitions showing the relations between the constituents of the transfer model



Reference (Domain)	***Problem (Codomain)***
bRf	pRo
fRp_d	fRp_d
b: behaviors *f: features* p_d: parameters	*p: performances* *o: objectives and constraints* p_d*: parameters*

Along with the aforementioned relations, these tuples are capable to create a model as a network similar to artificial neural networks. In the proposed model, instead of a converged solution as in ANN, the layers of network are reflected into co-domain as a symmetric model to converge a solution for the stated problem. Considering the complexity of this process compared to the capability of AI applications today, this model aiming to learn from natural being still requires a human inclusion, perception and decisions. Yet, developing such network models based on nodes and layers provides a viable decision support system for the information transfer process.

Therefore, a novel holistic metadata model including the network model is proposed here as a template for mapping in nature-informed studies. By definition, metadata which is “data about data, aim at facilitating access, management and sharing of large sets of structured and/or unstructured data”, and metadata models are the models to manage this complex data structures (Kerhervé ve Gerbé 1997).

Here, the proposed model is designed to orchestrate metadata that control capta of both reference and problem set in order to relate them to create tuples but also to enable a new informed model to emerge. The informed model is designed to answer the research question of problem area with the knowledge informed by a reference which is nature in this case. Therefore, informed model which is driven by the problem area needs to be supervised by the model constituted with the captured data of nature.

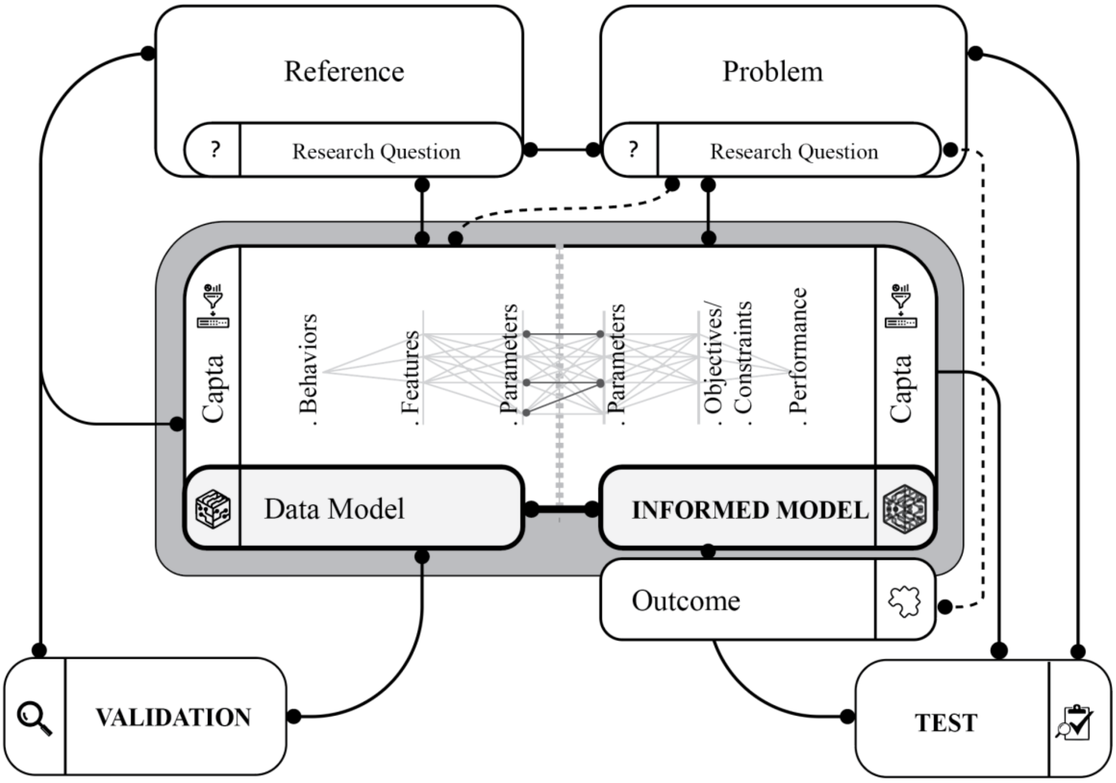


Figure 3.12. Metadata Model for Nature-informed Studies

The process of information transfer in nature-informed design can be explained as an n-fold flow as presented in Figure 3.12. In this process, as problem area in the codomain address a research question, a matching question is being posed to the domain. These questions are required to be complementary to solve the problem, yet they are needed to be situated in their own context. As a result of these questions, capta of reference which are features, relations and behaviors and capta of problem which are objectives and constraints and targeted performance(s) creates multiple n-dimensional tuples. Among them, the selected one is required to be followed for the transfer learning model. As these tuples being constructed, the relations among the data of each domain are required to be identified and modeled. As these definitions constitute the first steps of information transfer among domains and defines the rules, method and scope of the supervision of nature. Because the resultant data model constructed from capta of reference will play a crucial role to supervise the model being constructed for the problem itself as well as the objectives, constraints and the targeted performance.

In this model, there are two control points: validation and test. The former one is designated to validate the accuracy of data model constructed for the reference beings. The method of this validation varies such as literature and experimentation depending on the field, scale and the complexity and only validated models are eligible to supervise a model to be informed. The second one is the test in which the outcome(s) of the informed model is tested against the stated problem with objectives, constraints and targeted performance.

3.3.2.3 The Assessment of the Transfer

It is a known that case studies are mostly acknowledged as valid ways to assess the performance of generic models through number of criteria showing the precision, the validation, and the convergence of the model. These criteria determines the overall performance of a model through the assessment of each phase by the researcher. The questions determining performance of proposed model are summarized as in the table below.

Table 3.2. Assessment Table for the Information Transfer

	Data	**Capta**	**Mathematical and/or Computational Models**	**f(x): Mapping**	**Transformation**
Precision	Is accessible and/or observable data presents the knowledge of the domain?	Is captured data reflects the searched performance?	Does the model exhibit the behavior of the reference? What is the result of dimension reduction in the model(s)?	Does mapping process carries all the information regenerated in the model(s)?	
Validation -constraint -limitation -accuracy			How the performance of the models will be evaluated?	What are the conditions to map the model into the target?	How the performance is changed compared with similar or conventional equivalents?
convergence		Does capta reveals the performance of the reference to inform another area?	Does the relations constructed in the model converge with the beings'?		*
scalability		Which references can also target this problem area		What are the possible areas that this model can be mapped into?	In which extend the problem area can be transformed?

These questions are answered during the conduction of the case studies. As the targeted problem area brings several specific problems in the field of building sciences, in this thesis, the chance of assessing the model from different perspectives become possible. Yet, there are even more unique cases that model can be carried out not only in the targeted problem areas, but also in the field of building sciences in general.

In this context, the problem areas targeted in this thesis aims to explore path finding for robotic construction, developing generative tool for designers and also evolutionary algorithm to optimize the module parameters in order to occupy maximum space in a given boundary with the information retrieved from crystal formations.

3.4 Crystal Formation as a Reference

Crystal formations that can be observed both in biotic and abiotic nature as organic, inorganic or metal crystals are always matter of research in many fields, with their formations, adaptability, growth, behaviors and more. All these behaviors exhibited in crystals have also been changing in relation with their scale from micro to macro which make them more appealing for further studies. The current literature and observations show that crystal formation processes, their growth in changing environments even with defects, their micro to macro structures are excellent sources for many architectural problems that we observe in various scales.

Many disciplines like crystallography, material sciences, physics and mathematics focusing on crystals to understand, model and predict the behavior of materials in nature. Each of these disciplines approaches crystals from a different perspective and scale. Likewise, in the scope of this thesis, the gathered and observed information on the crystal formation is compiled to create a data model to inform different problem areas found in architecture.

Figure 3.13. (a) crystal cave (retrieved from http://ngm.nationalgeographic.com), (b)Combination of Pyrite, Quartz, Sphalerite, Galena, Calcite (retrieved from http://www.mineralsbulgaria.com on 08.04.2018)

Crystals exhibit various types of behaviors according to their inner structures (unit cell and habit of the crystal) in relation with external forces like changes in gravity, anti-gravity, temperature fluctuations, changes in lighting, air pressure, airflow, amount of the resources etc. The effects of each factor can be observed and analyzed on a single crystal. Furthermore, crystals are also taking attention with their capability to survive and resist even in adverse environmental conditions, and their growth ability and structural intactness in any direction, coexistence with many other crystal formations and occupying their containers like in geodes. Besides, the growth phenomenon in crystals shows a complex system behavior which is mostly peculiar to biotic nature; with various interdependencies, dynamic orders, interactions, and etc. In this context, crystals are unique examples to inform various parts of architectural design.

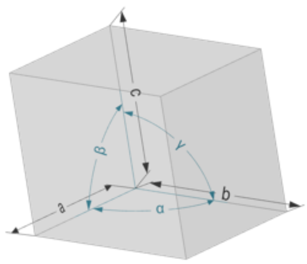


Figure 3.14: Unitcell configuration

In ideal and defected states crystals show different types of symmetry relations, and during phase transitions it is possible to observe the change from low to higher order symmetric configurations (Bärnighausen 1980).

Information gathered in crystal formation in various scales has great potential to inform number of problem areas in architecture. In the realm of this study, generative, structural, self-x, adaptive and responsive performance that architecture targets in design process are concerned as the subjects that can be informed by the crystals.

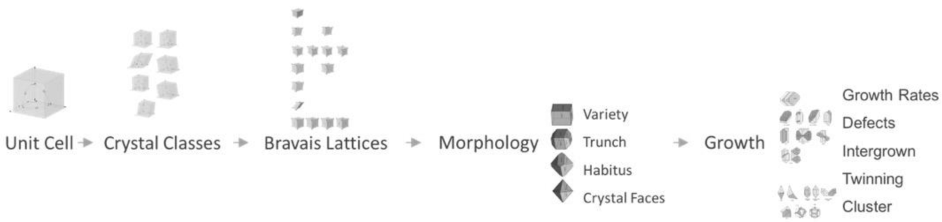


Figure 3.15. Relationships between different scales of the crystal formation

One of the important phenomena to be learnt from crystals is the formation processes which provides a valuable lesson to the force-form relation in architectural design. Crystal formation is a multilevel process starting from the *unit cell* which is the basic unit repeating itself in a lattice configuration. Then, during the growth process depending on the factors determining growth i.e., crystal classes and Bravais lattices, the morphology which is referred as costume of crystal emerges. In this process, the defectious behavior is as decisive as environmental conditions to form the crystal in its current state. These relations are summarized in Figure 3.16 in different scales.

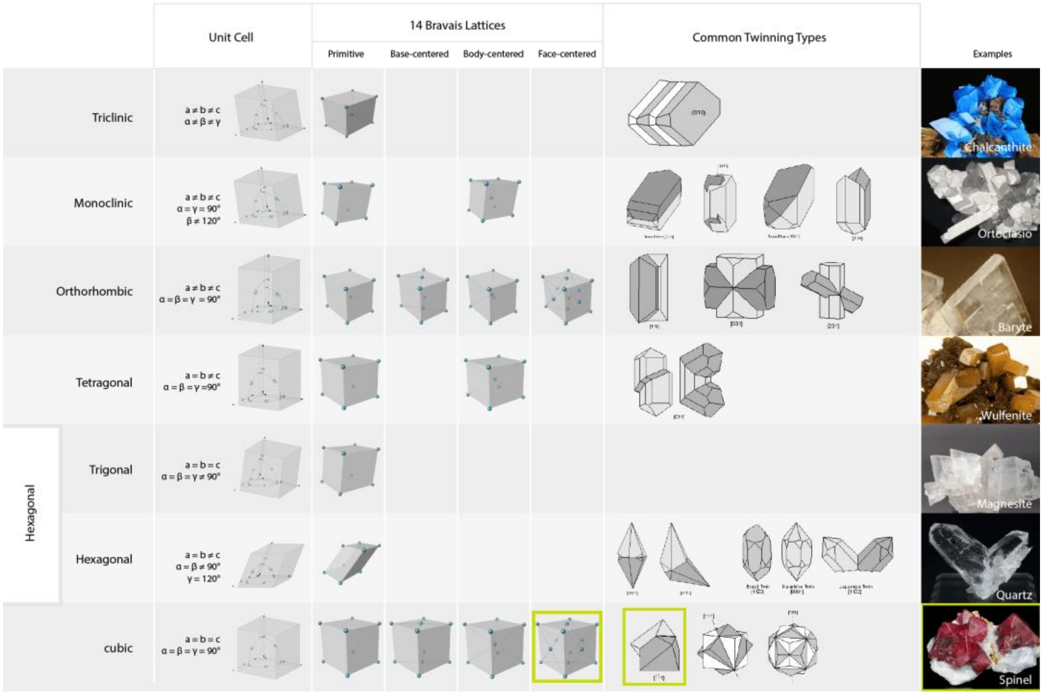


Figure 3.16. Drawings of unit cell and Bravais Lattices are generated by the author

The growth process of both single crystals and defects like intergrowth and twinning are promising for architecture with its unique characteristic of repetition of the 3D pattern while adapting into a different environment. The simple ordered pattern underlining the complex structure of crystals is important for architecture to comprehend and 3-dimensional tessellations which can evolve and grow in time. Therefore, the growth mechanism and its notation in material science are explored to understand the available information on this area.

Growth of the crystals actualizes according to the lattice of the crystal structure and differing surface energies. The resultant faces are defined with Miller indices which can be described as relative vectoral coordinates based on the crystal structure based on Miller notation system (Miller 1839). The "*Miller indices of a crystal plane* are defined as the *reciprocals of the fractional intercepts (with fractions cleared) that the plane makes with the crystallographic x, y, and z axes of the three nonparallel edges of the cubic unit cell."* (W. F. Smith 2004).

One example of the growth mechanism can be seen in Figure 3.17(a) and the some of the outcomes of such growth are represented in the Figure 3.17(b). The differentiation of the Trachts is proved to be related with the growth rate which is related with environmental conditions like temperature, pressure, air flow etc. The outcomes of such variation can be seen in Figure 3.18.

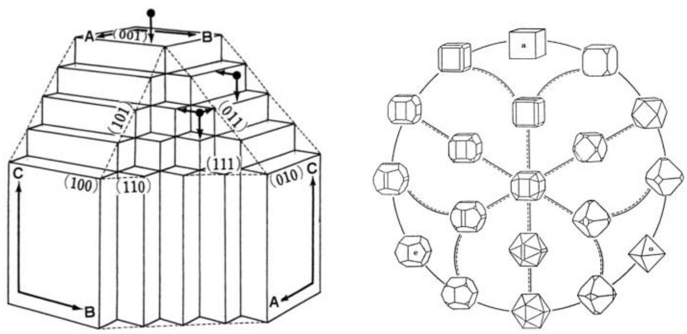


Figure 3.17. (a) F (flat), S (stepped) and K (kinked) faces based on Hartman and Perdok's Periodic Bond Chain (PBC) analysis, (b) Tracht variation of pyrite crystals (Sunagawa 2005)

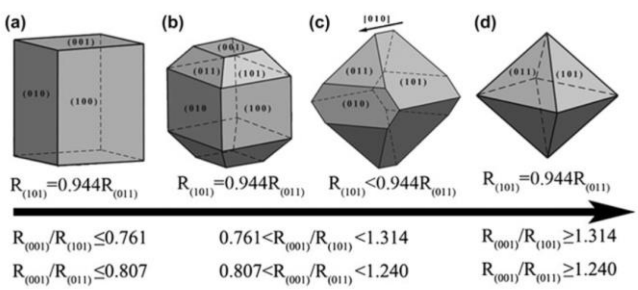


Figure 3.18. Morphological evolution of Al6Mn IMCs dependent on the growth-rate ratios of (001), (011), and (101) planes (a)–(d).

The aforementioned environmental conditions have not only great impact on the surface growth rates, but also causes some defects that alter the structural symmetry in many dimensions. Considering the higher dimensional defects, although these defects increases the surface energy on the surfaces, they can be observed as the response and survival method of the crystals towards its changing and challenging conditions. Therefore, in this study, the incremental growth mechanism of crystals is examined with its flawless and defected behaviors to inform the generation and construction processes in architecture.

Furthermore, crystal **polymorphism** is found as an appealing trait with its capability to adapt to various environments as well as preserving the inner order. Although polymorphic crystals have different habits and costumes, the faces which grow as a response of the environment providing the efficient solution for the growth process will occur and the response of the environment based on crystal defects and growth rates based on the **inherited code** of the crystal (Kang, et al. 2014). This code, which can also be interpreted as the genetic code of the crystal, regulates all the behavioral features of the crystal including the defects, and can be explained by means of symmetry operations of the unit cell and the lattice structure.

By definition "*Crystal defect is an imperfection in the regular geometrical arrangement of the atoms in a crystalline solid. These imperfections result from deformation of the solid, rapid cooling from high temperature, or high-energy radiation (X-rays or neutrons) striking the solid. Located at single points, along lines, or on whole surfaces in the solid, these defects influence its mechanical, electrical, and optical behaviour*." [3]. The defects that are observed in the crystals can be classified in 0D, 1D, 2D, and 3D as Point Defects, Linear Defects (edge dislocation, Screw dislocation), Planar Defects (a stacking fault, a twin region, and

[3] https://www.britannica.com/science/crystal-defect retrieved on 23.05.2019

Bulk Defects. These defects are explained below (Ramachandran, Halfpenny ve Roberts 2017).

As each feature, behavior and form of crystals are impressive and instructive, as it is stated before, capturing the data of relevant features, and mapping them with the objectives and constraints of problem area is an intricate task. It requires the designer or design team to be involved in broad literature survey, and even hands-on observations. Therefore, in the scope of this thesis, a series of observations are planned, conducted and recorded to observe the searched behaviors. Only then, the provided models could be developed.

3.4.1 Observations

An experiment to observe crystal growth is conducted to inform the development computational models resulting from TLM by following the procedure of “crystal growth from solutions” (Pritula and Sangwal 2015). Growth experiments for crystals in solutions can be carried out by using following methods.

1. Temperature-Changing Technique: Slow cooling method
2. Solvent Evaporation Technique
3. Temperature Gradient Techniques
4. Growth from Boiling Solutions

Among them, slow cooling method and solvent evaporation technique is used to observe and record the change in time is employed in the realm of the thesis. All the experiments that are shown below are based on the same procedure:

1. Preparing an oversaturated solvent in high temperature
2. Pouring the solvent into the test container depending on the experiment
3. Cooling the environment slowly while allowing the solvent to evaporate
4. Monitoring the crystal formation and documenting the data (size, temperature and formation)

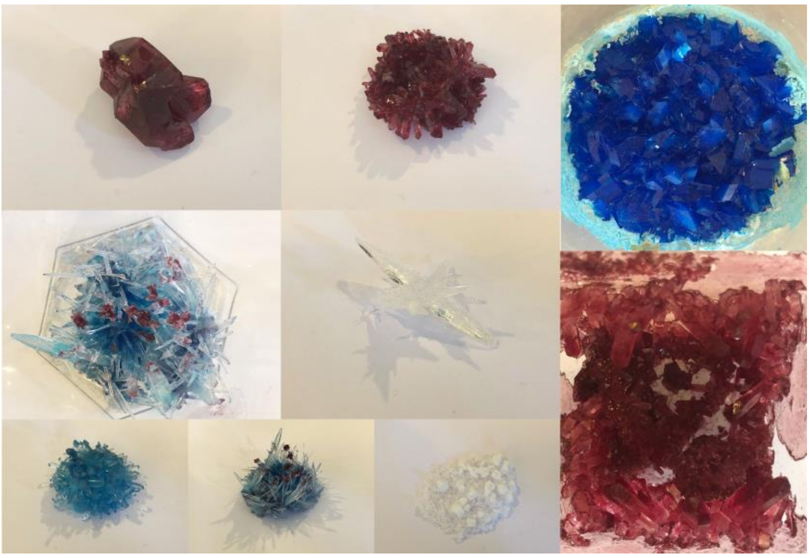


Figure 3.19. Potassium sulfate crystals are produced as initial observations

The initial observations are conducted with crystal growth kit providing colored potassium sulfate powders and plastic containers (Figure 3.19). Result of experiments on growth process shows that:

- The cooling solution in a container tends to form many nucleation resulting a cluster consisting of small bodies.

