The Third Digital Turn of Non-Standard Architecture

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I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

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December, 2020

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ABSTRACT

This thesis explores Non-Standard Architecture, a movement in Postmodern architecture on non-Euclidean parametric and algorithmic formalism, and suggests a series of inherent limits prevented its full realisation. The thesis answers how these limits might be overcome by formulating the Third Digital Turn of Non-Standard. The Third Digital Turn emerged from the Second Digital Turn, an architectural movement from 2012 that realised parametric architecture through novel methods of form finding and construction using parametric data models and robotics. Through the Third Digital Turn the thesis formulates the *Statutes of Non-Standard Architecture* that describe the process of legislation in terms of the invention of new practice for Non-Standard Architecture.

The thesis traces the evolution of the Second Digital Turn through novel interpretations of geometric lineage across architectural epochs, and identifies parametrisation with the codified law of architecture beginning in the Renaissance. The thesis identifies a gap between the possibilities of digital technologies in architecture and the current capacities of the building industry to realise them. Persistent challenges to achieving these objectives of automation are the limits of the regulatory environment and conservative construction practices. The thesis argues that such inherent limits can be overcome by reconsidering the existing regulations that frame technology and by implementing a methodology for ecological governance in architecture.

The thesis contributes to the field in two key areas. First, it evolves Non-Standard architectural codification

and production processes to extend the capacity of existing skills and technologies. Second, it indicates opportunities for environmental sustainability with protocols for Non-Standard design and construction, functional grading of material and automation in architecture.

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CHAPTER 1

The Sovereign Parametric in Architecture

OBLITI PRIVATORUM PUBLICA CURATE[1]

1.1 The Limits of Non-Standard Architecture

The thesis identifies sovereign architecture with the *Statute of Korčula* in 1265, followed by the *Statute of Dubrovnik* in 1272, as a precursor of Alberti's treatise *De Re Aedificatoria* (*Ten Books on Architecture,* ca. 1450), which provided an institutional basis for the discipline and profession of architecture. The *Statute of Korčula* and *Statute of Dubrovnik* unified residential buildings according to a strict city proposal on the predominance of the public over the private interest (Figure 1.1). With this sovereign codification of the city Statute beginning in the Renaissance, the thesis identified Non-Standard Architecture as the core legal system to guide urban development and construction, as well as use of public areas, integrating parametrisation to define architecture and the city. The *Statute of Dubrovnik* made precise provisions for planned urban development based on a high degree of rationalisation in the use of space and municipal structure. Among Renaissance and Baroque monuments in Dubrovnik, parametrisation was inscribed into fortifications and the monumental stone walls with city

Figure 1.1.

Figure 1.1. *OBLITI PRIVATORUM PUBLICA CURATE,* 1443. Portal of the Council Hall in the atrium of *Rector's Palace* in Dubrovnik. Photograph by Nenad Gattin.

[1] Ragusan Renaissance epigraph (1443) on *Rector's Palace* by Cicero referring to Plato's thought in *Republic* on the priority of the public (common) before private. The epigraph indicates Ragusan political prudence and its republican ideals.


Figure 1.2.

gates, with the most outstanding buildings dating from the eleventh century *Rector's Palace* (Figure 1.2) and *Sponza Palace*.

This thesis addresses the limits of realising Non-Standard Architecture by investigating a Third Digital Turn, formulated in the *Statutes of Non-Standard Architecture*: on governance of Non-Standard Architecture, on codification of Non-Standard Architecture, on rationalisation of Non-Standard architecture, on graded materials for Non-Standard Architecture, on automation of architecture and on implementation of research in academia and practice. The Statute emerged from the Second Digital Turn of Non-Standard Architecture, a movement that began in 2012 as an unequivocal moment in the development of the formal possibilities of parametric architecture. By evaluating recent developments, the thesis characterises the Second Digital Turn by novel methods of form finding, material selection and construction methods that use parametric data models and robotics.[2]

The thesis identified the First Digital Turn as being in the 1980s with the parametric design method of designing complex forms using a computer with parametric and algorithmic procedures. This evolution is traced through novel interpretations of geometric lineage across architectural epochs, beginning with the Renaissance, through to the Baroque and Modernism. Following the analysis, the thesis identifies a gap between the possibilities of digital technologies in architecture and the current capacities of the building industry to realise them. The

Figure 1.2. *Rector's Palace* in Dubrovnik. Photograph by Institut za Povijest Umjetnosti.

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[2] Melika Aljukic, "The Second Turn of Non-Standard Architecture," *Architecture Bulletin: Futures*, vol. 76, no. 4 (March 2020): 33–36.

regulatory environment and mainstream construction practices are challenges to achieving automation. These limits can be overcome by reconsidering the regulations that frame technology and implementing a methodology for ecological governance in architecture.

In this chapter, Section 1.2 traces the *Statute of Korčula* and *Statute of Dubrovnik* in the thirteenth century that first enacted a law for urban development and construction disciplining architecture to conform to specific planning regulations (Figure 1.3). Since the Renaissance, the codification of laws in architecture led to radical changes. Section 1.3 relates the codification of Non-Standard to the First Digital Turn and the Second Digital Turn in Non-Standard Architecture. Section 1.4 identifies research questions. Section 1.5 describes and elaborates on the research methodology. Section 1.6 presents the structure of the thesis on the Third Digital Turn of Non-Standard Architecture.

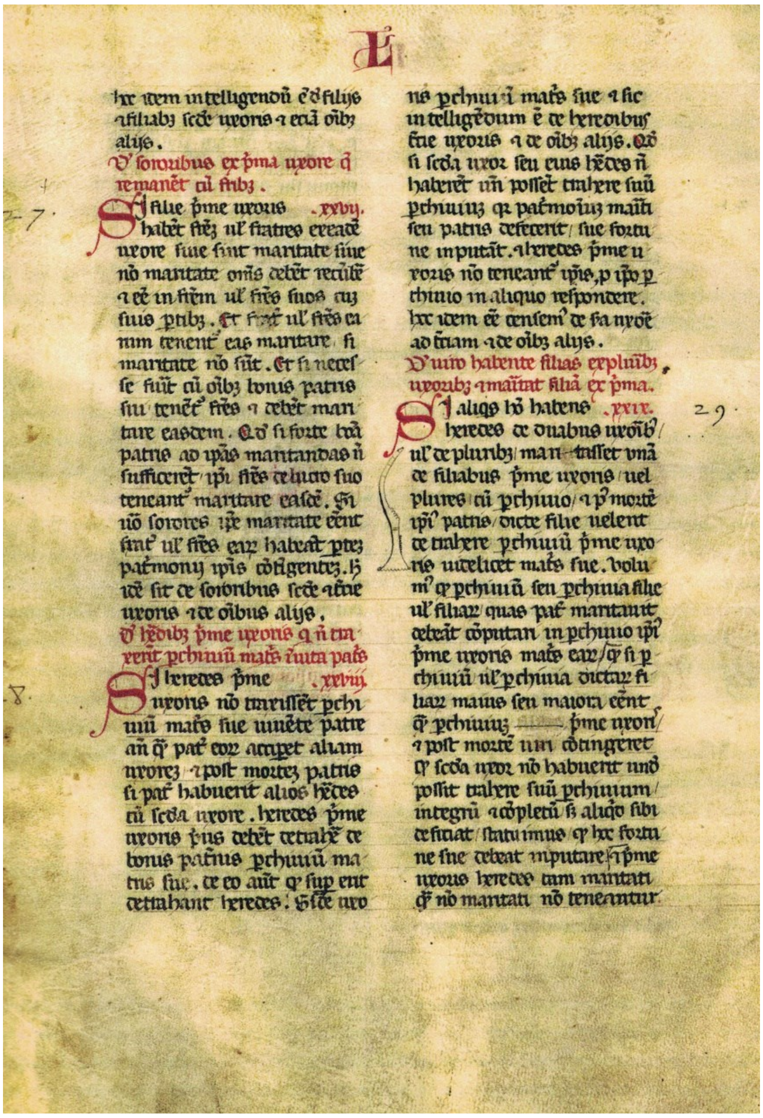

Figure 1.3. *Liber Statutorum Civitatis Ragusii*, 1272. Nella Lonza ed. *The Statute of Dubrovnik of 1272,* trans. Vesna Rimac (Dubrovnik: Državni Arhiv, 2015), Book V.

1.2 Non-Standard Codification of Renaissance Architecture

1.2.1 *The Statute of Korčula*

This thesis identifies the beginning of sovereign Non-Standard parametrisation in the Renaissance with the *Statute of Korčula.* The Statute was a pivotal legislative codification of architecture emerging from local methods of shipbuilding and stonemasonry to prescribe regulations for Korčula town planning and architecture, as well as ecology (Figure 1.4). The thesis traces the method to systematise and rationalise Non-Standard architecture design as pivotal to the Statute.[3] The Statute is the oldest existing legal code of Dalmatian cities written in 1214 and approved in 1265 that guaranteed the autonomy of the island of Korčula and protected the island community. Together with the *Statute of Dubrovnik*,[4] the *Statue of Korčula* is the first legal code on architecture and city planning published by the Dalmatian cities. Earlier codification methods included the fourth century *polis* ideology in Ancient Greece, discussed by Aristotle and Plato. The codification of architecture is then elaborated on in Alberti's treatise *De Re Aedificatoria* (*Ten Books on Architecture*), which provided an institutional basis for the discipline and profession of architecture. Alberti's theorising of the mathematics of perspective cast the Renaissance architectural project as one fully visualised and designed on paper by the architect,

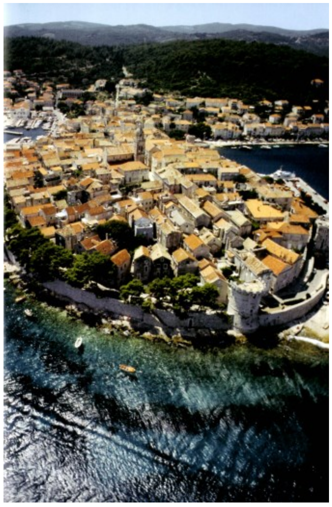

Figure 1.4.

Figure 1.4. Korčula Mediterranean city in Croatia. Photograph by Ivo Pervan.

[3] Antun Cvitanović ed., *Korčulanski Statut* (Zagreb: Tisak, 1987), 133.

[4] Nella Lonza ed. *The Statute of Dubrovnik of 1272 Liber Statutorum Civitatis Ragusii,* trans. Vesna Rimac (Dubrovnik: Državni Arhiv, 2015), Book V.

who thus claimed full responsibility and authorship for a design project. In addition to ascribed civic, intellectual and moral attributes, Alberti affirms shipbuilding as the intellectual basis of the architect's work. The architect must know the parts of the ship, how one ship differs from the next, and how parts of construction hold together.[5]

The *Statute of Korčula* enacted parametric city walls and towers *ex nihilo* in 1265 on a strategically important position, parallel to the course of ships sailing from the Mediterranean Sea to Venice (Figure 1.5). The fortification system reinforced city walls at the points of expected attacks, especially the port, protected from the winds and waves in the southwest corner of the town (Figure 1.6). The city walls were built high in the gothic manner, with later lower bastions added from the outside (Figure 1.7). The bastions included five round towers around the town. The thesis traces Pythagoras' mathematical theorem established between locations of *Zakerjan Tower* (C), *Velika Kneževa Tower* (A), *Svih Svetih Tower* (B) and *Cathedral* (S). With the *Cathedral* (S) at the centre of the Pythagorean triangle tower locations A, B and C were located at equal distance apart (Figure 1.9).

[5] Leon Battista Alberti, *The Use and Abuse of Books* (Illinois: Waveland Press, 1999), 128–29.

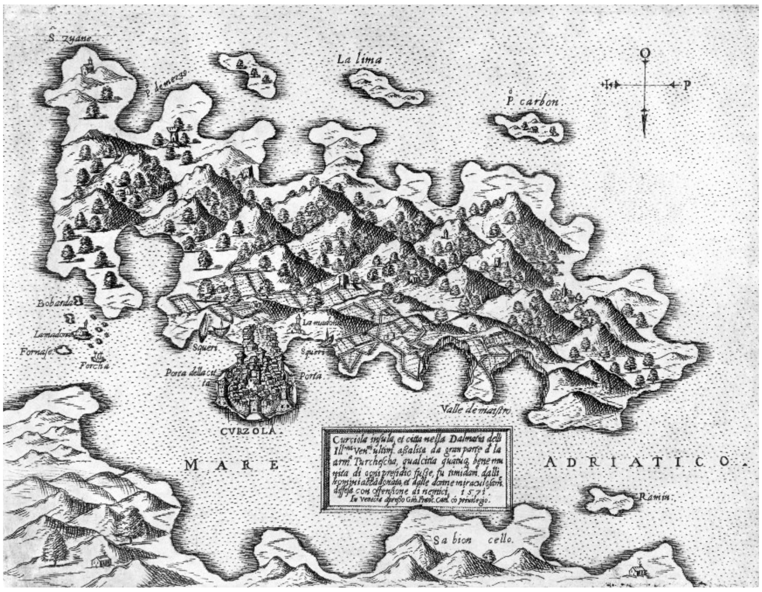

Figure 1.5. Map of Korčula, 1571. Giovanni Francesco Camotio, *Isole famose, porti, fortezze, terre maritime sottoposte alla Serenissima Signoria di Venetia, ad altri Principi Christiani, et al Signor Turco poste in luce* (Venice: Alla libraria del segno di S. Marco, 1574), 19.

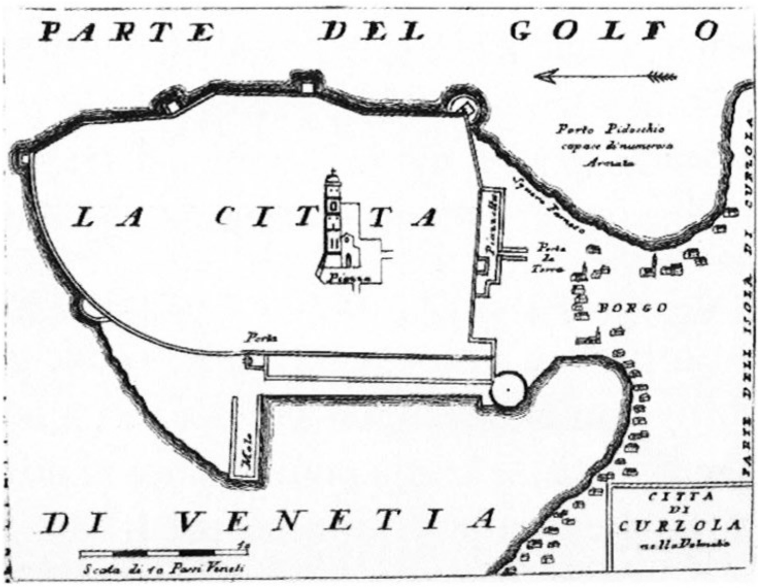

Figure 1.6. Survey of Korčula by V. M. Coronelli, 1688. Korčula Town Museum, Korčula.

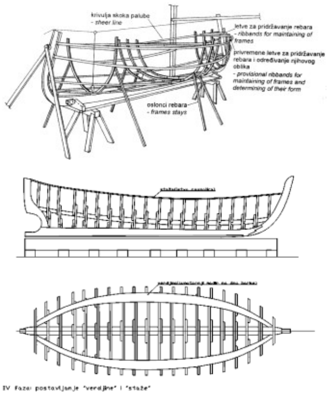

Figure 1.8.