- When a single crystal is placed at the bottom of the container filled with the supersaturated solution, the free molecules contribute to the growth of the seed crystal resulting a larger bulk of a crystal

- When a single crystal is suspended with a fishing rode into the container, the impact of container is minimized and the growth directions of crystal (or the cluster) are only dependent on the growth behavior of the unitcell.

- In a different container having a textured surface, crystals tend to be formed on these surfaces as we can also notice in geodes in nature.

Following the initial observations, a series of more controlled observations are designed targeting the growth in metastable zone and to be documented with time-lapse videos.

In this process, it is important to note that if the solvent passes from stable zone to unstable zone too quickly, the number of nucleation, thus the seed crystals will be high and it will be hard to monitor and record. Therefore, the container will be partly isolated to have longer metastable period.

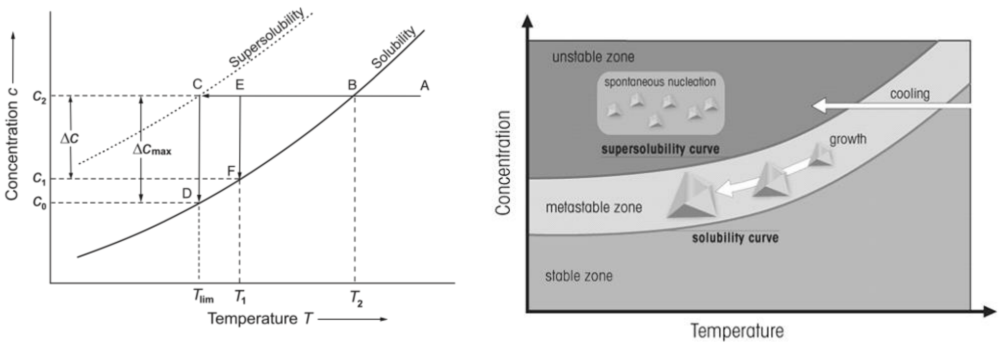


Figure 3.20. The relation between temperature and concentration during cooling (retrieved from https://syrris.co.jp/applications/what-is-crystallization-and-what-are-the-methods-of-crystallization/ on 15.11.2020)

Growing seed crystal is a straightforward process that requires a heated supersaturated solution (92°C) transferred from the larger container into a shallow one via a cone and a paper filter. The petri dish having 120mm diameter is preferred to observe the growth with 1000x 2MP portable digital microscope camera. The schema of the experiment is illustrated in Figure 3.21.

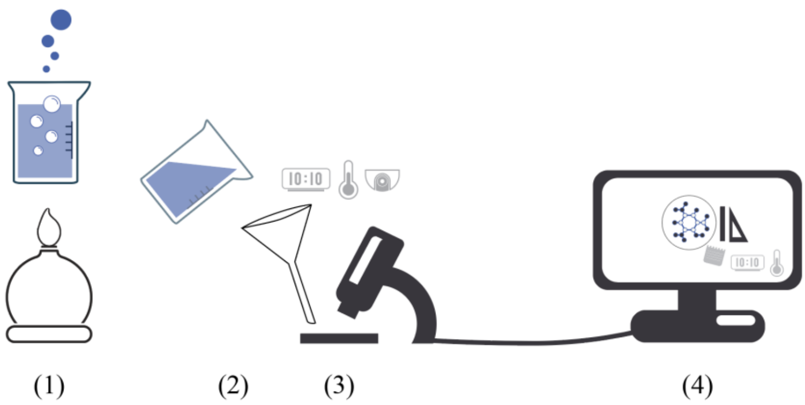


Figure 3.21. schematic presentation showing the experiment setup

Following experiments are designed to observe different behaviors of crystal formation to locate the information related with the problem area. As we problems necessitates to respond the needs of filling spaces, adaptation and response to obstacles, these behaviors are observed in the experimentation setups.

For these observations, chalcanthite ($CuSO_4 \cdot 5H_2O$) crystals are preferred to be monitored considering the growth time, color to follow the process and variations and ease of access to the material. As mentioned before, each process is recorded in a video and one of them is presented in Figure 3.22 and Figure 3.23.

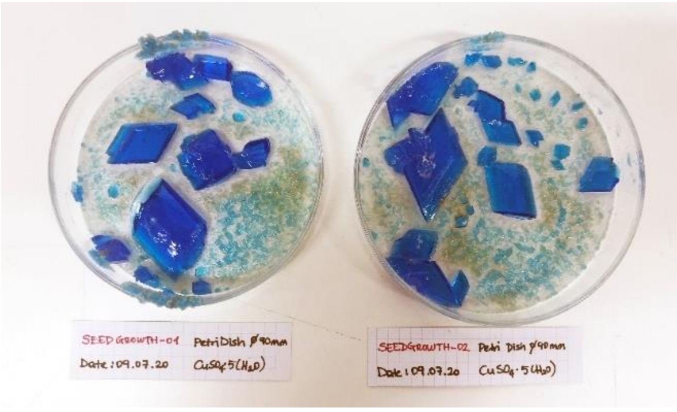


Figure 3.22. Growth of Chalcanthite ($CuSO_4 \cdot 5H_2O$) Crystals

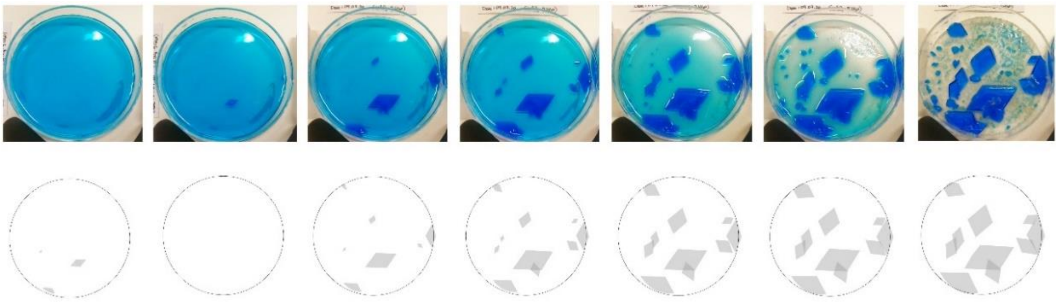
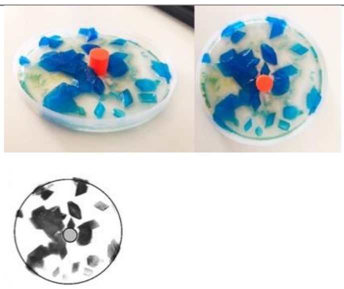


Figure 3.23. Deciphering the record of Chalcanthite crystal growth

The results of the observations indicating the effects of container, obstacle and slight flow in the formation processes are included in developing the required models.

Table 3.3. Findings of observations on crystal growth

Factor	Images	Findings/Observations
Container		The surfaces of container serve as suitable surfaces for nucleation and growth. Each growth in different container is unique and yet similar with size and variation.
Obstacle		Obstacle places in the middle of the container creates an additional surface for growth and due to flow of mixture around the obstacle and textured surface of it, crystals tend to be formed more frequently around the object.
Flow (Leakage)		Small containers printed with FDM printers had small gaps at the bottom causing the mixture to leak in the process. As a result of flow occurred in the container, initial seed crystals formed during nucleation located in those areas and finally block the gaps avoiding further leakage.

3.4.2 Informing Architectural Formation Processes

Information like features, behaviors, processes gathered on crystal through literature and observations are decoded and organized in relation with the performances that architecture is seeking for as shown in Figure 3.24. The possible relations i.e., data paths confirming the problem area are then explored. It can be seen that both in reference and target domains, behaviors and features are defined and related within themselves and with each other. These data paths shown in the figure (Figure 3.24) are the most noticeable ones and new secondary paths can be found in relation with the problem area. It is believed that this mapping enables us to model data and transfer the information to inform architecture.

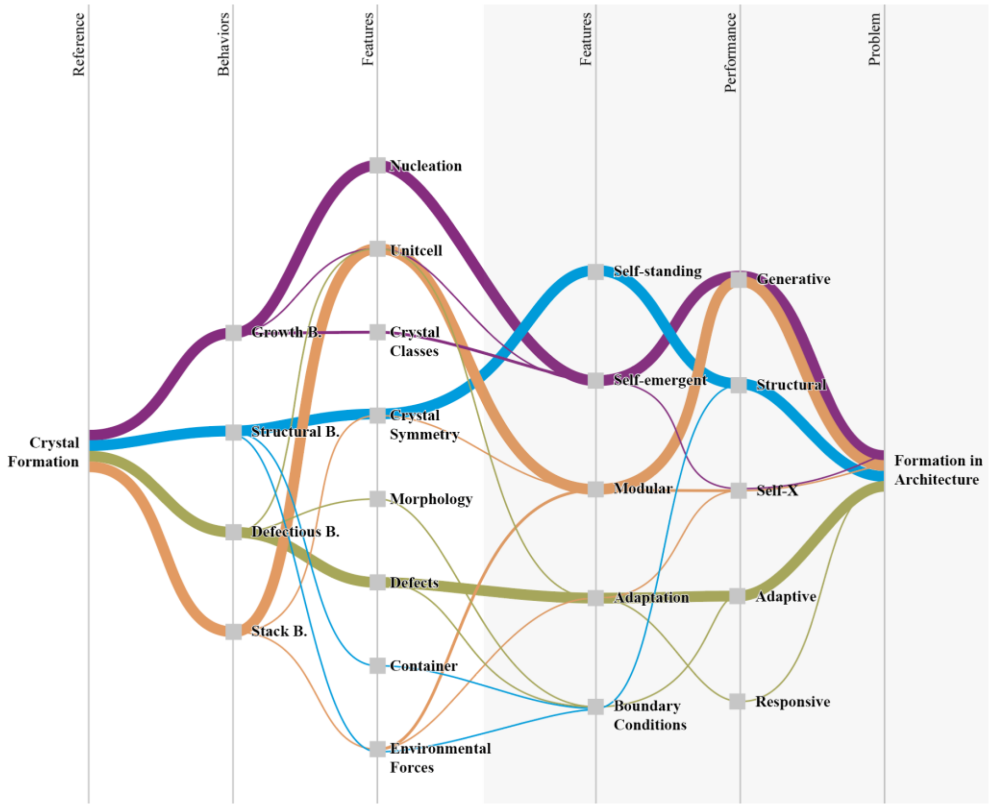
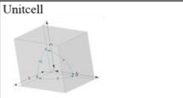
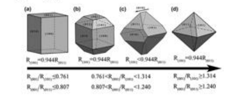


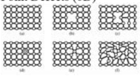
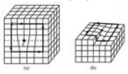
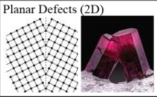
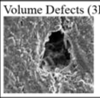
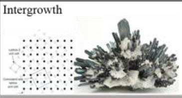
Figure 3.24. Resultant data paths between crystal formation and formations in architecture

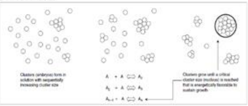
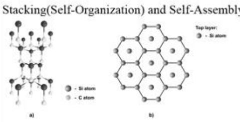
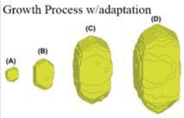
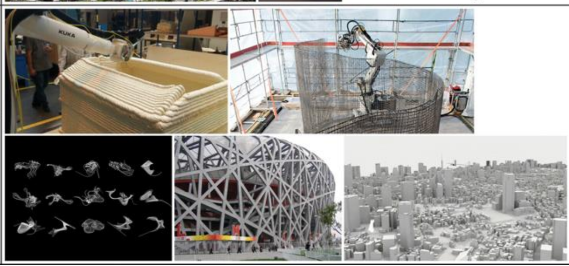
As it is seen in here, determined data paths are not only related with the data stops that paths are passing through, but also more with side paths affecting the targeted information transfer. Therefore, the transfer learning model TLM is vital to understand, model and transfer the information stored in the capta of reference domain.

This initial mapping introduces several information transfer paths that can be used to inform number of areas in architecture. Some of the relationships are presented in Table 3.4. These relations are constructed in different scales for both crystal formation and architecture from single components to intricate behaviors/performances.

Table 3.4. Possible mapping scenarios between crystal features and processes and architecture

Domain: Crystal Formation		**Codomain: Architecture**		
Features	**Parameters**	**Potential Areas**	**Target Information**	
Unitcell 	- Angles: alpha, beta, gamma - Dimensions: a,b,c	Building Block: - construction block (brick, aerated concrete etc.) - Space organization - Blocks in urban design	- Exploring different building blocks - Finding new ways of aggregation - Finding relation between existing spaces	
Crystal Symmetry: Crystal Classes and Bravais Lattices 	- Symmetry - Dimensional Relations - Relations between modules			
Morphology 	- Shape - Adaptation	Responsive Building Blocks - Tilings : 2D and 3D - Facades Adaptive Design Processes	- Understanding the change in morphology - Defining the response against forces	

			Failure		**Adaptation/Response**	
	Defect Types	**Parameters**	**Target Information**	**As a response to:**	**Target Information**	**As an adaptation strategy:**
Defects	Point Defects (0D) 	- unitcell parameters - different material - missing atoms	- How to cure the failure - How to prevent it - How to refill		- How benefit from vacancy to find a pattern	
	Line Defects (1D) 	- Axis defining defect - Forces creating the dislocation			- New typologies with increased surface area	
	Planar Defects (2D) 	- Plane defining the defect - Forces - Container - Nucleation process			- Higher order symmetry	
	Volume Defects (3D) 	- Vacancy - External Force			- Positive spaces - Dialogue with outdoor space	
	Intergrowth 	- Two crystal formation - Two lattices - Surface Energy	- How to find a way to exist together - How to prevent the second kind		- Retrofitting - Extention - Adaptation to changing needs	

Processes	**Features**	**Target Information**	**Potential Areas**
Nucleation 	- Environment Saturation	- Finding the emergence point - Determining the orientation at the point	
Stacking(Self-Organization) and Self-Assembly 	- Crystal properties and symmetry - Surface energy - Movement during nucleation	- Organization rules - The assembly method for the units - Response of the organization against the environmental forces	
Growth Process w/adaptation 	- Crystal properties and symmetry - Surface energy - Defects - Growth order - Habitus - Structural stability	- Finding the paths of production process - Exploring different morphologies - Defining the unit according to targetted form - Predicting how the growth will proceed	

As it is presented in the table, crystal formation is studied in three scales: (1) Features of flawless crystals, (2) Defects, and (3) Processes with increasing complexity.

The basic features of crystal formations namely, unitcell, crystal symmetry, and morphology depending on dimensional, and relational parameters are informative in developing new construction block (brick) design, space organization in buildings or urban design as well as two- and three-dimensional tiling, and façade designs. It is seen that stacking, aggregation and strong adaptation characteristics of crystal formations are significant features which can bring new insight in architectural design process.

In the growth process of crystals, the impact of any impurity, especially crystal defects play an important role not only to change the costume but also to establish the structural stability of them. As defects can be classified according to their dimensions, 0D, 1D, 2D and 3D respectively, or as intergrowth crystals if there are more than one type, each one of them has potentials to convey different information. Defects carries two-fold information within their behavior: (1) learning to cure during a failure and (2) creating a pre-coded defect to response a new/changing/unpredicted environment. Both features are informative for architectural process presenting the valuable features of defects and defectious behaviors that can inform both healing/recovering and adaptability performances targeted in architecture. This two-fold information is presented in the "Defects" of the presented table.

It should be noticed that processes of crystal formations possess multi-layered information of both flawless and defectious behaviors, related mechanisms, resultant forms, required energies, and habits. As shown in the last part of the table, nucleation phase of a crystal carries the information of emergence with the definition of location and orientation which can inform urban design, pop-up structures and even street art. On the other hand, the ability of self-organization and self-assembly of crystals can inform the space organization, and stacking-based construction techniques as well as recently developing studies of self-assembling materials and robotic constructions.

Finally, growth process, which is also the focal point of this thesis, is consist of all the previously mentioned features and behaviors as well as the environmental factors. Growth process of crystals with the help of models created for specific purposes has great potential to inform the path finding processes, different morphologies, design of units(modules) in architecture and even prediction of space/building/urban growth. Some of the possible informed areas of studies are presented in the last part.

3.5 Remarks

In this part of the study, as nature-informed architecture (NiA) is proposed as a holistic approach, the actors of NiA which are redefined as reference, and act of information transfer and the resultant model are discussed and redefined.

Considering the scope of reference domain in nature-informed studies in general, it is seen that nature is mostly acknowledged with its biotic part and usually as a perfect entity or a system. However, when the potentials of abiotic nature as a source of information for architecture are explored, it is seen that abiotic nature has even more benefits as a source of information. Moreover, the defectious behaviors observed in nature are not always undesired by the natural beings, instead they are crucial parts of their survival mechanism. Therefore, understanding and learning from defectious behaviors as well as flawless ones are promising for nature-informed architectural studies. In this vein, in this thesis, crystal formation is presented as the reference for targeted learning process aiming to inform architecture for a number of problem area.

As a part of NiA approach, a new transfer learning model (TLM) is proposed to facilitate data transfer from nature to architecture for case studies presented in this thesis and for future studies providing a decision support system like a heuristic search. Although introduced model is explicitly defined with datasets, data models and input-output relationships, it is a fact and also known by experience that this process is always open to feedbacks to change itself in a recursive way until it reaches its goal. Therefore, to assess the nature-informed architecture idea with its position and tools, a series of case studies are designed. In these studies, while performing the transfer, the proposed model is implemented and results are shared with future potentials.

CHAPTER 4

CASE STUDIES: SUPERVISION OF CRYSTAL FORMATION

This chapter is dedicated to further the discussions on potentials of abiotic nature and defectious behaviors to inform the architectural design over the example of crystal formations along with proposed method. In the presented studies, the model referred as TLM is to be employed.

Here defects are found to be a significant source of information for architecture, not only to adopt the strategies of nature to cope with them, but also to understand the role of defects on the responsive, adaptive and resilient nature of beings. There are two-fold impacts of defects in crystal study; implicit and explicit ones. As visual defects like edge dislocation and twinning are explicit ones that are also studied, the change in the growth rate and its direction are implicit ones that are embedded in the growth mechanism. Although the reference model is developed based on this phenomenon, the visual defects are the only ones addressed in one of the studies.

In the realm of this study, discussions are elaborated through the case studies for which subject matters are introduced in the previous chapter; namely; path finding for robotic additive manufacturing, design of tool for stackable building blocks and optimization of module configuration to occupy a predefined volume. TLM as the proposed method in nature-informed studies is to be employed. The summary of the cases with respect to NiA components are presented in Table 4.1.