Figure 1.7. Drawing of Korčula from the sixteenth century by C. Astenga. State Archive of Torino, Torino.

The pivotal tactic of parametrisation for the Korčula town ellipse was established from the Korčula town perimeter. It refers to local methods of wooden shipbuilding to generate the curvature between points using the perimeter circle divided into parts according to the street pattern. The term spline describes slats of wood that were bent and nailed to the timber frame of the hull, developed with the method of shipbuilding. As evidenced in the Korčula town plan, the ribs of the ship correspond to the street pattern. The first official document about woodcraft in Korčula is the *Statute of the City and Island* from 1214, pointing to shipbuilding as a key industry in Korčula, specifically concerning wood cutting and the production of tar for the needs of shipbuilding. The thesis traces codification of woodwork by *kalafati* (woodworkers who filled the fissures between the boards) and *maranguni* (craftsmen in wood) who were well known around the world at the time Korčula was built. This early authorship was a secret method *Mezzaluna-buška* of constructing wooden ships without a drawing plan (Figure 1.7). The method was based on a small lath, *buška,* marked with

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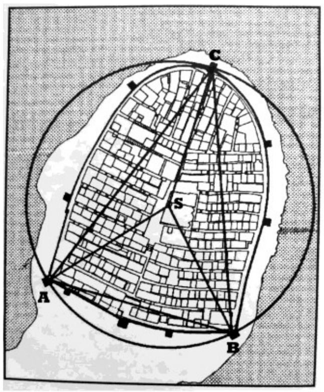
Figure 1.8. Buška – mode of constructing wooden ships without a drawing plan. Korčula Town Museum, Korčula.

elementary measurements for constructing a ship. These increased proportionally depending on ship size. The circle was divided into a number of parts according to length. For instance, if a barge was ten metres long, the circle was divided into ten parts[6] (Figure 1.10). Thin boards called *murili* were used to convey measures on wood (Figure 1.11). A manual tool *blanje* was used to make linear and curved elements of the boat, such as the mast and oars. The *Statute of Dubrovnik* refers to strict planning in writing for *kalafati* patrons to arrange for their ships to be ready, well arranged and coated at their expense.

The Statute confirmed the use of stone and limited its export from the island of Korčula by reporting exports to the government and requiring payment according to weight. Although the *Statute of Dubrovnik* had religious passages, the codification in Book V focused on strict planning of architecture and urban design. The plan of Korčula is a pivotal architectural codification of town planning and building, evidenced still today as a city, generated with the first legislative codification of site specific architecture emerging from local methods of shipbuilding and stone cutting. Similar language within shipbuilding and stonemasonry was used as well as being practised, often as a family business. This suggests a direct link for transferring the spline geometry making in wood from shipbuilding to parametric design in stonemasonry and architecture.



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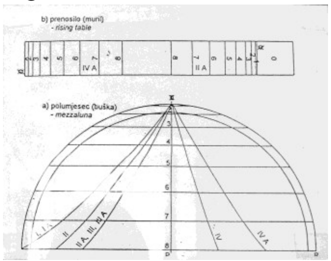

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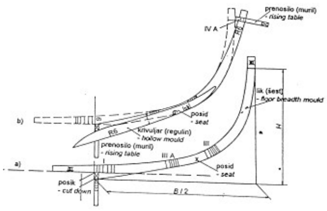

Figure 1.11.

Figure 1.9. Pythagorean theorem in Korčula city plan. Berislav Kalogjera, *Korčula: Portret Jednoga Grad na Istočnom Jadranu* (Korčula: Matica Hrvatska, 1995), 59

Figures 1.10. and 1.11. *Buška* – mode of constructing wooden ships without a drawing plan; and *murili* – thin boards for conveying measures on wood. Korčula Town Museum, Korčula.

[6] Roko Markovina, "The Building Technology by the Korčula Wooden Shipbuilding 'School,'" *Manual for Graduate Students in Mechanical Engineering at the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture* (Split: University of Split, 2003), 243.

Figure 1.12.

Figure 1.13.

The thesis identifies the parametrisation of Korčula set out with parallel street divisions to emerge with the *buška* method to generate curved geometry (Figures 1.10 and 1.11). The method used for building ships would have been implemented to generate Korčula's town plan, towers and fortifications. The urbanised town scheme consists of the main street, which stretches along the ridge of the small peninsula on which the town was built in a north–south direction (Figures 1.16 and 1.17), and the elliptical perimeter street along the city walls following the outline of the peninsula. Parallel streets with double rows of houses descend towards the city walls. The fishbone geometry of the street system allowed for ventilation. At the same time, the design angle of the streets reduced the effects of the wind and sun to give citizens sheltered and comfortable accommodation. In this simple urbanised scheme, the typology of the residential architecture developed over centuries (Figure 1.12), from small houses to palaces which were formed by the connection and rebuilding of several houses into one entity, often grouped around a courtyard. The *Statute of Korčula* detailed the division of streets, regulating one half of the area above the street to the owner on each side to build a vaulted habitable space or bridge (Figure 1.13). The height of the arch was determined by the barrel and tub, to allow access under the arch without difficulties.[7] In addition to built up vaults, Non-Standard methodology is identified in the semicircular arches and windows of Renaissance architecture (Figures 1.18 and 1.19).

Figure 1.12. Parametrised plan of Korčula indicating year of buildings without subsequent intervention. Joško Belamarić, *Osnutak Grada Korčule* (Zagreb: Ex Libris, 2005), 34.

Figure 1.13. Vaulted bridge in Kaporova Street in Korčula, Photograph by Melika Aljukic.

[7] Antun Cvitanović ed., *Korčulanski Statut* (Zagreb: Tisak, 1987), Book III, Statute CXLVI.

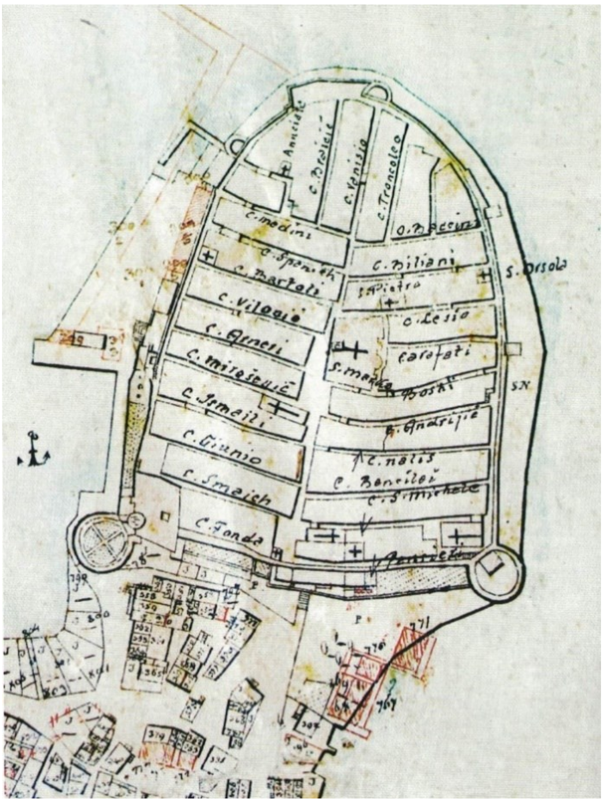

Figure 1.14. Plan of Korčula with the streets named according to families who live in them, 1869. Korčula Town Museum, Korčula.

Figure 1.16.

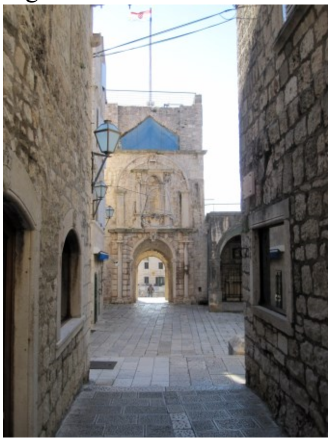

Figure 1.17.

Figure 1.15. Aerial image of Korčula. Photograph by Ivo Pervan.

Figures 1.16. and 1.17. Central street in the old town of Korčula has been named Statute of Korčula 1214. Views in both directions, north to St. Mark's square and south to Korčula Town Gate. Photograph by Melika Aljukic.

Figure 1.18.

Figure 1.19.

Figure 1.18. *Zakerjan Tower* in Korčula. Photograph by Melika Aljukic.

Figure 1.19. Renaissance portal on the house in the street Korčulanskih Bratovština, Korčula. Photograph by Melika Aljukic.

The *Statute of Korčula* was revised – first in 1265, then in 1271 and 1432 – with aspects of its governance that can be traced today at Korčula, for example, in the geometry of the town plan. The streets follow the regular pattern separated by two parallel rows of houses, whose fronts face the street, while the wastewater canal is situated at the back. Originally, unified lots inside the elongated narrow blocks were enlarged, and houses grew in height, which was particularly visible in solutions of the elaborate fronts (Figure 1.20). The geometrical order of the residential blocks has never been changed, except for adjustment of the original irregularities of the system in the north part of the town, as if rows were adjusted to the curve of the walls.[8]

The symmetrical order of the town plan with rhythmical series of houses allowed cohesive collective living, limited to around 1000 citizens. The amended revisions of the Statute that affect construction today aim to save the city from losing residents through emigration and gradual demolition of abandoned houses, ensure basic hygienic conditions and preserve the immediate environment from pollution and destruction of greenery.[9] The revisions supersede earlier controls of the *Statute of Korčula* that bound residents to live in the city, with failure to do so punishable by confiscation of the house.

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[8] UNESCO, "The Historic Town of Korčula," *World Heritage Conservation*, accessed October 10, 2020, https://whc.unesco.org/en/tentativelists/5105/.

[9] Alena Fazinić, "Korčulanski Statut i Graditeljstvo Korčule u Srednjem Vijeku," *Korčulanska Spomenička i Kulturna Baština* (Korčula: Matica Hrvatska, 2009).

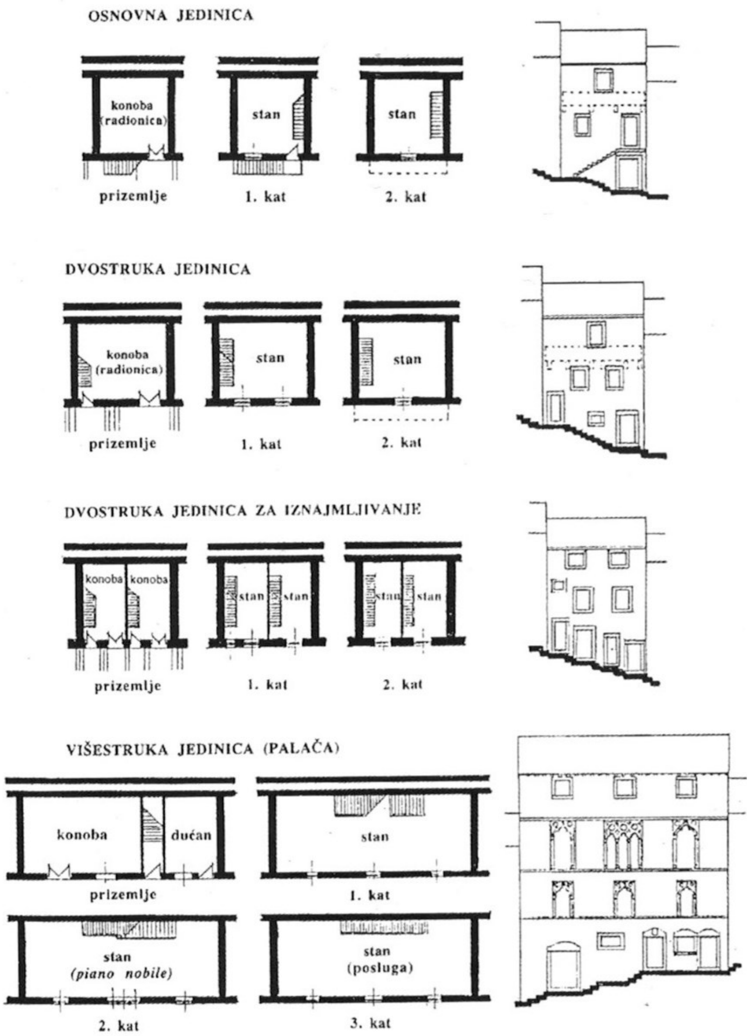


Figure 1.20. Typical Renaissance architecture plan and section of the house in Korčula. Joško Belamarić, *Osnutak Grada Korčule* (Zagreb: Ex Libris, 2005), 38.

Figure 1.21.

Figure 1.22.

Figures 1.21. and 1.22. Dubrovnik fortification walls and *Minčeta* fortification tower. Institut za Povijest Umjetnosti. Phtotograph by K. Tadić.

Since the Renaissance, Non-Standard Architecture has become codified digitally with the parametric representational technique of non-uniform rational B-splines introduced by de Casteljau's algorithm in 1958 with an algorithmic function for operations like lofting that enabled smooth and continuous forms and surfaces. Likewise, the stone cutting method has been automated with six-axis industrial robots, but it remains a mechanical and time-intensive process. Beginning with the Renaissance, the thesis argues the limits associated with the Non-Standard construction practices that began with the *Statute of Korčula* need to continually evolve, referring to Renaissance Non-Standard methods to conform to new technics of design and automation.

1.2.2 *The Statute of Dubrovnik*

The ideal city planning evident at Dubrovnik, aiming to control its hinterland through city walls and fortifications (Figure 1.21), appears to have developed through an emerging parametric system during the Renaissance codified by the *Statute of Dubrovnik.* One of the most impressive parametric aspects is seen in the *Minčeta Tower* (Figure 1.22). Designed by architect Michelozzo di Bartolomeo and engineered by Beltramo of Milan and Franciscus Allemanus, the tower bastion links the city walls and consists of a series of gun ports to provide all-round defensive fire. The parametric features of its design lie in the codification of Statute, Quattrocento perspective, a parametric method of wood and Renaissance stereotomy to represent and build parametrisation that reflected the needs and demands of society. Similar to the shipbuilding and stereotomy practice reflected in the city planning and architecture of Korčula, the *Statute of Dubrovnik* codified architecture to parametrise the city walls and towers. The parametric wooden model of *Minčeta Tower* was presented by Michelozzo to the Senators of the Renaissance city-state Ragusa (1385–1808), present-day Dubrovnik. With the approved design, Michelozzo was responsible for architectural drawings and construction supervision of *Minčeta Tower*.[10] Michelozzo's approved design was a new typology of fortification for the *Minčeta Tower* by introducing vertical instead of oblique external walls and internal circular balconies for access to casemates in the wall of the tower (Figure 1.23). Within the thick tower walls, the design of the casemates featured a funnel geometry for internal openings. Each casemate had a chimney for ventilation from the cannon fire smoke. In addition to the first statutory architectural plans, the first statutory building inscription was the ancient Ragusan epigraph on *Rector's Palace* from 1443. It stated Ragusan republican ideals in Latin, carved in Roman letters. The Ragusan epigraph predates Alberti's inscription in Rimini on *Malatesta* fortress from 1446.[11] The inscription on the fortress provides awareness to preserve the freedom of the city and thus the individual.