Table 4.1. Case studies vs NiA components

	Inanimate Nature	Flawless behavior	Defectious behavior	Feature Mapping	Model Mapping	Extending the potentials
1.Determining path for robotic additive manufacturing	●	●			●	
2. Generative model for 3D modular system design with limited typologies	●	●	●	●		
3. Optimization of module configuration to occupy a predefined volume	●	●		●		●

In addition to the presented features of case studies, it is important to note here that as the first case is initiated with a predefined problem which is searching for the solution in nature especially in crystal formation, the second one is started with the findings of symmetry features in crystals and determine the problem area. Therefore, with both cases, the applicability of the method on the common top-down and bottom-up approaches have been demonstrated.

This chapter has been designed as consisting of four parts: (1) general methodology followed by each case study, (2) proposed computational model (3) case studies: (a) problem area, (b) research questions, (c) act of mapping, (d) transfer learning process and (e) outcomes.

4.1 Methodology

Considering the extensive research on holistic/synchronized processes design and construction, the observed problems in the field are handled with nature-informed architecture approach with proposed model; TLM as described in section 3.3 (Figure 4.1).

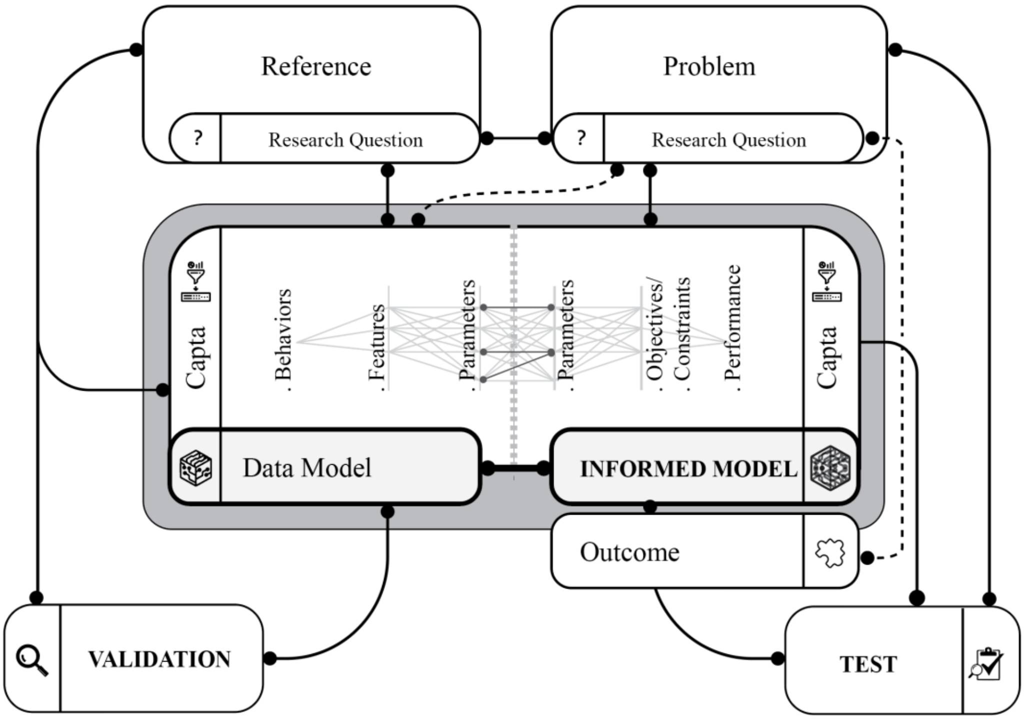


Figure 4.1. Transfer Learning Model

Considering the stated problems, the data of reference and target domains are revisited each time revealing not only features but also parameters enabling us to model the behavior of the reference and the targeted performance. The initial search map revealed in Figure 4.2 showing relations among data of each research area within their domains. Based on the initial map, paths to be followed are explored for each case.

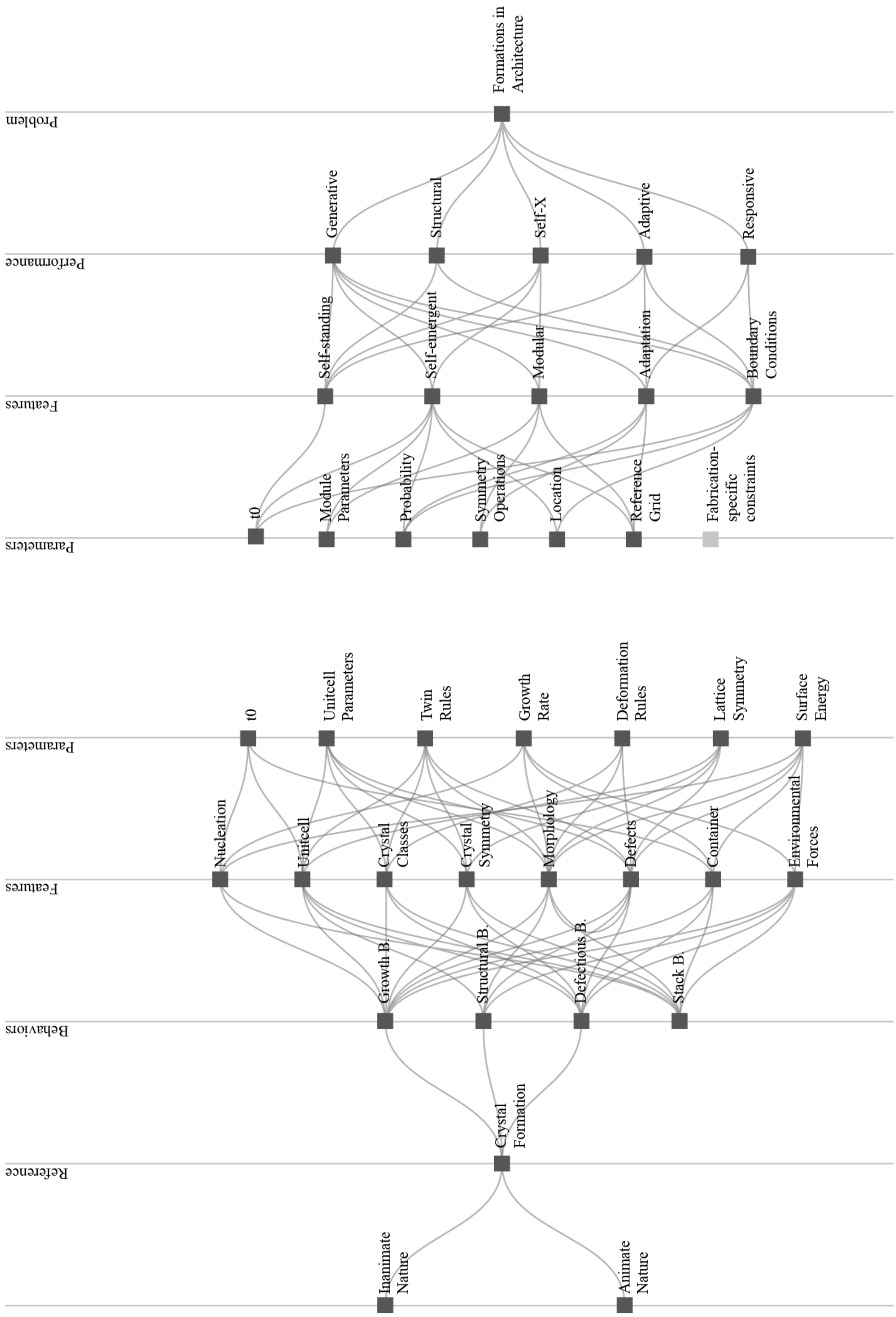


Figure 4.2. All possible cross references constructed between crystal formation and architectural formation.

The captured data sets of each one of the problems have their own peculiarities and thus their data exhibits variations. The relations between the dimensions of domain and codomain and more detailed explanations on cases and execution of TLM on each one is presented in the following part.

After determining the data paths, a reference computational model is required to be constructed based on the collected and observed information on crystal formations. For this purpose, two models are developed in different stages of this study: an early model and the supervisor model.

Then, the reference model is used to generate the informed models aiming to meet the requirements of the problem. As the reference model is validated with literature and observations, the outcome of the informed model is tested with the requirements of the problem.

4.2 Development of a Reference Model

In order to show the relations, a benchmark model is developed based on the crystal class, metrics regarding the unit cell (lengths {a,b,c} and angles {alpha, beta and gama}), growth rates of faces of units based on environmental factors and surface energies. The information related with crystal formations are retrieved mainly from International Tables of Crystallography and Crystallography Information File(s) (CIF) data retrieved from *crystallography.net*, and *www.ccdc.cam.ac.uk.* Also, the results of the model development are controlled with the results obtained from VESTA software (Momma and Izumi 2011).

The introduced computational model is developed on Python Scripting Platform with provided CIF files, and with the knowledge of possible defects especially twinning planes in Rhinoceros and Grasshopper modeling environments. With this model, the growth process is aimed to be simulated in both nano- and meso-scales.

The interface of the benchmark model is designed using “Human UI” add-on developed at NBBJ by the Design Computation Leadership Team[4]. In this model, the interface is designed as three tabs: (1) unitcell defining the unit parameters, (2) growth enabling user to decide on the growth features and (3) results showing the analysis results and providing options to transfer the geometry into Rhinoceros environment.

This model is developed as the interface of mapping process in which data of one domain is transformed to be mapped into the target domain. In this process the role of defects is found to be valuable to study both the explicit defects, and implicit ones. As the explicit defects include the visual defects like twinning, edge dislocation or bulk defects, implicit ones determine the order and speed of crystal growth in different conditions. Overall, defects are acknowledged as the key actor defining the adaptive capability of crystal and this is what this thesis is aiming to adopt for architecture.

4.2.1 UnitCell

As this model is capable of defining its own unitcell depending on crystal classes and dimensional values (a, b, c, alpha, beta, gamma) and symmetry operations. It is also possible to import the CIF file of an existing crystal containing relevant information (Figure 4.3).

[4] https://www.food4rhino.com/app/human-ui . Last accessed on 06.12.2020

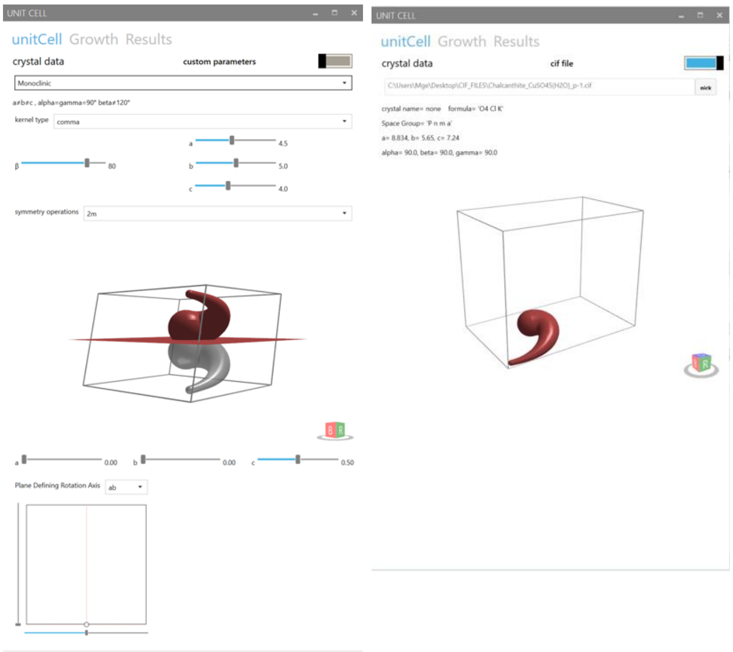


Figure 4.3. Interface of unitCell part of the computational model: (1) custom parameters and (2) importing CIF data developed by author

The crystal classes and related symmetry operations are adopted from International Tables for Crystallography as shown in Figure 4.4. In this table, the common symmetry operations that are observed in crystals belonging to crystal classes are defined.

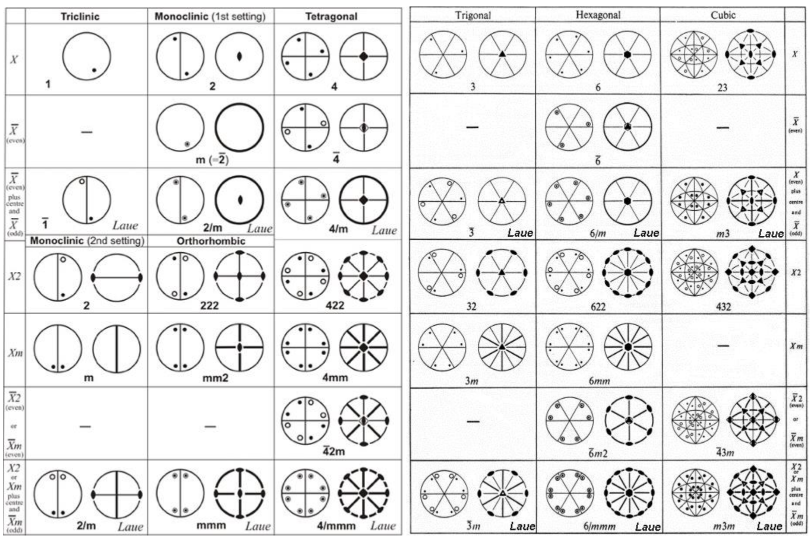


Figure 4.4. Crystal classes and symmetry operations as found in International Tables for Crystallography (Wondratsche and Müller 2011)

Based on these operations, basic symmetry operations are defined within the designed computational model to generate the symmetries in a single unit (Figure 4.5). These outcomes achieved with simple 3-dimensional symmetry operations showing the variations even in a single unitcell which can be amplified with lattice formation and defects.

In crystal formations found in nature, the locations of mirror plane and rotational axis vary depending on molecular arrangement. Similarly, in the proposed model, the parameters defining these symmetry actuators are open to change through the provided interface. The impact of these symmetry operations is shown inside the interface with a kernel and symmetry operators. A 3dimensional comma is preferred for the presented table (Figure 4.5), but it is also possible to choose a single sphere, pyramid or a spike (as a line), and also to use a custom one through the algorithm as it is shown in the second case study of this thesis.

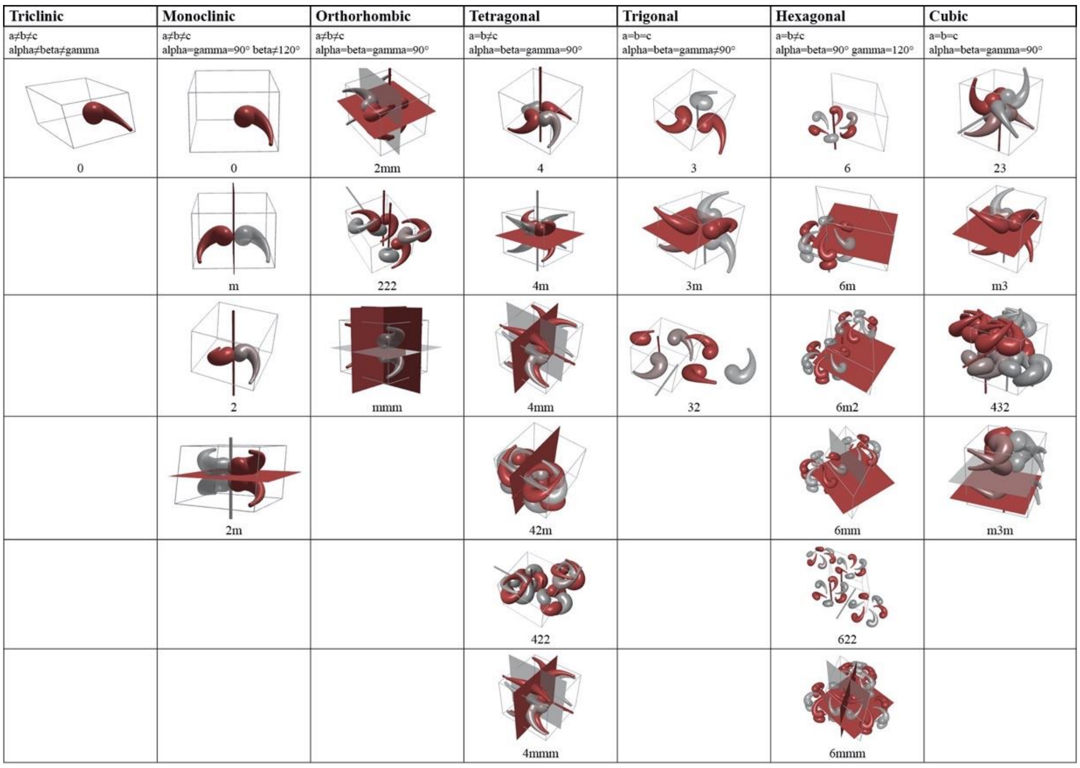


Figure 4.5. symmetry operations defined for each crystal classes as a result of the model developed by the author

4.2.2 Growth

The growth mechanism of the benchmark model is based on the Monte Carlo simulation which is highly acknowledged method in understanding and predicting crystal growth (Nývlt 1996) (Zepeda-Ruiz and Gilmer 2015) (Kastner 2010).

In the proposed model, a container and the obstacle(s) are defined as both the environment of growth determining the limits and also the locations of interactions that unit tends to grow towards. For this purpose, the solids defined as poly-surfaces which are obtained from Rhinoceros user interface are being converted into meshes providing vertex points to act as attraction points for the models.

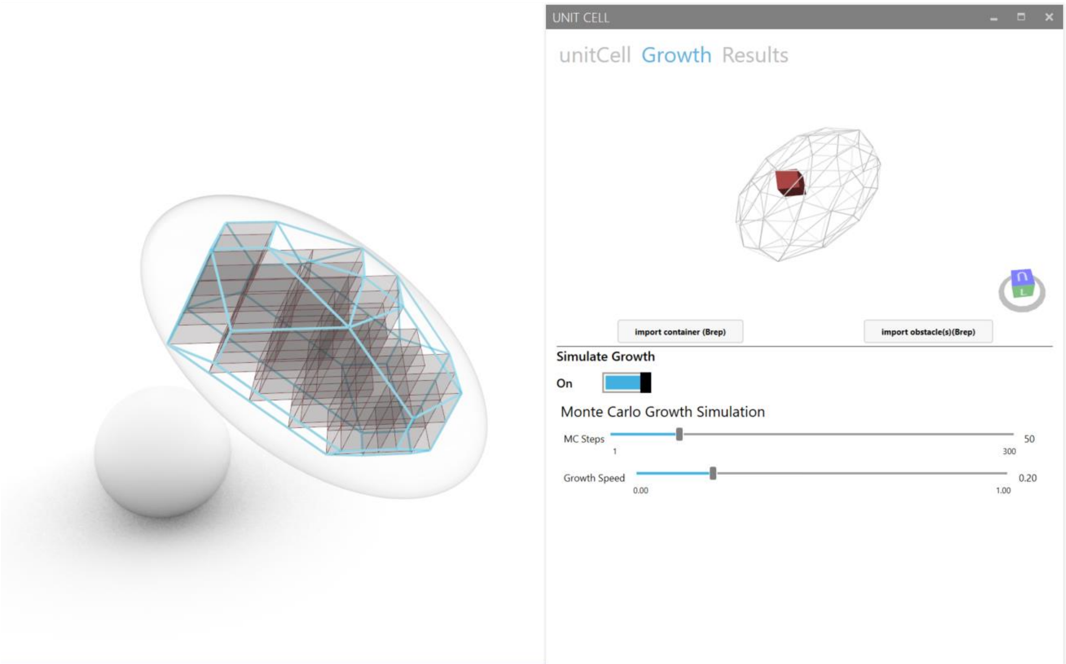


Figure 4.6. Growth tab of the computational model developed by author

Moreover, for each instance the surface energies of each faces are calculated based on their distance between these vertices and the predicted surface energy representing the kink state of a crystal (Figure 4.7). Hence, with the following formula the score of ability to grow for each face can be calculated as also shown in Figure 4.8 and the cluster will grow towards the highest score cell.