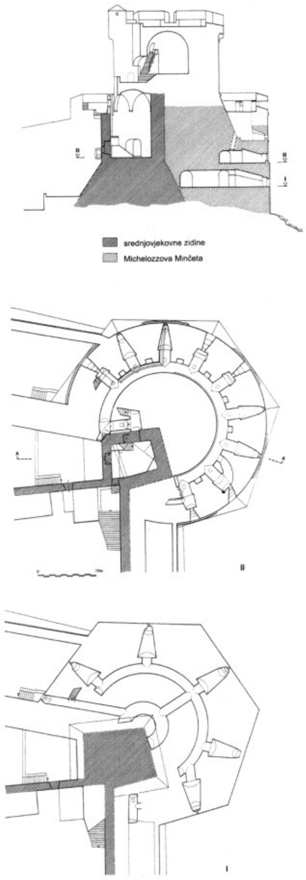


Figure 1.23.

The Republic of Ragusa received the first clear evidence of legislation for Ragusan town planning in May 1272 in the *Statute of Dubrovnik*. Its codification of laws was a remarkable improvement in the legislation and administration of Dubrovnik that balanced public and

Figure 1.23. *Minčeta Tower* plan and section with gun ports, Michelozzo di Bartolomeo, Dubrovnik. (1461–1462). Ana Deanović, *Utvrde i Perivoji* (Zagreb: Institut za Povijest Umijetnosti, 2001), 57.

[10] Ana Deanović, *Utvrde i Perivoji* (Zagreb: Institut za Povijest Umijetnosti, 2001), 53.

[11] Charles Dempsey ed., *Quattrocento Adriatico* (Milan: Nuova Alfa Editoriale, 1996), 5–6.

Figure 1.24.

Figure 1.24. Stradun, Dubrovnik. Institut za Povijest Umijetnosti. Photograph by Krešimir Tadić.

private interests. The forty-five chapters of the Statute's fifth book deal with municipal regulations, building laws and contracts and land tenure. The Statute supplemented a series of regulations that codified Roman practice for fire, sanitation, structural collapse and, in particular, disputes between neighbours. The *Statute of Dubrovnik* was one of the first precedents of ecological governance in planning and architecture, realised and persisting to this day. The codification of planning laws included provisions for new developments within the economic and socio-political life of the city. In 1272, according to the *Statute of Dubrovnik*, a substantial revision to the old city (*urbi Ragusii*) was legally planned for the enlarged new part (*nova civitas*), which was once called a suburb (*burgus*). Compared to the irregular city blocks of the Middle Ages that began in the seventh century, the Statute of 1272 and the Regulation of 1296 initiated regular streets in the new parts of the city. This decision was associated with changes in the community, removing the type of individual building that housed the owner and their dependants.[12] The public space became squares with a number of broader streets. Man's measure in the city was reflected in the walk through the main street Stradun in five minutes and the visibility of the whole (Figure 1.24). From the *Statute of Dubrovnik* in 1272 to the more extensive provisions from 1296 which regulated construction, there was a clear effort to give the street the importance of public space. The extensive regulations in the Statute, as well as numerous reforms of the Statute which occurred in the fourteenth century, provide ample evidence

[12] Marija Planić-Lončarić, "Shared Spaces in the Residential Zones of Medieval Dubrovnik," *Radovi Instituta za Povijest i Umijetnost*, vol. 12–13 (1988–1989): 75.

of Dubrovnik's considerable focus on rationalising city life in both time and space to achieve a solid social community and framework. The third *Statute of Dubrovnik Liber Viridis,* comprising legislative acts of the period 1358–1460 (Figure 1.25), marked the inauguration of the world's first quarantine system as a response to the Black Death pandemic in 1348. For those coming from infected areas, the decree stipulated one month of quarantine before being admitted to the city or surrounding land. This control is still enacted today for disciplining architecture during a pandemic. In 1431, under the *Statute of Dubrovnik*, the *lazaretto* quarantine was built (Figure 1.26). The same principle was followed and applied *ad hoc* in Milan (1410), Venice (1486) and Florence (1527). The fourteenth and fifteenth centuries were characterised by the erection of new, well-planned parts of Dubrovnik through a very strict municipal discipline, as shown by the regular architectonic units and the system of straight streets (Figures 1.27 and 1.28).

Figure 1.25.

Figure 1.26.

The written controls regulated the division of streets between residents on either side (one third at ground level, but one half of the air space above the street each), while the central third was the responsibility of the commune. Within this space, owners could build an external staircase or corridor for private use on the street (Figure 1.29). One half of the area above the street belonged to one side of the house and the other half to the other side to build a vaulted habitable space above the street.[13] Each house had to be 5.5 metres wide and separated from the neighbouring house by

Figure 1.25. Depiction of Dubrovnik in the third *Statute of Dubrovnik Liber Viridis,* 1358–1460.

Figure 1.26. *Lazzaretto* quarantine in Dubrovnik. Lazareti, *Zavod za Obnovu Dubrovnika*, accessed October 10, 2020, https://zod.hr/.

[13] Nella Lonza ed. *The Statute of Dubrovnik of 1272 Liber Statutorum Civitatis Ragusii,* trans. Vesna Rimac (Dubrovnik: Državni Arhiv, 2015), Book V, Statute I.

Figure 1.27.

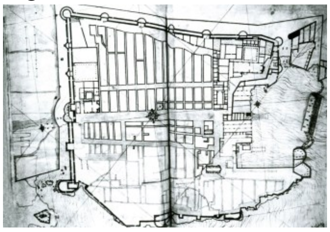


Figure 1.28.

Figure 1.27. Painting of Dubrovnik by Giovanni Batista Fabri in 1736 showing the city and its suburbs before the Great Earthquake of 1667. Collection of *Rector's Palace*, Dubrovnik.

Figure 1.28. Plan of Dubrovnik, 1600. State Archive of Torino, Torino.

a sewerage channel. The levels of the house followed a typology of wine cellar or workshop on the ground floor and living accommodation above. After a catastrophic fire in 1296, the *Statute of Dubrovnik* called for wooden construction to be replaced with stone for safety and durability. The *Statute of Dubrovnik* became more definite on external staircases for the streets running east–west, regulating new residential access with only one staircase on the street. This abolition of external staircases was the first regulatory intervention to create an east–west traffic system and orthogonal streets in a north–south direction. The orthogonal street grid was designed according to the Statute's strictly prescribed width of streets, the layout of housing and public spaces, specification of stone as the building material instead of wood, paving of the streets and squares, and advanced infrastructure.[14] Finally, in 1332 the *Statute of Dubrovnik* forbid the construction of private staircases on the street in the *burgus* to create wider, better looking, open and healthier streets.[15] The removal of external staircases produced a radical change in the type of house in general, with an internal staircase and permanent buildings in stone, with site-specific function and form.

[14] Nella Lonza ed. *The Statute of Dubrovnik of 1272 Liber Statutorum* Civitatis Ragusii, Book V, Statute XLI.

[15] Lukša Beritić, *Urbanistički Razvitak Dubrovnika* (Zagreb: Zavod za arhitekturu i urbanizam Instituta za likovne umjetnosti JAZU, 1958), 18.

The medieval city was divided into differently sized, irregular blocks of housing units with narrow, winding streets. A preserved example of such an early medieval apartment block is bordered by Stulina Street on the east and by Kneza Krvaša Street on the west (Figures 1.30 and 1.31). A small central courtyard exists in the southern part of today's Stijepan Gradić Street. This street was a right of way, which led to a small widening of the courtyard (Figure 1.33). With the codification of the *Statute of Dubrovnik* in 1272, the lane became the street, termed the Back Street during the fourteenth century. In the sixteenth century, with the construction of the Gradić courtyard in the southern part of the block, the street returned to function as an access lane for residents. Owners of the block tried to make full use of the available land. A well-preserved example of a vaulted built-up residential area above the street exists along the western line of the block, in the central part of Krvaša Street (Figure 1.32). The medieval house in Krvaša Street has a number of different external entries for the ground floor and first floor at different heights that were linked to external street stairs (Figures 1.34 and 1.35).

Figure 1.29.

Figure 1.29. External stairs in Pustijerna, Dubrovnik. Photograph by Zavod za prostorno uređenje Dubrovačko-neretvanske županije.