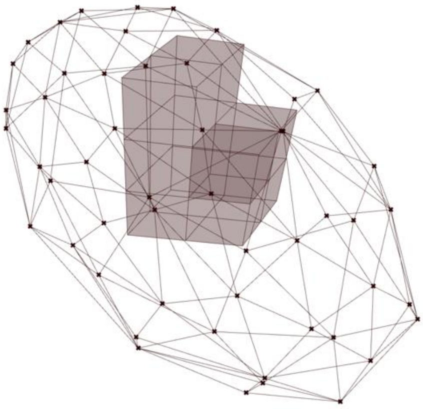


Figure 4.7. Container definition and growth of modules used in the designed model

$$S(x) = (num_x)^2 - Ndist_x$$

$$Ndist_x = \frac{dist_x - dist_{min}}{dist_{max} - dist_{min}}$$

$$dist_x = dist\left(centroid_{x,} vertex_{container(closest)}\right)$$

num_x: number of neighbor units

$dist_{max}$: maximum distance calculated between vertices and units

$dist_{min}$: minimum distance calculated between vertices and units

$dist_x$: distance of possible unit to closest vertex

$centroid_x$: centroid of the unit

$Ndist_x$: normalized distance

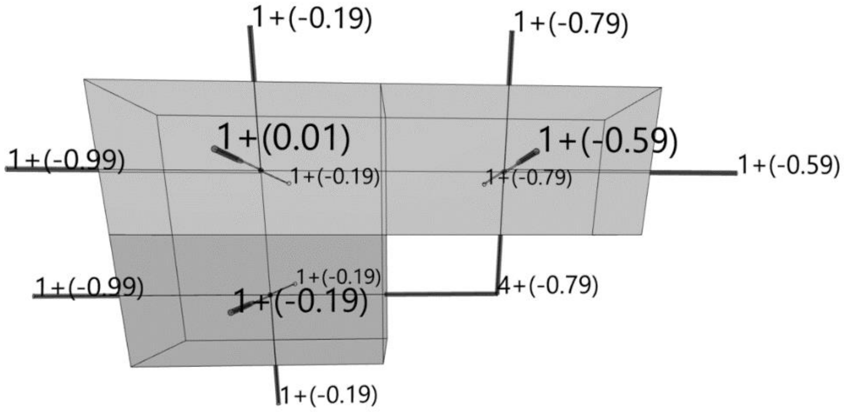


Figure 4.8. Score calculation of growth algorithm proposed by author

The resultant growth order obtained from the Monte Carlo simulation provides a process that supports itself during growth. This outcome is reached to be used in the first case study. Moreover, among previously mentioned defects, twinning which is a part of regular intergrowth relations found in crystal formations (Sunagawa 2005) is chosen to be explored further for the targeted problem area in architecture. In this vein, the potentials of twin formations are explored in the scope of second case study.

4.2.3 Outcome and Analysis

In the third part of the interface, following analysis results are presented: volume of container, volume of crystal cluster, occupancy of the cluster, number of units and length of the growth paths with buttons enabling to transfer the resultant geometries into modeling environment Figure 4.9.

The provided output of the model includes information in multiple scale: the geometry of the unitcell(s), lattice diagram, growth diagram representing the order of growth, symmetry operators and resultant convex hull geometry representing the overall volume occupancy. Thus, the last part of the designed model enables the user to obtain these resultant geometries with a “bake” command.

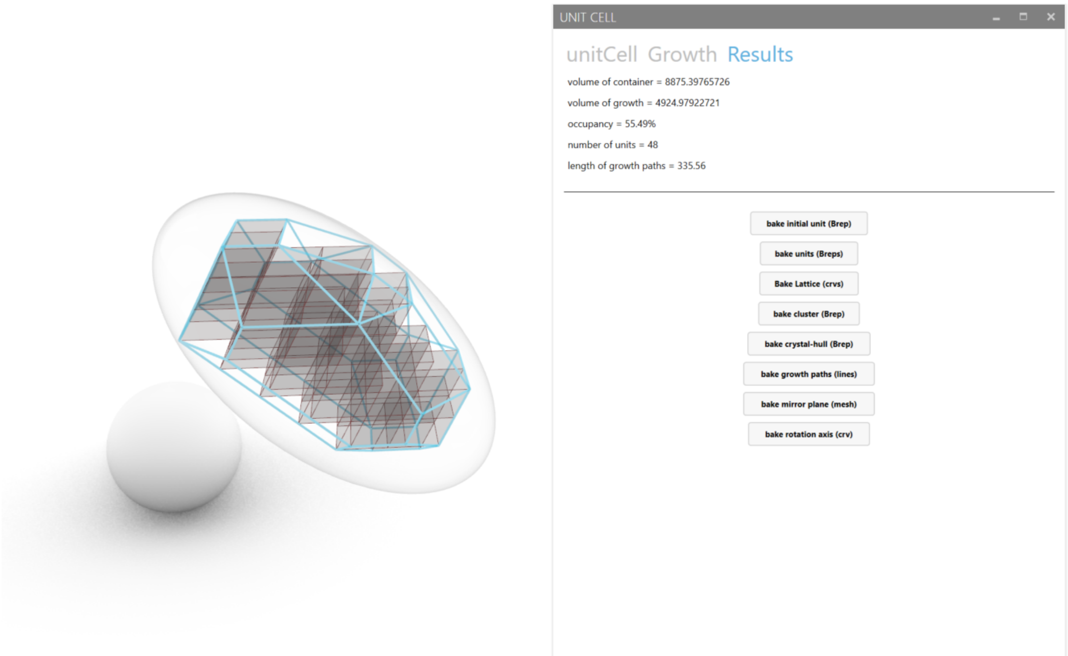


Figure 4.9. Results tab of the model interface developed by author

The designed model is aimed to be opensource which is available to be changed and enhanced for further exploration. Similarly, in the course of this thesis, the model is modified, enhanced and extended to serve for further explorations in the case studies.

4.3 Case 1: Path Detection for Robotic Additive Manufacturing (RAM)

Considering increasing number of researches on robotic construction, major problems are mostly related with path finding, and optimization of it in terms of cost and stability, to yield a well-established designing the construction process. Regarding this issue, the crystal growth based on the probability and surface energy provides a detailed information on paths and structural stability.

4.3.1 Problem Area and Research Question

Today with direct digital link between design and production (file-to-factory) and advancements in CNC technologies, the collaboration between architects, engineers and production processes is increased and architects started to be involved more in fabrication processes than before (Naboni and Paoletti 2015). As these applications can be considered as a part of upcoming *architectural intelligence* period (Yuan, et al. 2020), the number of them are increasing and these production techniques started to gain an important role in the common practice of construction. In this context, robotic construction and additive manufacturing are encouraging in the field with several examples from ephemeral structures like pavilions to targeted extraterrestrial structures as presented in Figure 4.10.

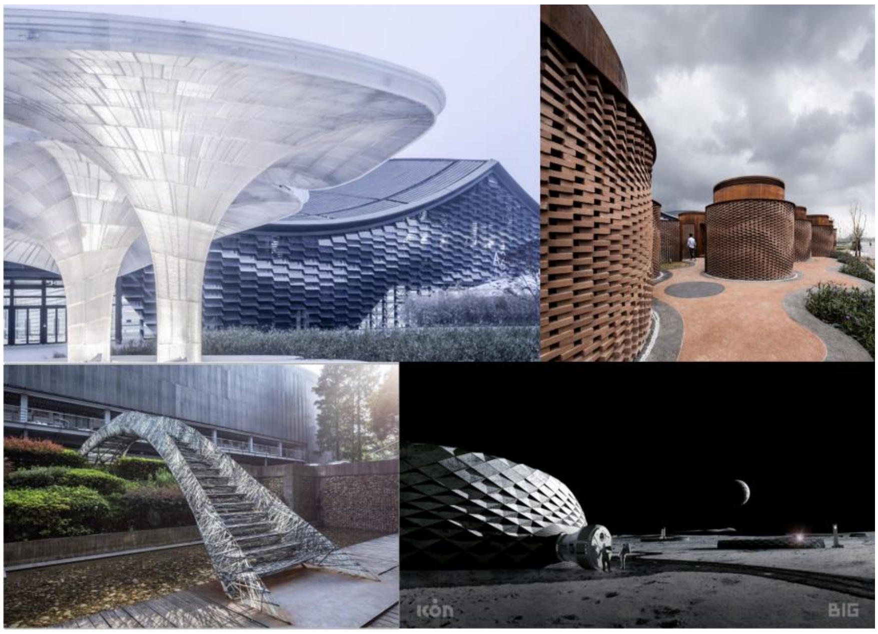


Figure 4.10. Examples of robotic and additive manufacturing in architecture. Retrieved from https://www.dezeen.com/tag/robotic-construction/ on 27.10.2020

As these applications can be supervised by humans, there is a vast majority in the field suggesting the need for automated construction phases. Among these phases, erecting a scaffold to support structure during construction is one of the times and material consuming one. With a similar approach, the mesh berried in poured structural materials (like concrete) working as a reinforcement are usually require human intervention and thus open to human error. Considering the large variety of materials to be used in additive manufacturing with different specifications like biodegradable, recyclable, or availability of reinforcement with additives for different mechanical performances, additive manufacturing methods are prominent to be adopted in this problem. Therefore, for considerations stated above, a study on path finding problem for robotic additive manufacturing for automated construction is decided to be conducted with the knowledge of crystal growth focusing on the ability of support itself during growth and the preferred order to be followed for this purpose.

4.3.2 Question posed to the reference

Considering the targeted performance for robotic manufacturing is to reach self-emergent and self-standing structure for wire-like structures, the collected data regarding the crystal formations and the benchmark model is revisited to compile the related parts to provide a supervisor model. In order to retrieve this information, the following question targeting the most fundamental feature of its formation is posed: "How crystals grow in an order while it is supporting itself". As a result of this concise question, the behaviors, features and extracted parameters are found significant in terms of the transfer learning model. These dimensions are presented in detail in the mapping process along with the dimensions of the problem area.

4.3.3 Mapping

The flawless growth behavior of crystals provides many important information regarding how the morphology is changing according to unitcell parameters, growth rate, and surface energy of the crystal depending on the environmental factors like forces and the container encapsulating the crystal growth. This behavior is found directly related with the generative performance seeking for the path finding issue of additive manufacturing and robotic fabrication. Path generation is directly related with the modularity and the self-emergency of the system. In addition to them, the fabrication-related parameters, objectives and constraints are also included in the mapping process defining the target model. Therefore, while the model is being constructed, these features and parameters are also included not as an informed part, on the contrary, as another dimension defining the target model as it can be seen in Figure 4.11.

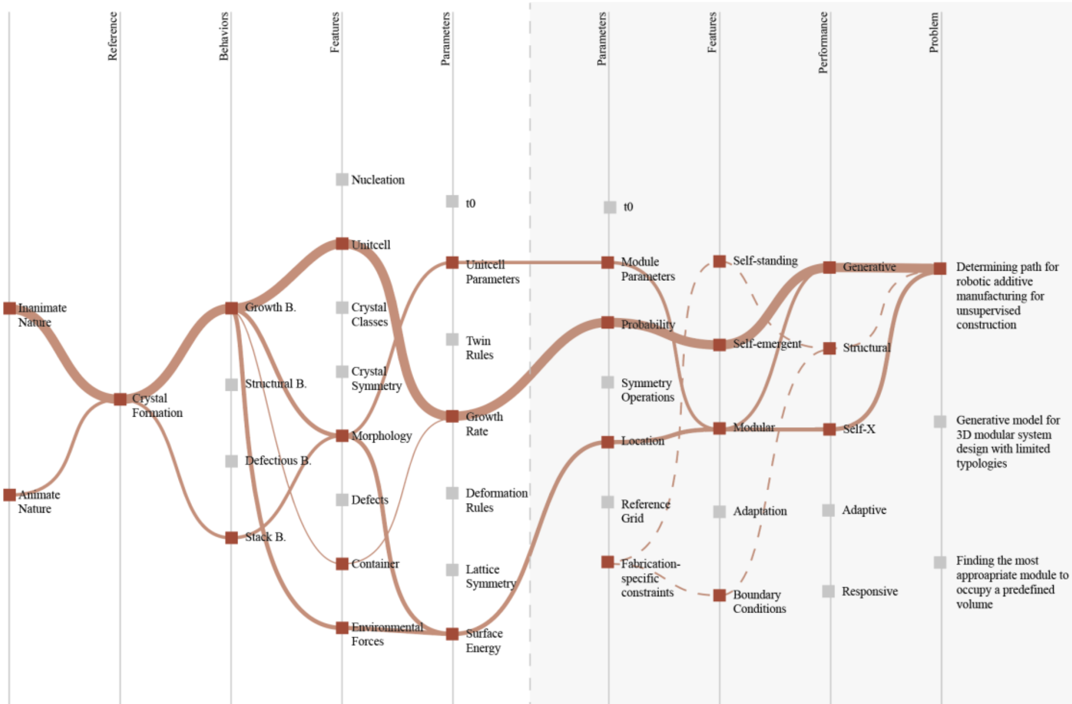


Figure 4.11. Mapping between crystal formation and path detection problem for robotic additive manufacturing.

4.3.4 Transfer Learning: Informing the Model

As learnt from literature, following the nucleation phase, crystals tend to grow on the surfaces of their reciprocal unitcell surfaces based on the surface energy and available molecules around it. Surface energy of formed crystal is based on not only environmental factors, but also the neighborhood relations. To be more specific, the probability of growth direction is dependent on the number of neighbors. Thus, crystals erecting on a surface and supporting itself are mostly obtain a closed form rather than branched structures. The order of this growth can be followed with a sequential wire diagram obtained in a time frame and the initial steps of this process can be seen in Figure 4.12.

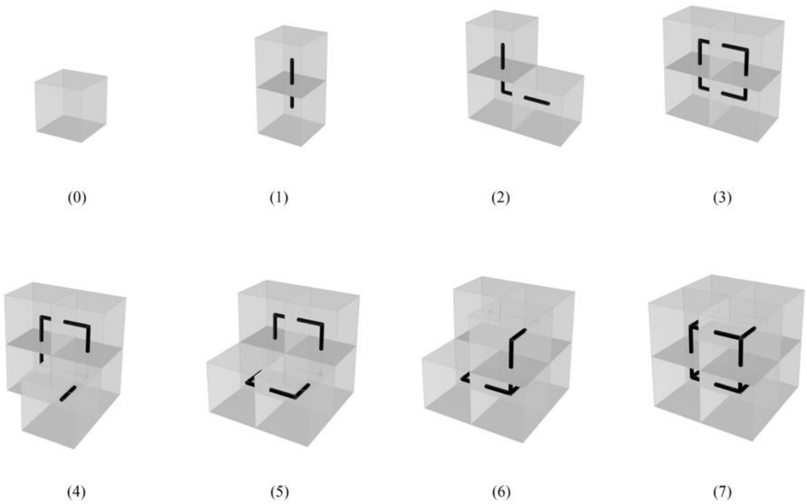


Figure 4.12. Sequential growth process of crystal formation as a result of proposed growth mechanism

Besides the neighborhood relations, the container which act not only as a source of material, but also as a boundary/obstacle determines this process. For instance, one instance of this process in a dome shaped container is presented in Figure 4.13.

Figure 4.13. Generation of crystals in a dome shaped container

Information gathered from the model based on crystal formation provides a valuable source for the problem area since the order of process is critical for a non-planar additive manufacturing with robotic arms considering the necessity to support itself while erected. Thus, the generative model based on Python scripting language is employed for robotic fabrication in Grasshopper 3D/Rhino with KUKA plug-in. the outcome of this process is not only an animation but also the G-code to run the process in physical environment. One of the examples of this process is presented in Figure 4.14.

In this process, in addition to the growth order, the direction to be extruded was critical and this is also calculated with the knowledge of author. Hence the informing process becomes a blended one with the information obtained from nature and the user.

4.3.5 Outcome of the Process, Test and Validation

The outcome of the first study is obtained as a g-code which can be interpreted by the robotic arm to follow the designed path during injection. The snapshots of this process can be followed as in Figure 4.14.

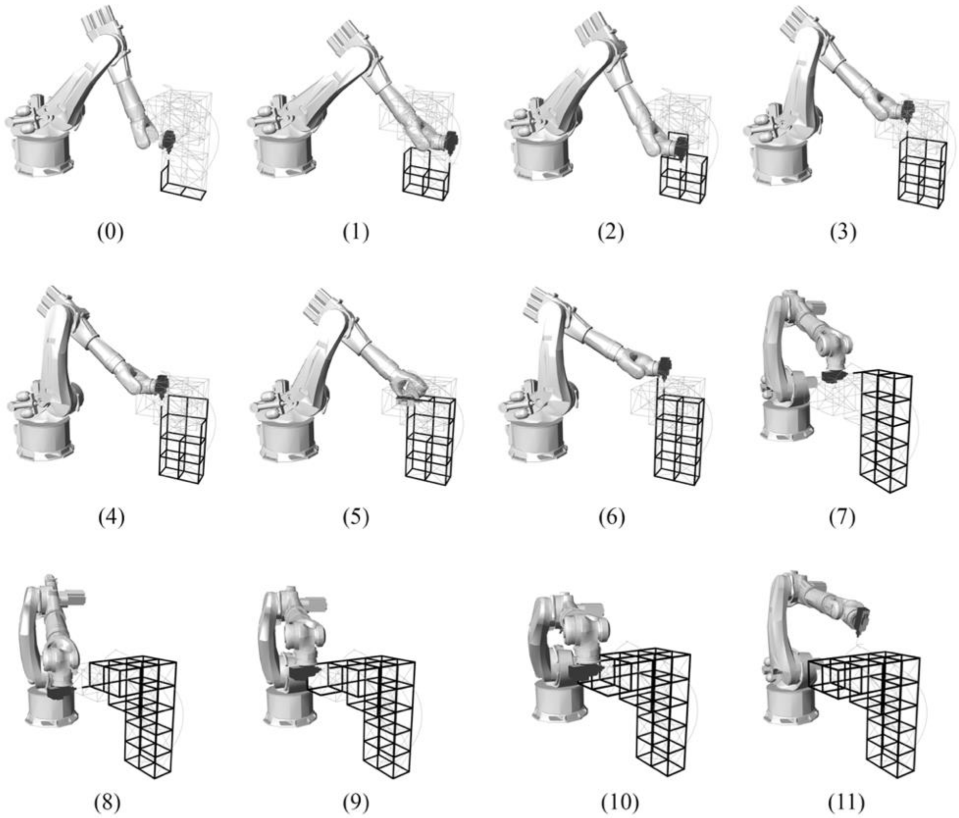


Figure 4.14. Generated path for robotic additive manufacturing process computed within the model designed by author

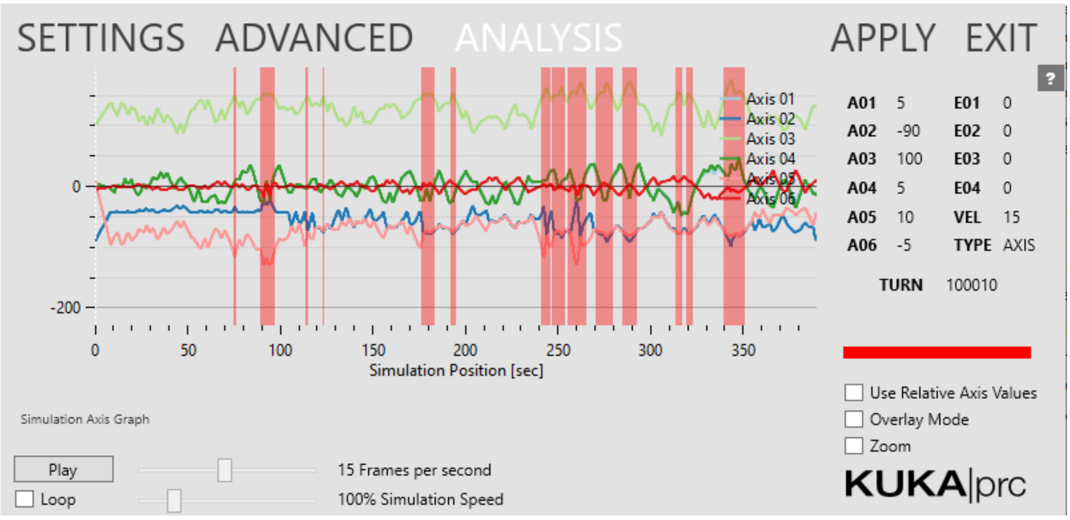


Figure 4.15. Simulation showing the positions of robotic arm

When the resultant paths examined visually and also through the simulation interface provided for grasshopper (Figure 4.15), the following conclusions were reached:

- The act of informing enables the model to support itself depending on the neighborhood relations.

- Cubical modules are preferred for the defined problem and the container, however, for different purposes and containers, model is developed to provide generations for different dimensions and angles.

- Considering the analysis results in the simulation software, further enhancement is required to avoid the abnormal movements (rotation) of axles.

- The targeted is assessed with four criteria: precision, validation, convergence and tolerance with the following table (Table 4.2).

Since the designed paths, fabrication process and final outcome is designed simultaneously, there is not any comparable process, model or fabrication technique. Therefore, the assessment of the final outcome is made within its own requirements, needs and targets. These criteria are the ability to seamless and supportless construction process and fill the targeted volume. As the goals regarding the construction process is reached successfully, filling the volume is limited with the module size and shape. Therefore, this study has potential to proceed with multiple modules or different variation of a single one.

Table 4.2. Assessment of transfer learning process for Case-1

	Data	**Capta**	**Mathematical and/or Computational Models**	**f(x): Mapping**	**Transformation**
Precision	Collected data on crystal growth (without defects) represents the basic behavior.	Captured data found adequate for the problem.	Reference model reflects the behavior of the reference being and its behavior. The informed model precisely shows the operation of robotic arm.	During the mapping process, some of the features of the model like nucleation is omitted due to increased complexity.	

Validation -constraint -limitation -accuracy			Performance of the reference model is evaluated with comparison with the literature and the results of the observations.	Parameters of both reference and target domain are paired.	Structural performance during the construction is increased. Further study on optimization of robotic arm movement is required.
convergence		Captured data on crystals reflects the behavior of flawless crystals. Capta of problem area covers the main issue targeted in this study.	The relations constructed in the model converge with both the crystals and the targeted production technique.		The transformation performed between the behavior-performance and parameters serve to understand and model both cases.
scalability	Besides crystals, modular growth can be observed in cells, animal swarms and animal architecture.		Model can be extended to include defectious behaviors to create unconventional surfaces	The information found in crystal formation can be mapped into predict and design the growth of regions and cities.	Problem area can be redesigned to include fabrication specific requirements aiming to find an optimal solution.

Consequently, the proposed Transfer Learning Model (TLM) is developed with research questions being asked to each domain, gathered data, the targeted mapping process, data model of domain, informed model of the problem area and the presented assessments. The phases of this process are presented in Figure 4.16.

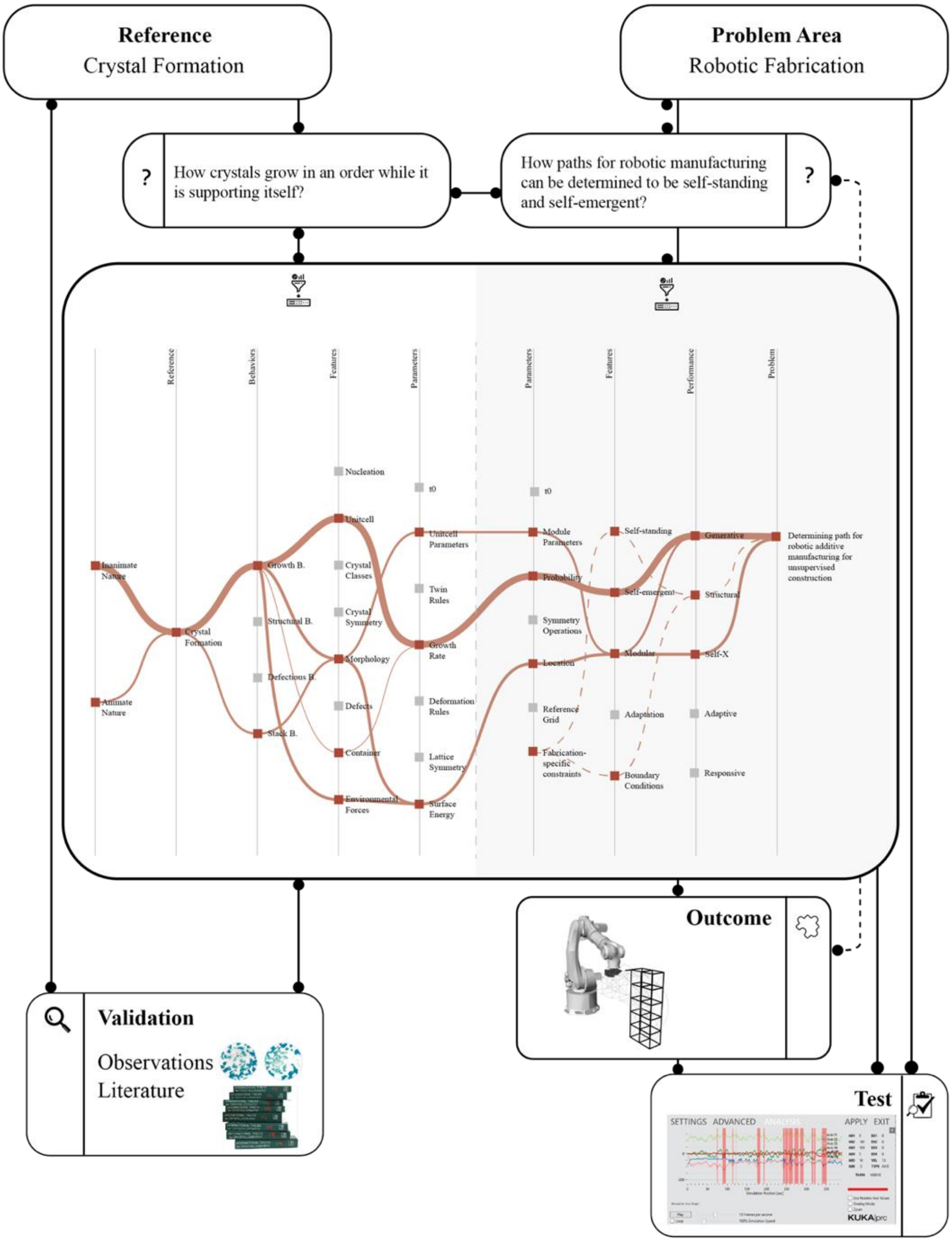


Figure 4.16. TLM for RAM case informed from crystal growth process

4.4 Case 2: Design Tool for New Kind of Building Blocks (BBT)

With new materials and assembly techniques, new kind of “bricks” have come to fore emphasizing connectivity and intactness. These bricks become the subject of construction with computer numerical control manufacturing technologies especially with additive technologies. Designing, and standing them together become challenging issues. In this context, crystals provide valuable formation processes with their regular symmetry and higher order symmetry features.

4.4.1 Findings on Crystal Symmetry

Symmetry in crystals is a broad subject that can be observed in many scales, from atomic scale (nano) to costume of a crystal (macro). Among these scales, the symmetry operations defined in a unitcell which is the module repeating itself through translation is the main one defining mechanical and behavior properties of the crystal. As the basic example, this symmetry determines the difference on mechanical properties (hardness) of graphite and diamond along with the bond types even though they are the allotropes of carbon (Figure 4.17).

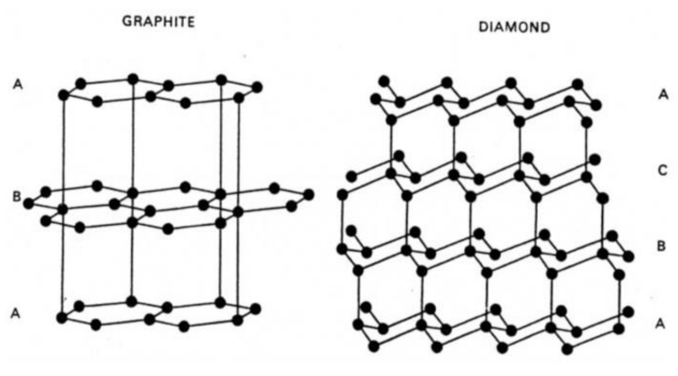


Figure 4.17. Crystal structure of graphite and diamond (Mallika, DeVries and Komanduri 1999)

Moreover, on an upper scale (lattice scale) where crystals tend to show defectious behaviors, twin formations bring a higher order or pseudo symmetry with introducing a symmetry of reflection (Psycharis 2016). Although these defects disrupt the order of the lattice, they are the responses of crystals towards environmental forces to resist, continue to grow and survive with a deformation defined within the unitcell configuration as described in part 3.4. In this vein, the behavior creating predefined defects in crystal formation and adapting a grid structure with its modular building blocks in architecture coincide. Therefore, considering the symmetry in the modules with reference to unitcell symmetry operations and being able to create defected ones to adapt its environment/container.

4.4.2 Problem Area and Research Questions

Since roman empire, the importance of building blocks made from stone, clay, gabions and concrete are undeniable not only in terms of masonry technology but also as a part of building tectonics. Although, ingredients of blocks have changed, evolved and optimized, and spans and heights have been enlarged with the advents in construction technology, the form and tiling methods have mostly remained same.

Figure 4.18. (1) Estudios Terra / Arquitetos Associados. Image © Leonardo Finotti, (2) Casa Havaí / Garoa + Chico Barros. (3) Galpões CL / VAGA. Image © Pedro Napolitano Prata retrieved from https://www.archdaily.com/ on 30.11.2020

On the other hand, with the advances in computational design tools, fabrication technologies and new ways to design, optimize and predict, customized mass production have been introduced to construction sector especially with the industry 4.0. In this vein, new kind of tectonics have started to be explored in architecture with different approaches and in different scales (Figure 4.19). Considering the stacking issue of building blocks in masonry construction, new kinds of patterns and ways of connect these blocks are still some of the relevant research topics.

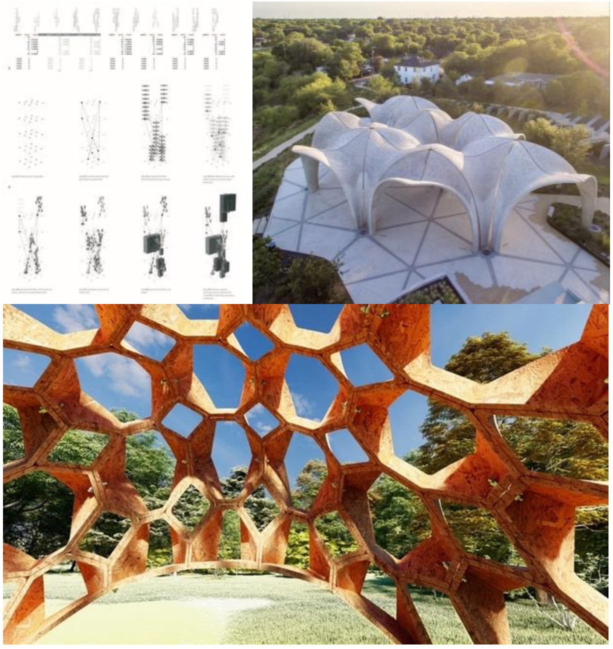


Figure 4.19. (1) Growth simulated on evolutionary-based algorithm (Weinstock 2010), (2) The BHP Pavilion at Confluence park, Credit: Casey Dunn. (Kudless, Zabel and Florian 2020), (3) Epithelial cell inspired-brick in Masonry shell System (Teng, Jia and Sabin 2020) retrieved from https://cyphylab.chora.tu-berlin.de/ecaade2020-galleries/

On the other hand, with the increasing interest on unconventional spaces with freeform surfaces, the adaptability of the blocks becomes a must. However, following these surfaces entails the need to create large number of block types which makes production and construction difficult and time consuming.

In this context, in the scope of second case study conducted in this thesis, considering the stacking behavior of crystal formation, its regular and higher order symmetry based on the unit and the lattice, the solution to the following question has been explored: “How customized standardized building blocks can be designed with minimum type and maximum flexibility?”. In parallel to the research question posed in architectural domain, crystal formation is explored based on its space filling (like in geodes), self-standing and self-assembly properties in lattice scale. In this search the symmetry operations defined in a single unitcell and found in lattice structure are found instructive.

4.4.3 Mapping

Data related with the defectious behaviors of crystals observed and obtained from literature provides information about adaptive behavior of crystals during growth. The parameters defining this behavior are found to be the unitcell parameters (a, b, c, alpha, beta, gamma) and twin rules determining the deformation and thus the resultant lattice symmetry. The defectious behavior of crystals is found to have a great potential to inform the adaptive capacity of building blocks creating variations to change direction and provide flexibility to the resultant partition like wall, slab, roof etc. In this mapping process, as module parameters are informed from the unitcell configuration, the adaptation strategies of modules are found to be related with the twin deformation rules. As a result of this mapping process, a generative model for 3d-module design is achieved that is aimed to become a tool for designers.

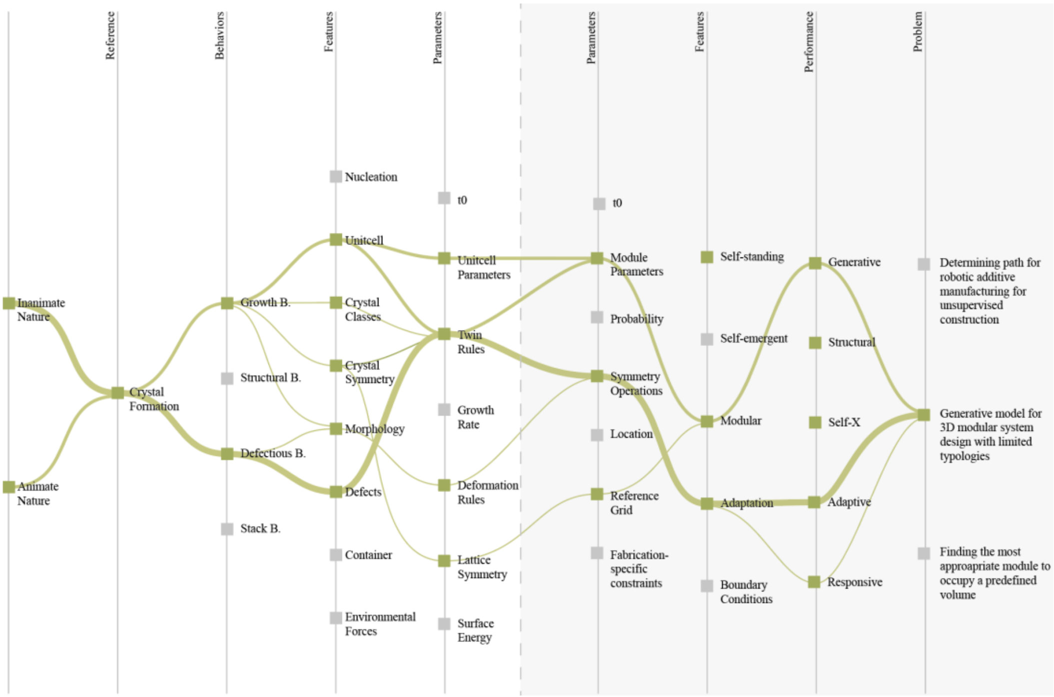


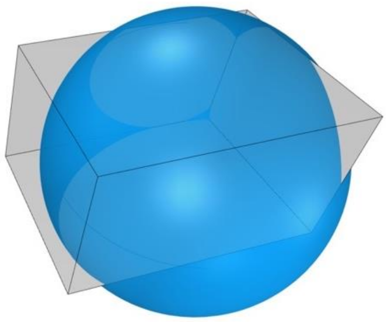
Figure 4.20. Mapping between crystal formation and building block design problem

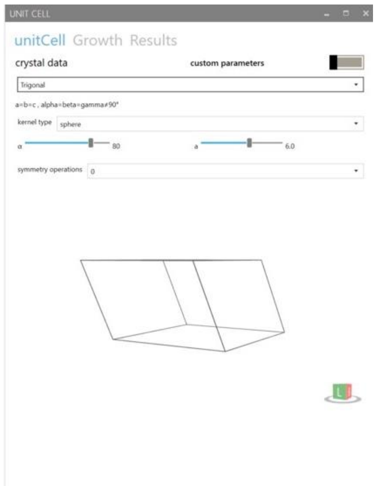
4.4.4 Transfer Learning: Informing the Model

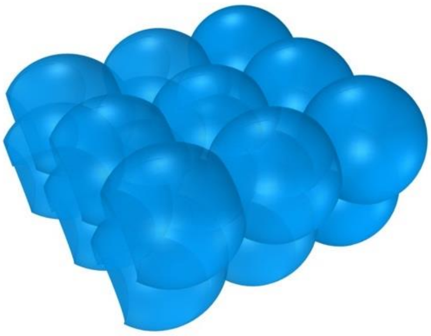
As it is presented in the unitcell section of the reference model development, the symmetry operations found in crystals are observable in nano scale with the orientation of atoms and also in macro scale with the surface formations of crystals. These symmetry operations defined in three dimension provides 230 space groups based on seven crystal classes. Based on the designed reference model, in this case study, the atom location definition technique of material sciences (which is commonly used in CIF), twin formations which is an ordered defectious behavior seen in crystals are incorporated in the current model to provide a control and flexibility for module generation.

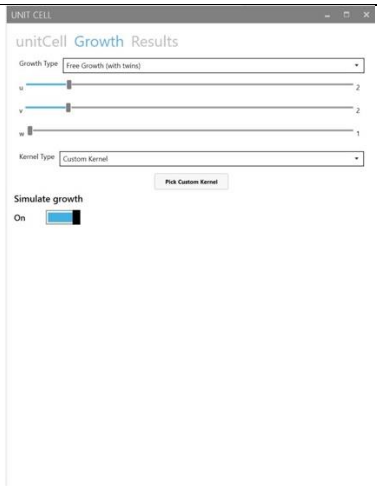
Initially, reference module is required to be defined with parameters of lengths and angles. Then, a custom module which is defined as a solid (or boundary representation – Brep) is required within the reference module. Then, as shown in the part 4.2.1, symmetry operations can be executed for this module to create the unit to be translated in a lattice structure. Then, to create connections between modules a series of Boolean operations are executed. For this case, to increase the adaptive capacity of the model, twin formations are included in the module with a control of mirror plane. Exemplary studies on a single sphere with 0 symmetry which is also called identity and an ellipse with *3m* symmetry is presented in Table 4.3 and Table 4.4.