Figure 1.30. Plan of Dubrovnik by Zavod za prostorno uređenje Dubrovačko-neretvanske županije.

Figure 1.31. Dubrovnik Aerial. Zavod za prostorno uređenje Dubrovačko-neretvanske županije.

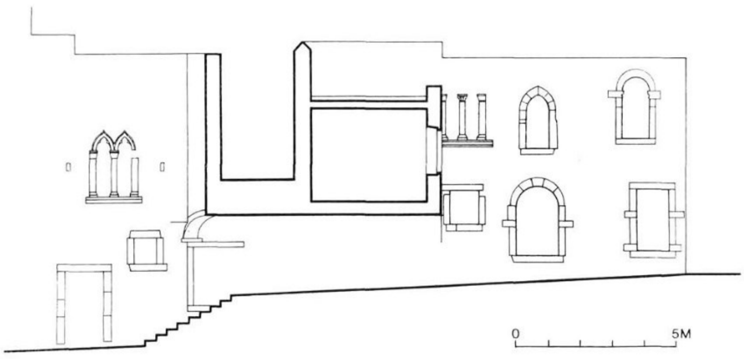


Figure 1.34.

Figure 1.32. Example of the external staircase and residential vault above the street. Section and facade of Romanesque-Gothic palace in Kneza Krvaša Street, Dubrovnik. Plans reconstructed by Ivan Tenšek.

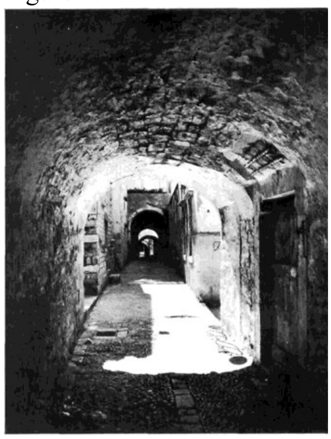


Figure 1.35.

Figure 1.33. Ground floor plan of the block between Stuli Street and Kneza Krvaša Street in Dubrovnik. Plans reconstructed by Ivan Tenšek.

Figures 1.34 and 1.35. Street of Pustijerne and *Palača Kabužic*. Nada Gujić, “Dubrovnik–Pustijerna,” *Radovi Instituta za Povijest Umijetnosti*, no. 10 (1986): 24.

Figure 1.36. Pustijerna, Dubrovnik. Photograph by Zavod za prostorno uređenje Dubrovačko-neretvanske županije.

Another example of medieval development is an elongated public area enclosed by reconstructed buildings used both as a courtyard and a street located in Restićeva Street in Pustijerna (Figure 1.36). Pustijerna is part of the oldest settlement on the southern cliffs of Dubrovnik, existing as early as the first half of the tenth century. This early forming of Pustijerna was prompted by the vicinity of the harbour and it was populated by people of various professions, including safeguarding, shipbuilding and trade. It was the part of the city that became a trading aristocracy. The construction of buildings was particularly intensive in the fifteenth and sixteenth centuries. The high quality Renaissance mansions withstood the tremors of the 1667 earthquake, and they are still evident today. The public areas enclosed by buildings were guarded and controlled at both ends and thus are represented as a zone of impermeability (Figure 1.37). The fortified aristocratic buildings were situated at the entrance and exit of the free zone (Figure 1.38). They were tower houses that connected the defensive function and representative appearance.

Along with the prominent vertical elements of the aristocratic building, there were arms of the lower part of the building located at both ends of the elongated courtyard (Figure 1.39).

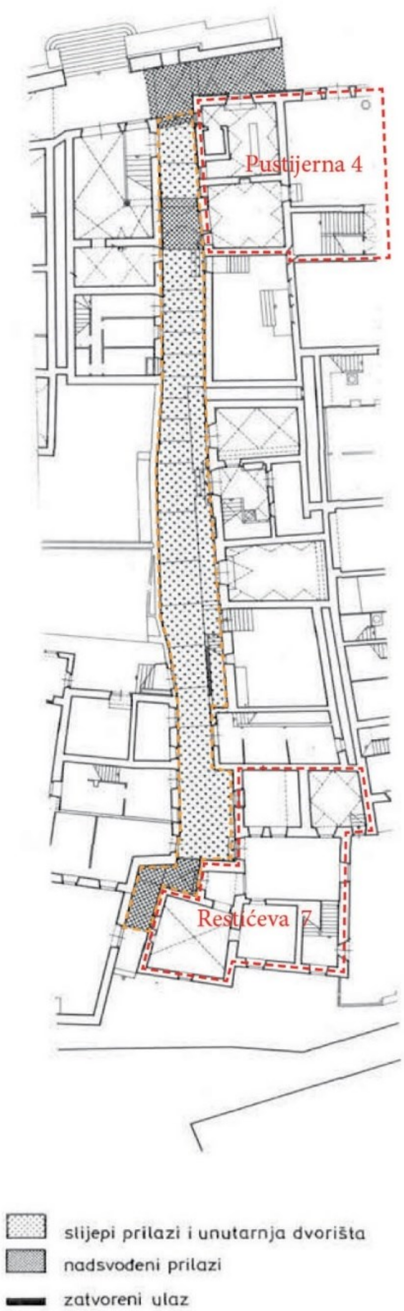


Figure 1.37. The ground floor of the rows of houses in Restićeva Street in Dubrovnik. Plans reconstructed by Ivan Tenšek.

Figure 1.38.

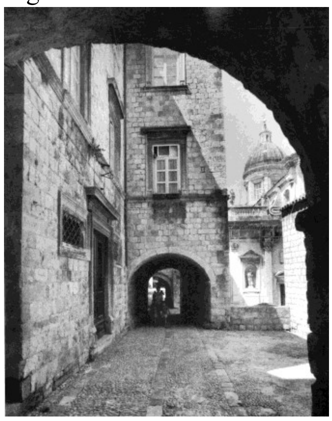


Figure 1.39.

Figure 1.38. Tower with entry into Restićeva Street in Dubrovnik. Nada Gujić, "Dubrovnik–Pustijerna," *Radovi Instituta za Povijest Umijetnosti*, no. 10 (1986): 15.

Figure 1.39. *Palača* in the street of Pustijerne 4 in Dubrovnik. Nada Gujić, "Dubrovnik–Pustijerna," *Radovi Instituta za Povijest Umijetnosti*, no. 10 (1986): 180.

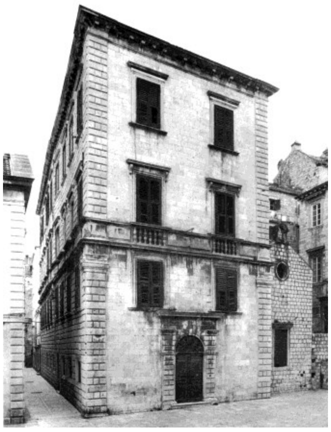


Figure 1.40.

The Baroque was important for the urban structuring of the present city after the destruction caused by the 1667 earthquake. The Baroque buildings added new typically Baroque elements in the centre of Dubrovnik city, in particular an internal staircase as part of an individual private house, independent from public space. Another important achievement was the structural transformation of the spatial organisation and distribution of architectural volumes in the historical nucleus of the city with many new representative buildings (Figure 1.40). The facade became an architectural expression of window frames and balconies as well as a mandatory representation of the public space (Figures 1.41 and 1.42). The new housing was an essential formative segment in the history of Ragusan architecture. On the one hand, architecture preserved the old urban layout integrating the new structures into the surviving parts of Renaissance buildings. On the other hand, the reduced population allowed smaller older houses to be combined into a larger building, generating more comfortable living conditions.[16] These spatial changes were visible in the interiors of the buildings and demonstrated with the new Baroque staircases. The Baroque staircase became the nucleus of a building. Two dominant spatial staircase concepts are differentiated: first, the concept of the Ragusan spatial palazzo that connected the stair to the main sala (Figure 1.43); and second, the staircase organisationally independent as a result of the Baroque reconstruction after the earthquake. The Baroque palazzo with an independently organised staircase relegated vertical communication

Figure 1.40. *Palača Sorkočeveić* in Dubrovnik. Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 124.