Table 4.3. Sequential growth of a sphere in a trigonal cell with *0* symmetry (Identity)









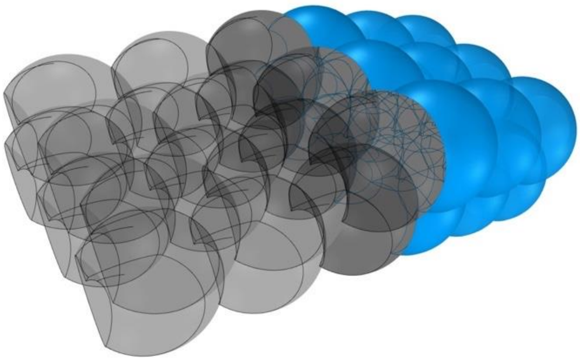
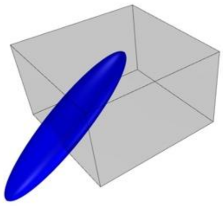
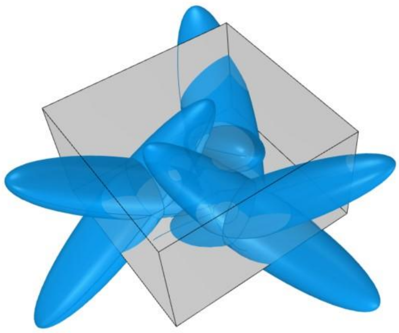
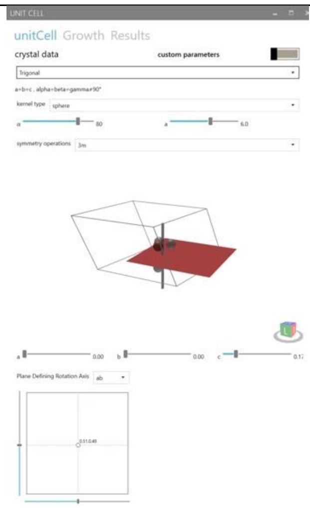
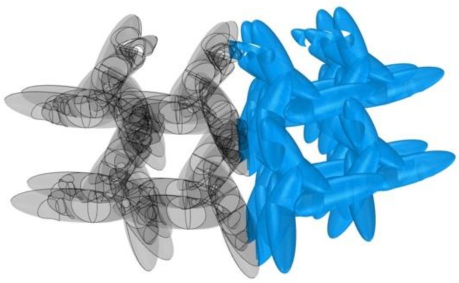


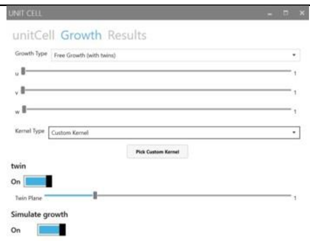
Table 4.4. Sequential growth of Ellipse in a trigonal cell with *3m* symmetry











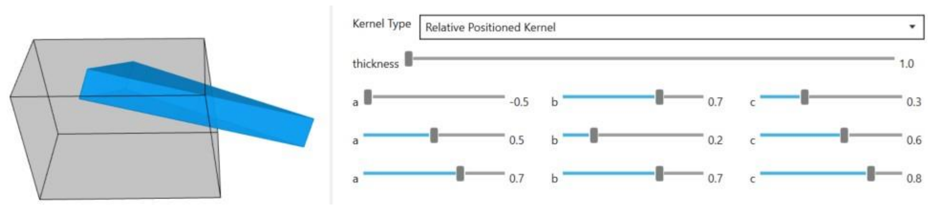
Secondly, the definition of the custom module is revisited once more to define a parametric one depending on reference. For this purpose, the method of atomic locations is used. In the method used in CIF, along with space group defining the symmetry operations and its operations, the locations of atoms are defined with their local coordinated within the unitcell considering the start of an axis as “0” and end as “1” (Figure 4.21(1)). Similarly, the model is extended to include such relations to create a custom module as shown in Figure 4.21(2).

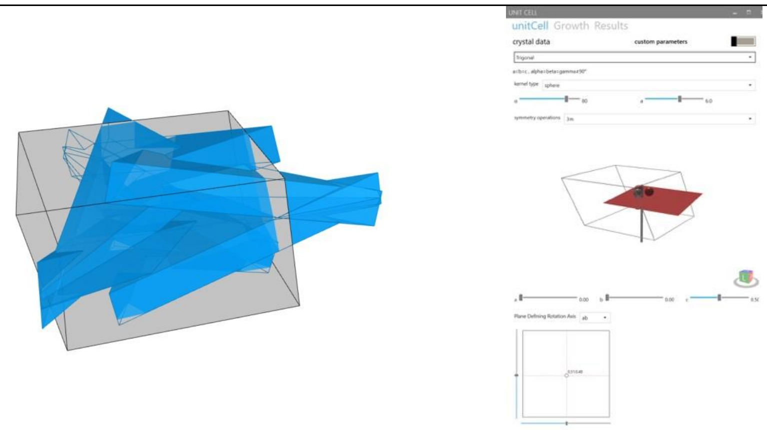
```
_symmetry_space_group_name_H-M 'P 21 3'
loop_
_space_group_symop_operation_xyz
 'x,y,z'
 '1/2-z,-x,1/2+y'
 '-z,1/2+x,1/2-y'
 '1/2+z,1/2-x,-y'
 'z,x,y'
 '1/2+y,1/2-z,-x'
 '1/2-y,-z,1/2+x'
 '-y,1/2+z,1/2-x'
 'y,z,x'
 '-x,1/2+y,1/2-z'
 '1/2+x,1/2-y,-z'
 '1/2-x,-y,1/2+z'
loop_
_atom_site_label
_atom_site_fract_x
_atom_site_fract_y
_atom_site_fract_z
Si1  0.00000  0.00000  0.00000
Al1  0.25800  0.25800  0.25800
Na1  0.74500  0.74500  0.74500
O1   0.12500  0.12500  0.12500
O2   0.66000  0.64500  0.05600
```

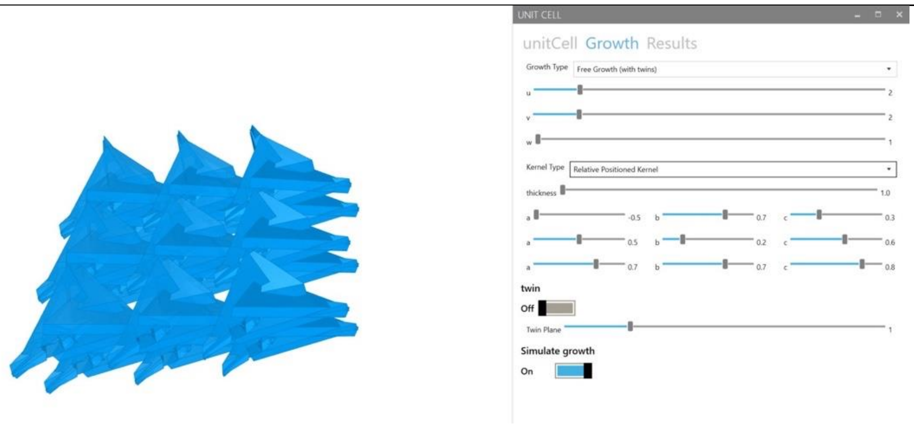
(1) (2)

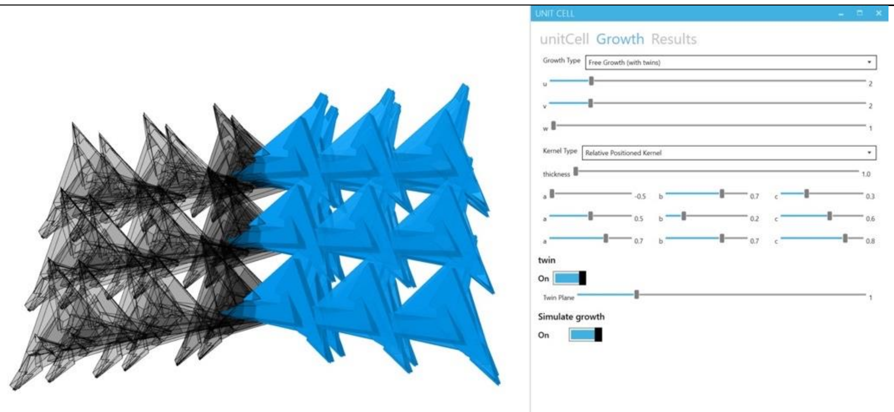
Figure 4.21. Local coordinate system of the model

Table 4.5. Growth of a module defined locally









4.4.5 Outcome of the Process, Test and Validation

As a result of the simulation growth and Boolean operations, model provides unique modules for stacking as shown in Figure 4.22. These modules are (1) initial modules, (2) modules located as the interface of mirrored part and (3) the mirrored regular ones.

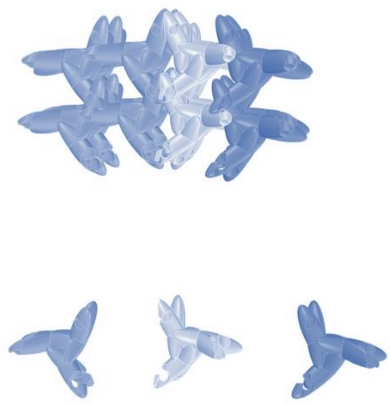


Figure 4.22. Resultant unique modules forming the 3d tessellation

These resultant models are printed with Fused Deposition Modeling (FDM) printer with Polylactic acid (PLA) thermoplastic. Depending on the size and the initial form, the precision of the connection details changes and yet provides input for design optimization.

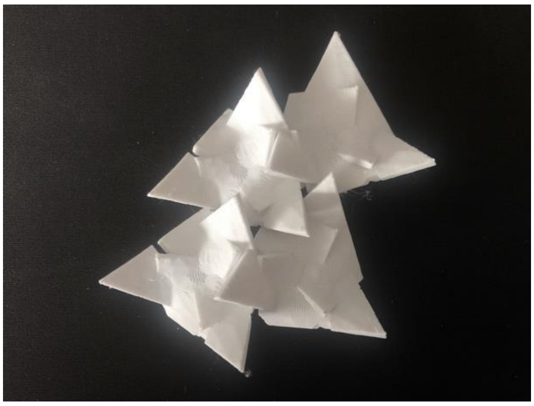


Figure 4.23. 3d printed model

Finally, the learning transfer process is assessed with the provided table (Table 4.6) and it is seen that although the designed model has great potential to be extended with more crystal defect types and more complex problems, provided model meets the requirements of the current research question. The overall process is illustrated in Figure 4.24.

Table 4.6. Assessment of transfer learning process for Case-2

	Data	**Capta**	**Mathematical and/or Computational Models**	**f(x): Mapping**	**Transformation**
Precision	Collected data on crystal growth (without defects) represents the basic behavior.	Captured data found adequate for the problem. Yet, definition of the twinning planes can be elaborated as in crystal formations.	The mathematical model designed for module design caries the precision of the defined initial model.	Mapping process is executed to meet the needs of tessellation.	
Validation -constraint -limitation -accuracy			Performance of the reference model is evaluated with comparison with the literature and the results of the observations.	Parameters of both reference and target domain are paired.	Speed of module design is radically increased.
convergence		Captured data on crystals reflects the behavior of flawless crystals as well as defectious behaviors.	The relations constructed in the model converge with both the crystals and the targeted module design.		The transformation performed between the behavior-performance and parameters serve to understand and model both cases.
scalability	Besides crystals, modular growth can be observed in cells, animal swarms and animal architecture.	Other defects types like edge dislocation can be included in the model.			The problem area can be extended to follow a specific curve, surface or a volume.

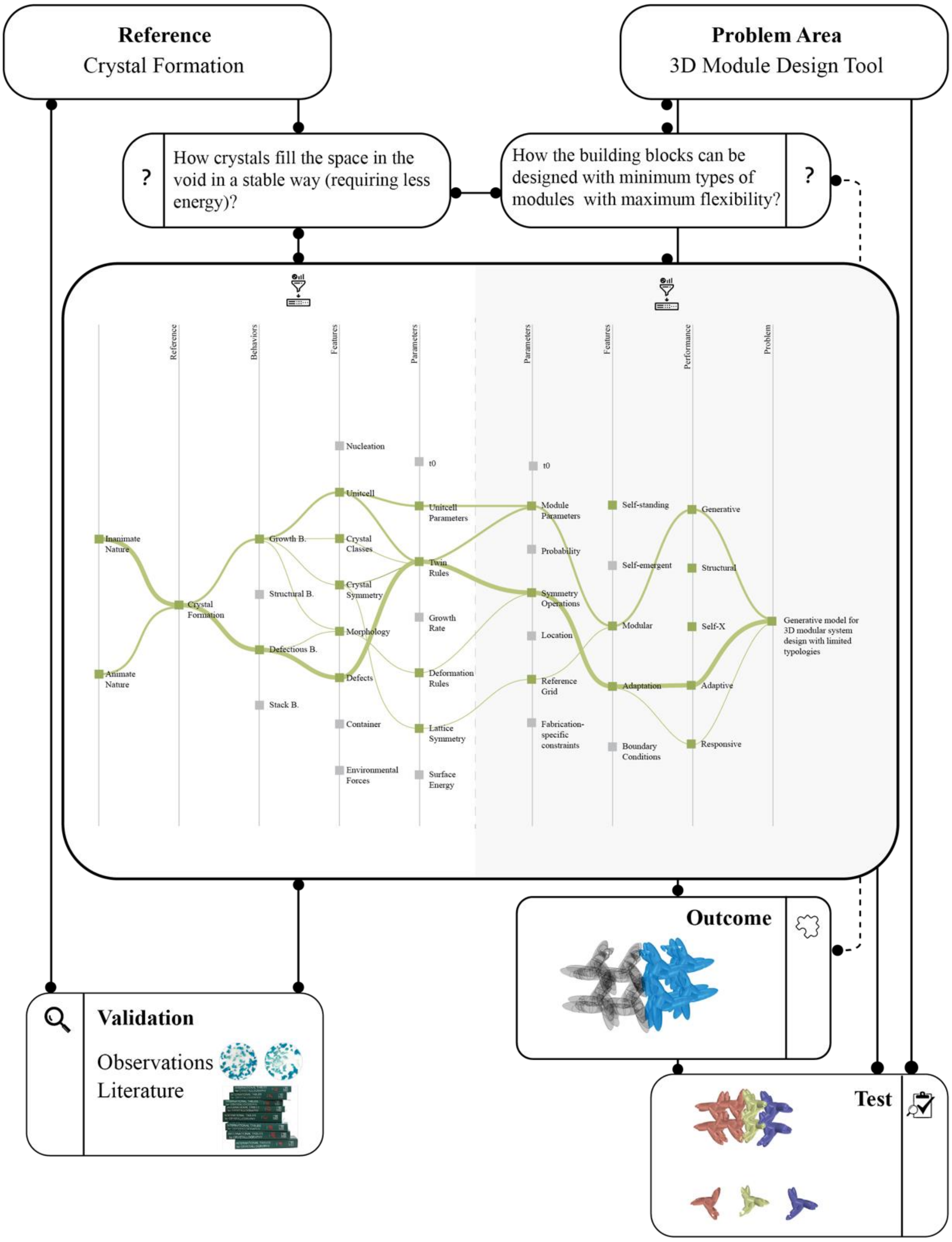


Figure 4.24. TLM for BBT case informed from crystal growth process

4.5 Case 3: Expanding the Possibilities, Extending the Potentials: X-Gen

In this case, the potentials of exploring, retrieving and modeling the captured data obtained from natural beings, and/or their behaviors to expand the application areas, enhance the potentials, and increase the possibilities by transferring the data model into a new medium/model/context. This process can be seen as the one step further than imitating/mimicking, instead it is an act to understand, model and transfer the observed behavior into a totally new context. This process not only transfer the information into a new medium for a new challenge through a data model, but also extend the potentials of the behaviors to operate in a different environment and for different challenges.

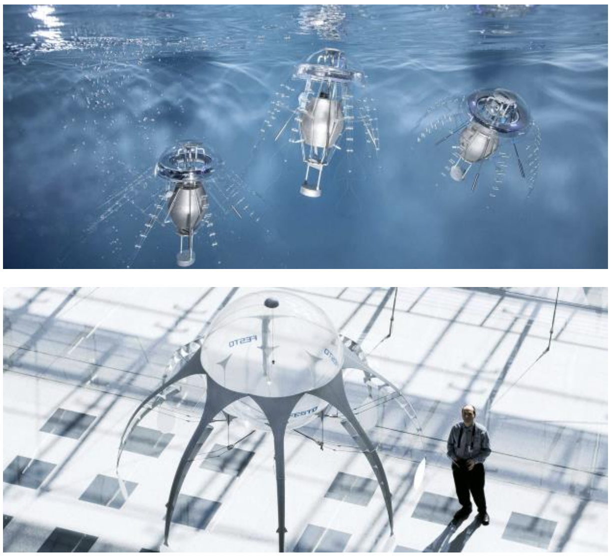


Figure 4.25. Aqua Jelly and Air Jelly projects by Festo retrieved from https://www.festo.com/group/en/cms/index.htm on 17.12.2020

The bionic robots: Aqua Jelly and Air Jelly designed by Festo can be counted as one of the well-known examples (Figure 4.25) portraying a similar approach. As it is observed in these studies, the information retrieved from jellyfishes about their movement is first adopted to create a bionic product mimicking the movement of natural being in water. Then, the founded relations and constructed model is used to design a flying robot achieving the flying capabilities that jellyfishes are not able to.

Similarly, nature-informed studies targeting data transfer from nature to architecture through capta and act of mapping follows a path that reach to a point where reference natural being are not capable of. As this process is realized through designing the captured data, data models and mapping processes, the optimization, generation and evaluation tools that are available today extend the existing the potentials to be adopted for other challenges. The ways to extend the current potentials can be counted as genetic/evolutionary algorithms, machine learning applications and other optimization tools targeting fabrication, production and construction.

4.5.1 Problem Area and Research Questions

As mentioned in the previous study, designing building blocks have always been a subject of interests of architecture. Although today, architects/designers are capable of designing and fabricating customized blocks, considering the cost of material, fabrication and construction, there is still a tendency to prefer the mass-produced standardized blocks from brick, aerated concrete or concrete.

Hence, in this case study, it is aimed to approach this problem area as an optimization problem in which the computational, fabrication and construction costs are optimized while a given form is defined as precise as possible. In crystal formations, geodes provide a great source of information on occupying a space with a single type of units. Yet, the type of unit in geodes are the ones exist in the environment and there is not any chance to find a more efficient one to form the geode. Therefore, here, the parameters defining the unit and the modeled growth behavior based on Monte Carlo method is employed to optimize the module which brings the following research question: “How a module can be determined to fill a defined volume as precise as possible with limited number of units?”

4.5.2 Findings on Geodes

Geodes as forms of crystal formations in a closed environment (rock) which can be referred as space filling crystals provides valuable information regarding the occupation capacity of different crystals (Figure 4.26).

Figure 4.26. Different geode types found in nature retrieved from https://geology.com/articles/geodes/ on 17.12.2020

In different scales, the geode formations are simulated with different approaches. In meso scale where polycrystalline clusters are considered with multiple nucleation location, models are mostly constructed based on the displacement of faces as in Figure 4.26-1. As a result of this approach, the resultant models provide the texture of geode in three stages: isolated growth, competitive growth and parallel growth (Garcia-Ruiz and Garcia-Ruiz 2002).

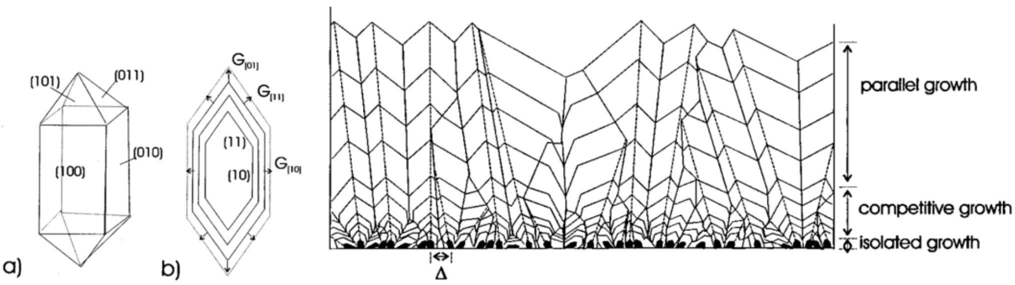


Figure 4.27. (1) Schematic single crystal growth and (2) Simulation of crystal growth starting with 35 crystals (Garcia-Ruiz and Garcia-Ruiz 2002)

On the other hand, in nano and micro scales, the growth mechanism can be modeled as in previous cases with the translation of unitcell depending on the surface energy, container and obstacles. In this case, especially, the container is a more determinant factor than previously presented case studies.

4.5.3 Mapping

The growth behavior modeled of the third case study is the behavior of single crystal unit is based on unitcell, its symmetry features and the container. As the parameters defining the unitcell play a crucial role on the size and volume of the module, the growth order is modeled based on the surface energy of kink states and the impact of container both as an obstacle and an attraction for the growth. The relationship between the growth and the container is found directly related with the main task of the case which is occupying the predefined volume. Moreover, the method of defining the building block is borrowed from crystal unitcell parameters. As a result, the generative model is achieved to find an optimal module to fill a predefined space which is determined with boundary surfaces.

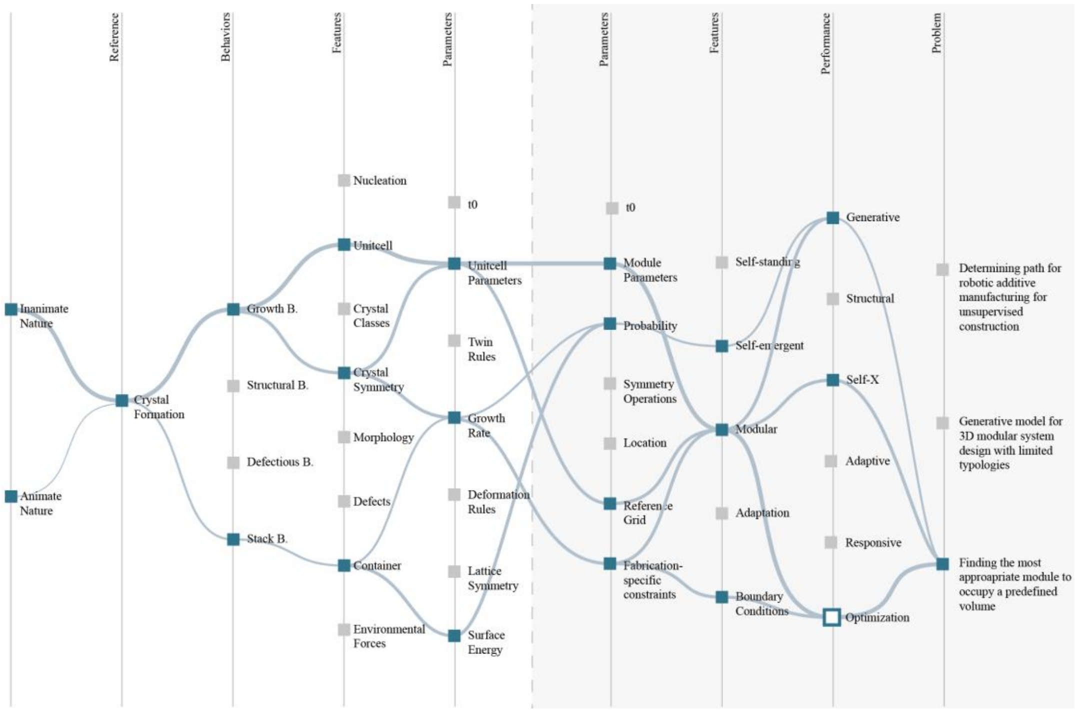


Figure 4.28. Mapping between crystal formation and module parameter optimization problem

4.5.4 Transfer Learning: Informing and Extending the Model

The generative model is developed in Rhinoceros modeling modelling environment with Galapagos component of Grasshopper along with the Monte Carlo based python script that explained earlier. In this model, unitcell parameters are defined as the variables of the genetic algorithm in which the occupancy ratio of the resultant convex hull ($V_{convexhull}/V_{container}$) is aimed to be maximized. In this process, the only constraints are the number of total units that is allowed to be created and the initial generation point which is the centroid of the volume. Additionally, for each case, volume of growth (convex hull), number of units and length of growth paths are presented in the interface.

The initial results of the following parameters are presented in Figure 4.30:

- $Container = Cylinder\ (\mathrm{d} = 25, \mathrm{h} = 25)$
- $a_{min} = b_{min} = c_{min} = 0\ (step = 1)$
- $a_{max} = b_{max} = c_{max} = 10$
- $\alpha_{min} = \beta_{min} = \gamma_{min} = 0\ (step = 10°)$
- $\alpha_{max} = \beta_{max} = \gamma_{max} = 150$
- $Max\ duration = 15 hours$

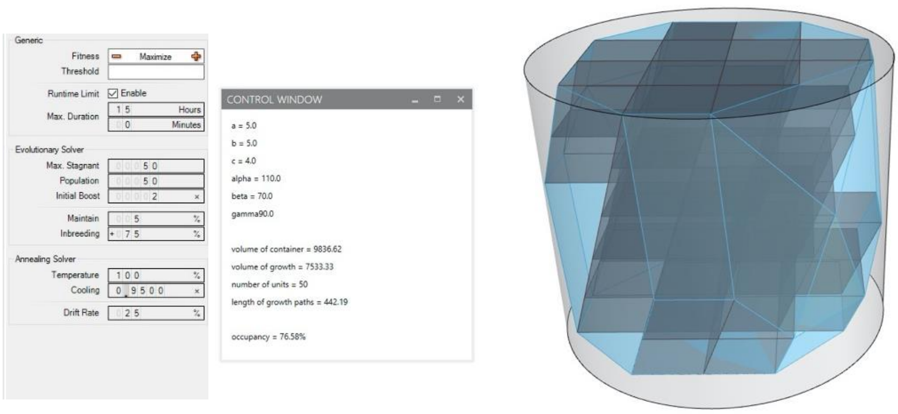


Figure 4.29. Parameters and results of the model

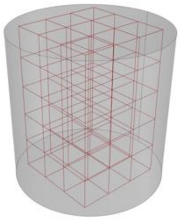
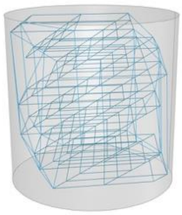
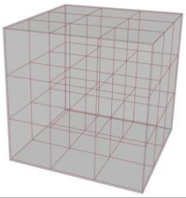
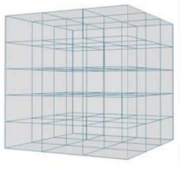
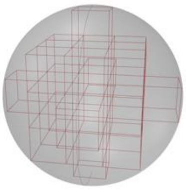
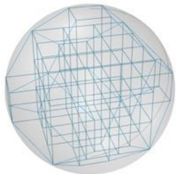
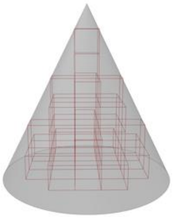
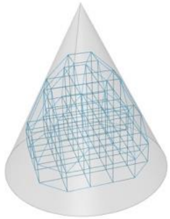
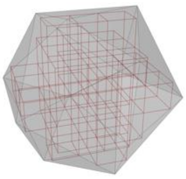
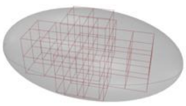
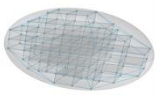
Figure 4.30. Resultant genomes of the evolutionary model

The process of learning in this case is different than the previous ones. In this study, while the unitcell and growth process features are preserved along with the modeling methods, by adopting an optimization algorithm, the potentials of the observed behaviors are extended to be able to determine the best module for a container. Although there are some limitations regarding the starting point or being not applicable to forms having a centroid outside of its geometric boundaries, the created potentials are valid for certain cases. Moreover, the resultant convex hull encapsulating the generated modules has planar faces and thus with more computational power and more flexible modeling environment, this model has potential to define a new kind of mesh model for any given solid defined in surface modeling programs.

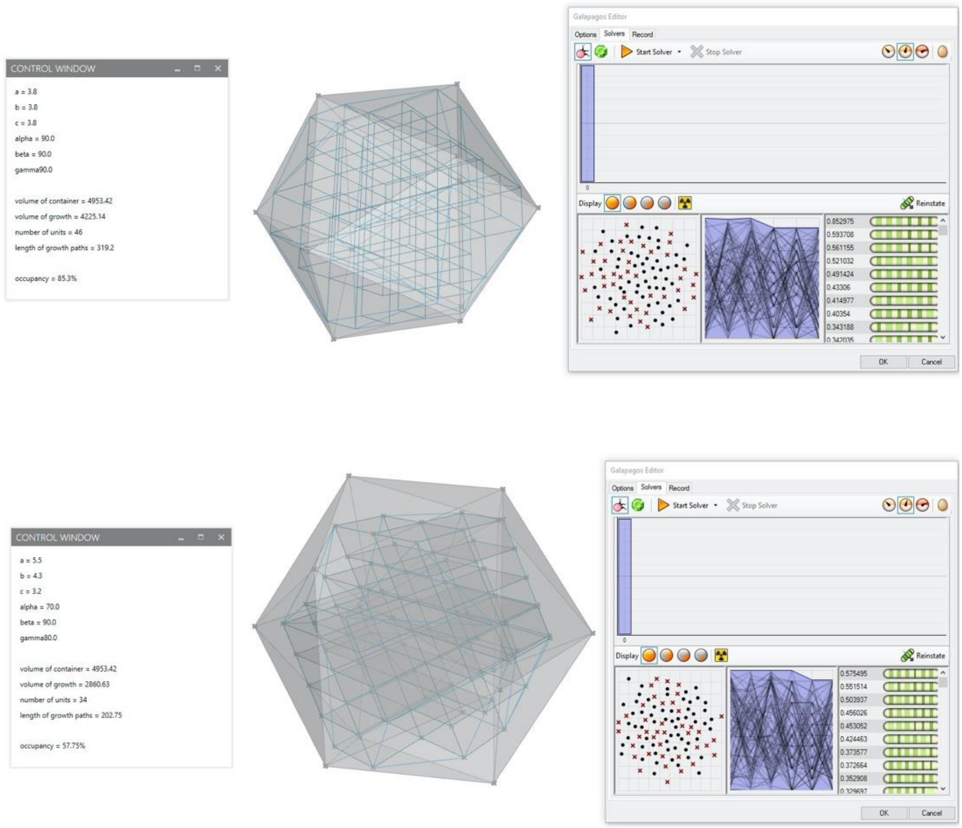
4.5.5 Outcome of the Process, Test and Validation

The outcome of the proposed model is tested with different boundary conditions with same starting point which is the centroid of the given volume and restriction of maximum 50 unit. Moreover, the same configuration is tested with cubic units with the same parameters. The results are presented in Table 4.7.

Table 4.7. Results of the proposed algorithm and the benchmark module generated with the model developed by author

Container	**Filling with cubic units (max 50 units)**		**Filling with optimized units (max 50 units)**	
	Result	#modules Module param. Occupancy	Result	#modules Module param. Occupancy
Cylinder (d:25, h:25)		45 modules 5*5*5 90,90,90 46%		41 modules 7,5*7,5*2,4 110,40,80 71%
Cube (l=25)		27 modules 8,2*8,2*8,2 90,90,90 95%		50 modules 8,3*8,2*5 90,90,90 98%
Sphere (d=25)		34 modules 4,8*4,8*4,8 90,90,90 72%		34 modules 4,8*4,8*4,8 90,90,90 72%
Cone (d=25, h=25)		50 modules 3,4*3,4*3,4 90,90,90 75%		50 modules 3,2*3,2*3,2 90 90 90 61%
Icosahedron (d=25)		46 modules 3,8*3,8*3,8 90,90,90 85%		46 modules 3,8*3,8*3,8 90,90,90 85%
Ellipsoid (r1=12,5 r2=25)		40 modules 5,6*5,6*5,6 90,90,90 67%		50 modules 6,3*6,5*2,4 65%

As presented in the table, the performance of the algorithm varies in different platonic and ellipsoid shapes. During the experimentation on different solids, it is seen that the starting values given to the algorithm plays an important role on the performance of the final outcome. For instance, in the case of icosahedron, the occupancy results of 90*90*90 degrees module and 90*90*120 degrees module are 85% and %58. Considering the space searching algorithm working in genetic algorithms, the reason of discrepancy is seen to stack in a local optima where there is a more optimal solution in the space. Therefore, in the proposed algorithm, the parameters of optimum cubic cells are provided as the initial values to be optimized. Hence, this process defines a wise guess state where starting point of the algorithm is being calculated before the evolutionary algorithm is executed.



(1)

(2)

Figure 4.31. Two different runs of algorithm started with different initial variables: (1) started with benchmark module, (2) started with 90*90*120 degrees module

Table 4.8. Assessment of transfer learning process for Case-3

	Data	Capta	Mathematical and/or Computational Models	f(x): Mapping	Transformation
Precision	Collected data on crystal growth and unitcell parameters represents the basic behavior.	Captured data found adequate for the problem. Yet, adoption of defectious behavior could enrich the solution space.	Reference model reflects the behavior of the reference being and its behavior. The informed model provides information regarding the modules and mesh structure.	During the mapping process, some of the location of nucleation is omitted due to increased computational time.	
Validation -constraint -limitation -accuracy			Performance of the reference model is evaluated with comparison with the literature and the results of the observations.	Parameters of both reference and target domain are paired.	Occupancy ratio is increased. Due to incrementally increasing computational time, tests are limited in the current modeling environment.
convergence		Captured data on crystals reflects the behavior of flawless crystals. Capta of problem area covers the main issue targeted in this study.	The relations constructed in the model converge with both the crystals and the targeted voxel and mesh production techniques.		The transformation performed between the behavior-performance and parameters serve to understand and model both cases.
scalability		Captured data can be augmented by including defects like edge dislocation, twinning and deformation.	Model can be extended to include defectious behaviors to fit unconventional surfaces more precisely.		The provided evolutionary algorithm can inform voxel-based mesh optimization algorithms for ML applications and production processes.

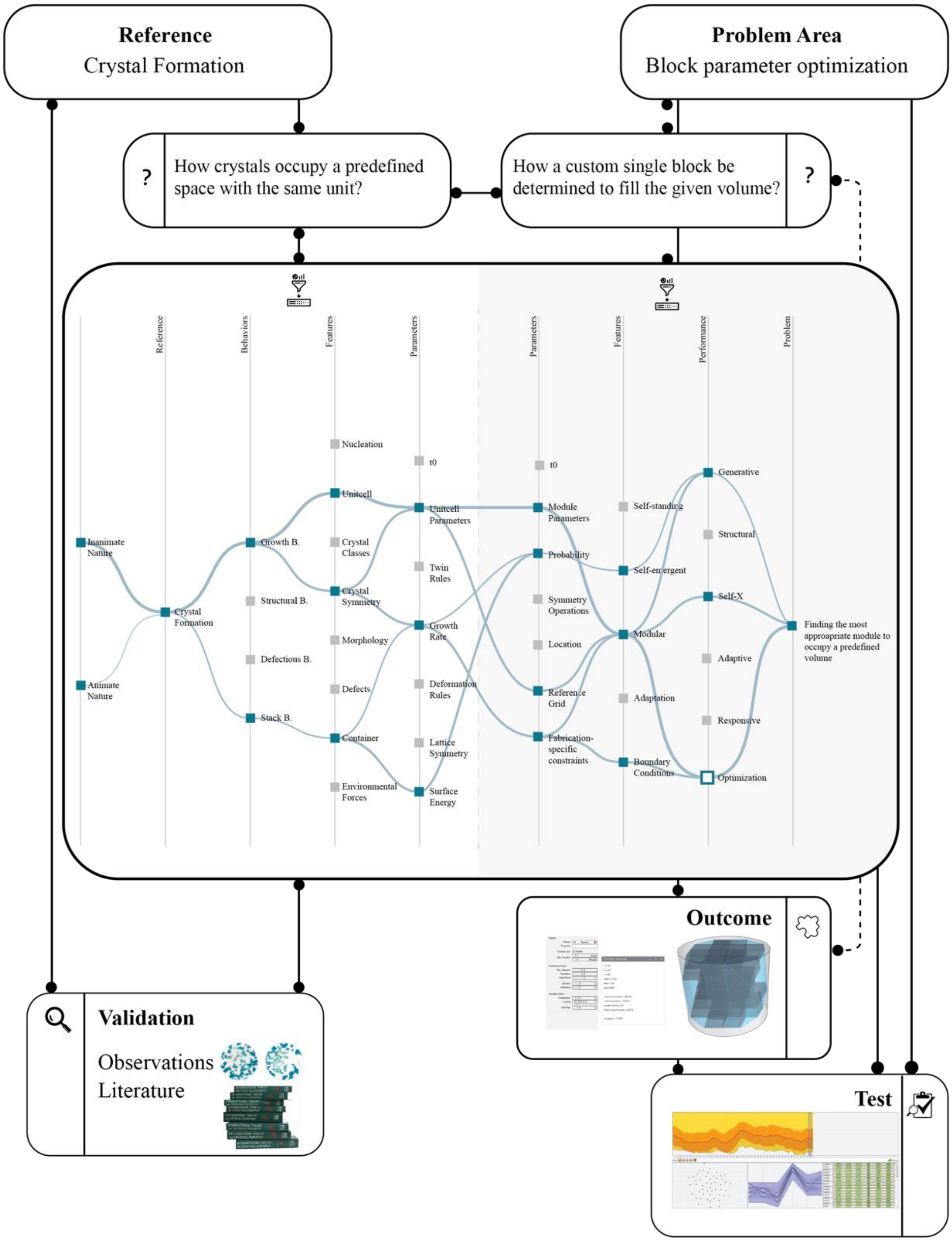


Figure 4.32. TLM for GenX case informed from crystal growth and module optimization processes

CHAPTER 5

CONCLUSION

Data of nature, understanding, and modeling it gained a great importance in the last decades with the expansion of observable scale in many dimensions. In this period, humankind's way of looking into nature and learning from it changed from mimicking to adapting, and from imitating to learning. With the advents in technology, abundance of data, and changing problems of architectural design, today, nature is already a source of information for architecture in many scales. In this thesis, this relation is revisited with current needs of architectural domain, exploring abiotic nature, defectious behaviors and elaborating the method of learning focusing on data transfer. As a result, a novel approach encapsulating all these constituents called nature-informed architecture (NiA) is proposed.