[16] Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 308.

separately, and clearly defined and articulated space with doorways leading into rooms clustered around the staircase on every floor (Figure 1.44). Baroque palazzo reconstruction represents the significant architectural achievement of the Baroque period that began sporadically in Renaissance housing. Staircases as independent structures, usually composed of two converging stairs, became the feature of representative palaces, ornamented by stone columns, arches and vaults and, in the eighteenth century, decorated by stucco ornaments.

The type of staircase varied by the architectural plan and the zoning of the city. Typological variants were common, with the staircase placed either along one side of the entrance hall or along the back wall, the latter type being characteristic of Ragusan architecture. The staircase was also fitted into adaptations of surviving Renaissance buildings. A preserved example of Baroque reconstruction of Renaissance *Palača Bošković* demonstrates resolution characteristic of the seventeenth century of Renaissance building adaptation (Figure 1.45). The original Baroque layout of the palace consisted of two rooms on every floor and a single staircase next to the sidewall (Figure 1.46). The staircase to the lobby and halls on every floor is resolved by stone profiled arches on pillars and pilasters (Figure 1.47). Similarly, the Baroque palace in Pustijerna 4 was built on the remains of a Renaissance building (Figure 1.48). The plan layout of the palace, specifically the staircase, is characteristic of Baroque resolution adapted to the irregularities of the urban context (Figure 1.49). The representative stone steps are wide and bordered by intricate stone balustrades and stone columns on high pedestals with profiled arches and circular vaults (Figure 1.50). The staircase and the vestibule are connected by a

Figure 1.41.

Figure 1.42.

Figures 1.41. and 1.42. Main portal and window with profiled frame. Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 137, 259.

Figure 1.43.

Figure 1.44.

Figures 1.43. and 1.44. Baroque staircase in *Palača Ranjina,* Gundulićeva Poljana 1, Dubrovnik. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 171.

stone arch on a pillar with leafy capitals. The east side of the building has a residential vault above the street extending two storeys supported by the walls on both side ends of the street. This is an evident trace of the *Statute of Dubrovnik* in 1275 that integrates on the ground one third of the street on each side into the building, leaving the central third of the street for public circulation (Figure 1.51). The house-tower Restić at the end of the street generates a fortification system for Dubrovnik with two levels of the vaulted area built above the street (Figures 1.52 and 1.53). The traces of Renaissance building include windows and the portal as well as the coat of arms of Gundulić. The plan layout of the tower with the stair location is a typical Baroque adaptation (Figure 1.54).

The *Statute of Dubrovnik* represented an important development in Dubrovnik's approach to planning its built environment and architecture. The codification of the Statute advanced in architecture into a series of specific legislation which this thesis extends into the Third Digital Turn of Non-Standard Architecture.

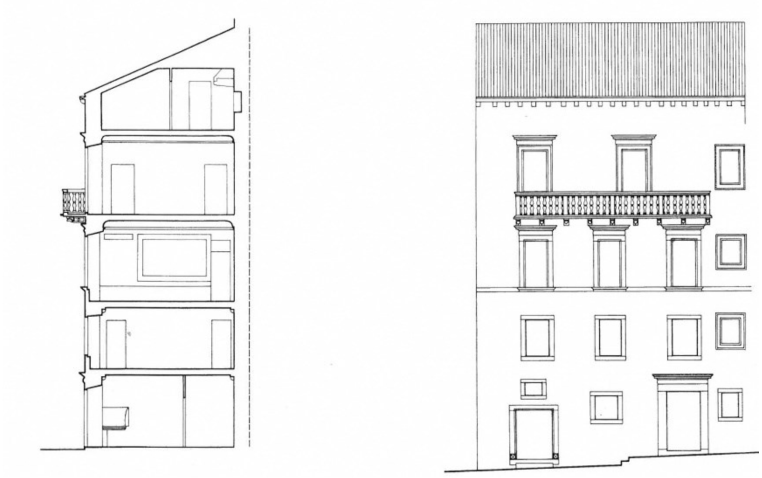


Figure 1.45. Section and elevation of Baroque renovation of Renaissance *Palača Bošković*.

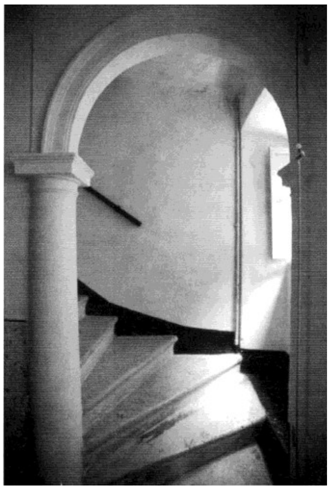


Figure 1.47.

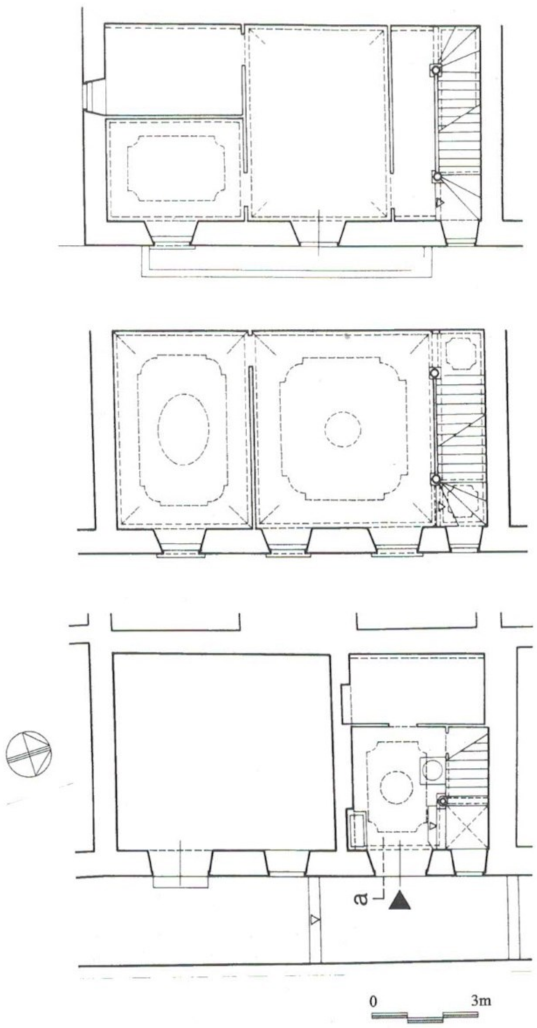


Figure 1.46. Floor plans of the Baroque renovation of Renaissance *Palača Bošković*, Boškovićeva 3 in Dubrovnik. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 222.

Figure 1.47. *Palača Bošković*, Boškovićeva 3 in Dubrovnik. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 223.

Figure 1.50.

Figure 1.51.

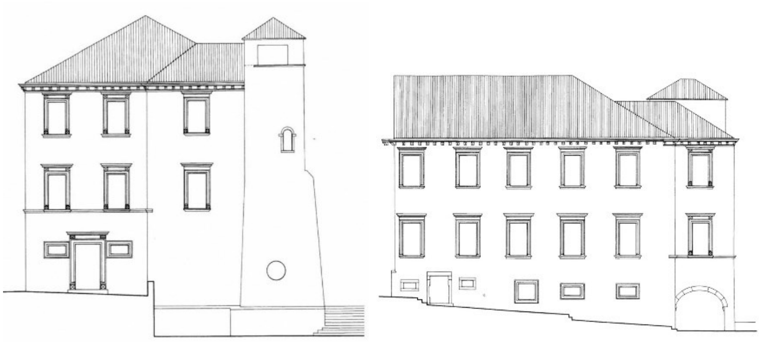
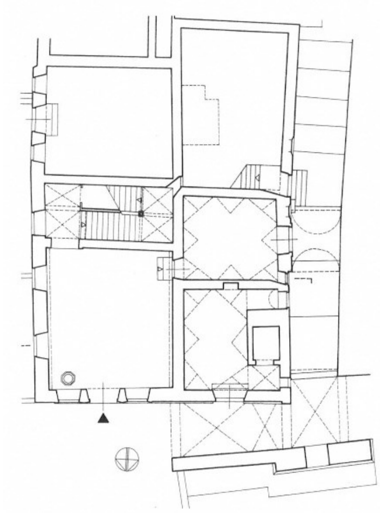


Figure 1.48. North and east elevation of *Palača* in Pustijerna 4, Dubrovnik. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 276–277.