Correspondingly, this study is constructed on the hypothesis addressing the change in the act of learning from nature, and changes in design and construction processes. Questions related with the hypothesis are affirmed in relation with the act of learning, lessons to be learnt to design/generate holistic processes and the role of architects in this transformation. The research, discussions and outcomes of these questions are presented as the outline of the thesis in Table 5.1.

Moreover, in the following part, the main discussion that this thesis aiming to bring forward along with concluding remarks and recommendations for future works are presented.

Table 5.1. Contributions of chapters to the research questions of the study

Research Questions	**Chapter 2**	**Chapter 3**	**Chapter 4**
Q1. How inanimate nature and defectious behaviors in nature be incorporated with architectural problems as sources of information?		**3.1. and 3.2.** The potentials of inanimate nature and defectious behaviors are shown.	**4.2 and 4.3.** The outcomes of this learning process are presented with case studies:
Q2. How the data transfer between nature and architecture be realized to transfer the information retrieved from nature in terms data selection, relations and role of model?	**2.1, 2.2, 2.3, and 2.4.** The existing studies aiming to transfer information from nature to architecture are studied as narrative and critical literature surveys **2.3.** The evolving definition of model is studied in part 2.3. **2.4.** As a part of crital literature survey, the features of reference and target domain are explored. Exploration on existing correlation among the data of problem space and the reference space are presented .	**3.3.** With the concepts of data, capta, behavior, parameter, objective, and performance the selection process is described The method of mapping data based on the data stops and dimensions are explained. The meaning of model is revisited and redefined in the scope of NiA The NiA approach and its proposed transfer process introducing TLM is presented.	**4.1.** Methodology which is adopted to specific case studies are presented. **4.2.** Selection of the relevant data and developed reference model is presented **4.3, 4.4, and 4.5.** The outcomes of the constructed correlations between crystal formation and architectural problems are presented with case studies
Q3. How the design processes and construction process will be designed/generated together? What can we learn from crystal formations in this problem?	**2.5.** The problem area of holistic design and construsction process design is discussed		**4.2., 4.3 and 4.5** Two of the mostly common issues of todays applications are illustrated and informed.
Q4: What will be the role of architects in this process? Will they serve as programmer or supervisor in addition to be the designer?	The traces of changing role of the architects have found in the literature, while exploring the common definitions of data, capta, model and mapping. Yet, the targetted role is presented through case studies: (1) to involve in interdisciplinary studies, (2) to manage the design process from idea to construction, (3) to be able to model, programme and assess both processes.		

5.1 General Discussion

In this part, the discussion carried throughout the thesis with literature survey, theory development and case studies are concluded with remarks. These discussions which are also the contributions of the thesis are congregated under a holistic approach proposed and referred as Nature-informed Architecture (NiA).

In the scope of NiA, along with current approaches, the concepts of data, data literacy, capta and model are revisited, and well-known terms: scale, precision, and accuracy are redefined for the proposed approach and the resultant model.

Considering the research projects conducted in the last century, it is seen that there are few moments that creates the paradigm shift in the praxis of learning from nature: (1) introduction of computational design and using robotics in architecture, (2) the use of artificial intelligence. Along with this thesis, it is seen that including the disregarded part of nature which are abiotic part and defectious behaviors, not only the reference of these studies will need to extend, but also the concepts of fitting and resilience should play an active role in nature-informed architectural studies, starting from the cases presented in this dissertation. These relations, paradigm shifts, and approaches are presented in Figure 5.1.

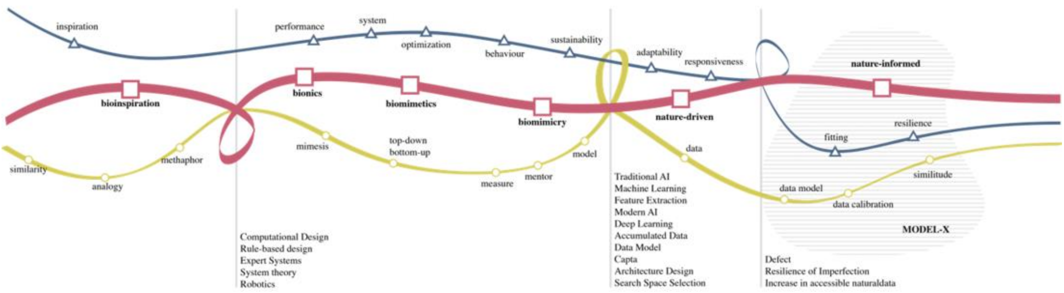


Figure 5.1. Position of NiA: Relations, paradigm shifts and approaches

This thesis is targeted four main issues in nature-informed architectural studies in general: the missed potential of abiotic nature and defectious behaviors, the role of data in information transfer process and the proposed metadata model.

5.1.1 There are New Challenges and New Roles for Architects

Today, architects started to take new roles in design processes with the available plenty of data, continuously developing tools and media and increasing need for intelligent systems. Thus, architectural practice broadened its task and started to include data design, system architecture and optimization. Among them, in the course of any data-driven process, data design process defining choices effecting the course and result of any model (Özgenel 2018) is crucial to understand the role of design in nature-informed architecture. Moreover, learning, understanding and modeling systems in nature and architecture for a specific problem requires an effort that architects have not often face with. In this vein, this dissertation poses new questions regarding new construction techniques, habitats and design methods aiming to find answers from nature through the acts of generation, self-repair and prediction. Approaching the common problem areas in architecture with these definitions are found helpful to understand the essence of problems and create related models to be informed from nature. In this thesis, the process of learning, understanding, modeling and transferring information of nature is called "design under the supervision of nature". Yet, the reference domain which is defined as nature in this thesis has potential to be any domain like engineering, chemistry or medicine that are able to present their data.

On the other hand, when the presented bionic and biomimetic research are assessed in narrative and systematic critical reviews, it is seen that the lack of studies on abiotic part of nature and defectious behaviors limits the reference domain significantly. However, as architecture can also be considered as a part of abiotic nature, among other disciplines revisiting nature for information, architects need to observe abiotic nature more.

5.1.2 Inanimate Nature and Defectious Behaviors Matters

As both narrative and systematic critical literature reviews show us that the focus of existing studies are mostly limited with living beings and their flawless behaviors that presents perfect patterns. However, as nature is studied thoroughly, it is seen that abiotic nature consisting of nonliving beings has an important role in the whole system not only for defining the environment for living beings but also presenting, engrossing features and behaviors. Among many other nonliving beings like winds, rivers, rock formations or precipitation, crystal formations have chosen to be studied further not only as a member of abiotic nature but also as a significant process located in the intersection set of biotic and abiotic nature. The crystallization process, which can also be called the solidification process, exhibits both flawless and imperfect behaviors that enable the growth, adaptation and survival of crystals as well as all living and non-living beings.

The defects that take the attention here are the response mechanism of crystal formation against environmental forces or changing conditions. As the crystals adapt to their surroundings, the symmetry of the crystals begins to deteriorate, and in some of these instances, crystal obtains a higher order symmetry. The potential of defectious behaviors is not unique for crystals, these defects can be observed in other members of animate and inanimate nature. Yet, the lessons are similar; the methods to respond, adapt, fit and survive and the data of these potentials brings great benefits for architecture.

5.1.3 Data as the Vessel of Information from Nature to Architecture

Today, there is a growing interest towards data, data science, data engineering and data design with the introduction of data management methods, machine learning algorithms and the concept of Big Data. This interest started to alter each discipline in how they approach a problem and even how to deal with it. In this context, architecture is not an exception. Although architectural design process has always started with data collection, management and modeling, with plenty of data related with each performance and environment of a building forces architects to adopt methods providing large data crunching capacity. In this vein, the definition of data, especially the captured data, which is called Capta, plays a decisive role in design process as it is explained in “data design” description (Özgenel 2018).

Likewise, defining relations among the collected data and creating model from these relations are found crucial not only in the scope of NiA, but also for each design project aiming to achieve a specific performance. Models have always been instructive for architecture in many different forms through centuries, yet the concept of data model is relatively new and necessary addition to the common approaches. While these models are important for architectural design process, they are even more crucial and critical for NiA. Considering the discrepancies of each domain’s knowledge, data processing methods and design approaches, data models provide a non-dimensional medium for information transfer through captured data and related parameters of each domain. This transfer process is called mapping in this thesis and the importance of it is presented within the discussions and case studies.

Moreover, as literature is revisited with the perspective of data transfer, it is seen that even the existing studies are aiming to cope with it with unique methods for each problem. However, a common model regulating this transfer is missing and thus, in this dissertation, a new holistic model aiming to transfer data through data models is proposed.

5.1.4 Transfer Learning Model as the Metadata Model

As one of the main outcomes of this thesis, transfer learning model (TLM) targeting a data transfer approach from nature to architecture is proposed. TLM is defined as a metadata model incorporating and regulating various data having different levels of complexities and also non-dimensional data models constructed within each domain. Benefiting from data science, set theory and machine learning approaches in this search, qualify the model to be generic. It is also possible to claim that the same model can be implemented to transfer information among any two domains. Hence, with TLM, a generic model with explicitly defined process phases and stages is proposed as it is aimed as a part of the objectives of the thesis.

The validity of the model is tested with a group of case studies focusing on crystal formation in different scales. For these cases, a generic model is designed as an opensource algorithm with a user interface. The model provides various inputs such as measurements (length, volume, number of units) as well as procedural data (growth order) for user to implement for different problems. This model is also implemented in the case studies presented in Chapter 4. As a result of three distinct case studies focusing on automated construction, custom building block design and optimization of reference grid (lattice) of building block are conducted and tested with the assessment criteria presented in the scope of TLM. Reminding that there are always more issues to be considered and included for each case, but still for the presented problem areas, proposed metadata model has proven its validity.

5.2 Limitations

There are different kinds of limitations encountered throughout the conduction of research related with observations, defectious behaviors and scope of the proposed model and these are listed below.

Limitations Related with Observations; Due to the long nucleation and growth processes and lack of observation and recording equipment, the number of crystal types were limited. Considering sensitive nature of crystals against change in environmental conditions, controlled ambient conditions are required. However, the fluctuations in the temperature during six/seven days of growth is affected the process and thus the results.

Missing data about Crystal’s Defects and Nucleation Phase; Despite the vast amount of data on the unitcell configuration and symmetry features of crystals providing detailed information about the behavior of crystal in nano and micro scales, there is a lack of information regarding the defectious behaviors, and the impact of environmental conditions on the growth mechanism. Moreover, even for other disciplines dealing with crystals, nucleation phase and the location and the orientation of seed crystal is almost unpredictable. Therefore, this limitation is acknowledged in this thesis with constraints, predefined conditions and probabilistic approach. Consequently, due to the lack of comprehensive data set, the transfer learning model is limited to be a rule-based model instead of pattern-based model that can be implemented with machine learning applications.

Implementation of Transfer Learning Model; In general, transfer learning model is proposed as a generic approach targeting to transfer information from any domain to another. In the scope of this thesis, this approach specifically studied within the context of architecture as NiA. It is important to note here that, considering this approach and its transfer learning model is tested with case studies focusing on only the built environment, there is a need for further case studies for other disciplines.

On the other hand, as this study is one of the precedents of many studies that can adopt the proposed approached and transfer learning model, with more detailed data collection processes, and including researchers from other disciplines and studying other reference beings, all these limitations can be eliminated.

5.3 Recommendations for Future Work

As it is seen in the systematic critical literature survey, in most of the presented studies, there is a need for an increase in a specific performance, implementation of a feature or a new kind of material. These needs direct researchers towards nature. However, today performances are becoming more and more intertwined and thus models representing them become more complex. Therefore, holistic approaches merging design and construction process with resultant performances are becoming more important. Like presented model (TLM), more metadata models are required to manage data in different scales and complexities as well as data models.

Moreover, considering the increasing attention towards self- behaviors like self-emergent and self-assembly, the related research can also be conducted under the supervision of nature.

Considering the potentials of abiotic nature, crystal formation can be counted as a single drop in an ocean. Events in atmosphere, sphere and oceans, formations of rivers, mountains provide valuable information to architecture with its nature to respond, adapt, fit and survive. Even in crystal formation that are studied thoroughly in this thesis, there are many other features and behaviors that can be captured, modeled and learned from like nucleation, defects (edge dislocation, point defects, bulk defects) and intergrowth.

For any future studies, while conducting observation studies, if ambient conditions can be supplied and observed with number of different crystal types collected data would be more precise and be used for pattern-based learning models. With large datasets related with flawless and defectious behaviors of reference beings retrieved from both literature and observations, this research can proceed with implementation of machine learning, especially deep learning models retrieving information directly from the capta without human intervention. It is believed that the patterns to be revealed in the data sets will bring more information into architecture.

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EDUCATION

Degree	Institution	Year of Graduation
MS	METU, Computational Design and Fabrication Technologies in Architecture	2013
MS	TU Delft Architecture, Urbanism, Building Science, Computational Design and Fabrication Technologies in Architecture	2012
B.Arch	METU, Architecture	2009
High School	Gazi Anadolu High School, Ankara	2004

WORK EXPERIENCE

Year	Place	Enrollment
2020-Present	METU Design Factory	Researcher
2015-2020	METU Dept. of Architecture	Research Assistant
2013-2015	METU	EU Project Researcher
2013	METU Dept. of Architecture	Student Assistant

FOREIGN LANGUAGES

Advanced English

PUBLICATIONS

1. Sorguç A., Kruşa Yemişcioğlu M. "Mimarlıkta Fabrikasyon Teknolojileri ve Endüstri/Mimarlık 4.0". Dosya 45: Gelecek, Teknoloji ve Mimarlık, ss.6-17 (2020)
2. Gönenç Sorguç, A., Özgenel, Ç.F., Kruşa Yemişcioğlu, M., Küçüksubaşı, F., Yıldırım, S., Antonini E., Bartolomei, L., Ovesen, N., Steino, N. "STEAM Approach for Architecture Education", eCAADe+SIGraDi Conference 2019, Porto. (2019)
3. Gönenç Sorguç, A., Kruşa Yemişcioğlu, M., Özgenel, Ç.F. "A Computational Design Workshop Experience for 21st Century Architecture Education", eCAADe+SIGraDi Conference 2019, Porto. (2019)
4. Gönenç Sorguç, A., Kruşa Yemişcioğlu, M., Özgenel, Ç.F. "Sayısal Tasarım Eğitiminde Doğa Öğrenili Mimarlık (Nature-Informed Architecture in the Computational Design Education), XIII. MSTAS, Kocaeli. (2019)
5. Gönenç Sorguç, A., Kruşa Yemişcioğlu, M., Özgenel, Ç.F. "Architecture 4.0: A New Manifestation of Contemporary Technology ", International Conference on Digital Transformation & Smart Systems, Ankara. (2018)
6. Kruşa Yemişcioğlu, M.; Gönenç Sorguç, A.; Özgenel, Ç.F. "Crystal Formations and Symmetry in the Search of Patterns in Architecture" eCAADe 2018, Lodz, Poland. (2018)
7. Gönenç Sorguç, A.; Kruşa Yemişcioğlu, M.; Özgenel, Ç.F. "Multiverse of a Form: Snowflake to Shelder" eCAADe 2018, Lodz, Poland (2018)
8. Sorguç Arzu,Özgenel Çağlar Firat,Kruşa Yemişcioğlu Müge (2018). Yazılımların Biçimlendiriciliği,Biçime Yabancı Örüntüler. MSTAS2018: Mimarlıkta Sayısal Tasarım Ulusal Sempozyumu (2018)
9. Gönenç Sorguç, A., Kruşa Yemişcioğlu, M., Özgenel, Ç.F., Katipoğlu, M. O., Rasulzade, R. "The Role of VR as a New Game Changer in Computational Design Education", eCAADe 2017, Rome. (2017)
10. Gönenç Sorguç, A., Özgenel, Ç.F., Küçüksubaşı, F., Kruşa Yemişcioğlu, M., Ülgen S. "Mimarlık Eğitiminde Tepkimeli Kinetik Sistem Taklaşımı"(Responsive Kinetic System Approach in Architectural Education), XI. MSTAS, Ankara. (2017)
11. Gönenç Sorguç, A., Kruşa Yemişcioğlu, M., Özgenel, Ç.F.,"Transcoding Crystals on the search for Extreme in Architecture", International Conference on Mathematical Modeling and Applications Based on Self-Organization (ICMMA 2017), 2017. (2017)
12. Gönenç Sorguç,A., Özgenel,Ç.F., Kruşa,M.,Küçüksubaşı,F., Ülgen, S. "Biçim Arayışında Sayısal İmalat/Üretim Teknolojilerin Dönüştürücü Gücü" (Transformative Power of Digital Manufacturing/Production Technologies in Form Finding), X. MSTAS, İstanbul. (2016)
13. Krusa Yemiscioglu, Müge (2016). Dogadan Ögrenmenin Yeni Mimari Tektoniklerdeki Etkisi. 3. Ulusal Yapı Kongresi ve Sergisi (2016)

Editorial

1. Gönenç Sorguç, Arzu; Kruşa Yemişcioğlu, Müge; Özgenel, Çağlar Fırat (eds.) (2017). MSTAS2017: XI. Mimarlıkta Sayısal Tasarım Ulusal Sempozyumu (XI. National Symposium on Digital Design in Architecture): İmkansız Mekanlar: Olanaksızın Olanağı (Impossible Spaces: Possibility of Impossible), Book, Editor, METU Faculty of Architecture Press (2017)
2. Nexus2014: Relationship between Mathematics and Architecture PhD-Day Book Contributing editor (2014)

RESEARCH PROJECTS

10.2019 –11.2019	Expo 2020 Qazaqstan Pavilion Acoustics Consultancy (2019-16-67-2-00-01) Consultancy / Project Researcher
05.2018 – 05.2019	Noise Removal with Generative Adversarial Networks for Building Documentation GAP-201-2018-2825 Project Researcher / METU
05.2018 – 12.2018	Istanbul New Airport Ribbon Wall Parametric Construction Detailing Consultancy/ Project Researcher
01.2017 – 12.2018	Greening the Skills of Architecture Students via STEAM Education (ARCHISTEAM) EU Project Erasmus + KA2 2016-1-TR01-KA203-034962
05.2016 – 06.2016	Istanbul New Airport Steel Construction – Computational Design Project Consultant, Researcher
02.2015 –12.2017	Design of Curriculum for Woodworking CNC Operators in Turkey EU Project Erasmus + KA2 2014-1-TR01-KA200-013304 Project Researcher / METU
02.2014 – 12.2016	Gişe Geçişleri İçin Aktif Gürültü Bariyeri SanTez – 0553.STZ.2013-2 Thesis Student/ METU
07.2013 –03.2014	METU Campus Vertical and Horizontal Noise Mapping BAP – 0811- DPT.2013K120500-3. Project Researcher / METU

06.2012 –01.2013	Hacettepe University Conservatory Building Acoustical Consultancy/ Project Researcher
04.2012 – 08.2012	Türkiye Büyük Millet Meclisi (Turkish National Assembly of Turkey) Acoustical Consultancy, Project Researcher
05.2012 – 07.2012	Türk Telekom Çağrı Merkezi Gürültü Azaltımı (Türk Telekom Call Center Noise Reduction), 2012-02-01-1-0011 Project Researcher
04.2012 – 08.2012	Türkiye Büyük Millet Meclisi (Turkish National Assembly of Turkey) Acoustical Consultancy