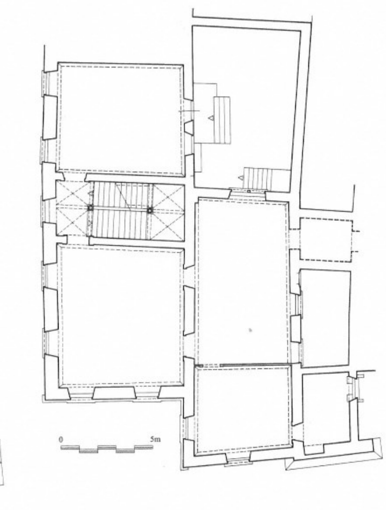


Figure 1.50. *Palača* in Pustijerna 4, Dubrovnik. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 139.

Figure 1.51. Baroque staircase of *Palača* in Pustijerna 4, Dubrovnik. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 87.

Figure 1.49. Ground and first level plan of a Baroque *Palača* in Pustijerna 4, Dubrovnik. Reconstruction of the first Baroque phase on the first level. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 276.

Figure 1.52. Section with a western facade and north facade of *Restić Palača* in Restićeva Street 7, Dubrovnik. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 290.

Figure 1.54.

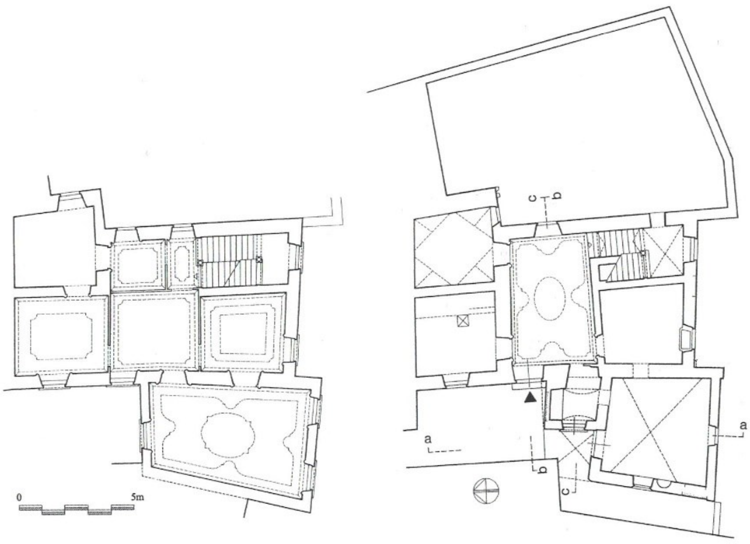


Figure 1.53. Ground and first level plan of *Restić Palača* in Restićeva 7, Dubrovnik. Reconstruction of the second Baroque phase of the ground and first palace level with a schematic representation of the ceiling stucco. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 289.

Figure 1.54. Staircase of *Restić Palača* in Restićeva 7, Dubrovnik. Example of staircase along the side wall in the vestibule. Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 61.

1.3 Non-Standard Codification of the Digital Revolution in Architecture

1.3.1 The First Digital Turn of Non-Standard Architecture


Figure 1.55.

The thesis identifies the First Digital Turn in the 1980s with the parametric design method of designing complex forms using a computer with parametric and algorithmic procedures. Following the Non-Standard codifications of Renaissance architecture founded on the method of shipbuilding and stereotomy, Baroque architecture established experimental projections of complex architectural geometry. Finally, an algorithm for evaluating calculations on a parametric curve was developed by Paul de Casteljau in 1958. Pierre Bezier further developed the algorithm at Citroen to integrate it for drawing and three-dimensional surface modelling of Non-Standard geometry based on non-uniform rational B-splines to guide numerically controlled machine tools. During the same time, lightweight structures were initiated by Frei Otto in 1964 at the Institute for Lightweight Structures and Conceptual Design (ILEK) in Stuttgart based on optimisation of the surface area using soap film experiments. The notion of physical autonomous formation processes is based on the air pressure of a sailing boat (Figure 1.55), with the earliest examples used for shading in the *Colosseum.* The lightweight structures demonstrated the principle of opposing curvature of the prestressed membranes in architecture (Figure 1.56). With the implementation of non-uniform rational B-splines, lightweight structures digitally combined the design and optimisation model.

Figure 1.55. Self formation of sails by air pressure. Regatta in Croatia.

The first computational power using the plywood technique for a formwork system was applied to realise a Non-Standard building of a significant scale, the *Sydney Opera House* (Sydney, 1959). While spherical geometry was implemented for shells to meet the requirements of repetitive factory production, the fabrication method had a Non-Standard approach by implementing an elliptic spline generated by bending plywood on steel frames for each mould to cast rib segments that changed in width widening upwards. This form finding procedure of developing lightweight structures such as shells (Figure 1.57) prompted a digital revolution in architecture through a number of architectural *avant-garde* movements: Deconstructivist architects in 1988, the digital revolution in architecture in 1990 and its Non-Standard seriality beginning in 2001. The movements culminated in a number of architectural exhibitions: *Deconstructivist Architecture* at the Museum of Modern Art in New York in 1988, *Latent Utopias* at Landesmuseum Joanneum in Graz in 2002, *Remote Echo* at the Jaroslav Fragner Gallery in Prague in 2002 and *Architectures Non Standard* at the Centre Pompidou in Paris in 2003.[17] Emerging academic work, including my architecture graduation project at the University of New South Wales in 2004,[18] explored geometric and volumetric possibilities of challenging the Euclidean basis of

Figure 1.56.

Figure 1.57.

Figure 1.56. Institute for Lightweight Structures and Conceptual Design in Stuttgart, accessed on August 1, 2020, https://www.ilek.uni-stuttgart.de/.

Figure 1.57. Sydney Opera House. Anne Watson ed., *Building a Masterpiece: The Sydney Opera House* (Sydney: Powerhouse Publishing, 2013, 36).

[17] Melika Aljukic, "Remote Echo," exhibition at the Jaroslav Fragner Gallery in Prague, 11 March – 6 April 2003.

[18] Melika Aljukic, "Unarticulated Topography," *Perform* (Sydney: University of New South Wales, 2004), 8–9. Exhibition at the Sydney Town Hall in 2004.

architectural form through serial mass production and economies of scale.[19]

The digital revolution in architecture was powered by the new computer technology that emerged in the late 1960s with new digital design operations. Although the Second Digital Turn developed parametric architecture's formal possibilities in the parametric data model, complementing the smooth and continuous forms and surfaces of its first turn, the full realisation of formal potential appeared obstructed by intrinsic and persistent limits. This thesis research suggests that the limit lies in a discrepancy between the figurative and formal possibilities promised by digital technologies in architectural design and the current reality and capacities of the building industry to realise them. However, seminal projects cited as exemplary of the Second Digital Turn, such as the *Morpheus Hotel* exhibited at the latest *Mutations/Creations* event on *Neurons, Simulated Intelligences* at the Centre Pompidou[20] representing transformations of creative fields driven by the influence of digital cultures,[21] were mostly hand-built using conventional methods of construction. One objective of this thesis is to identify the discrepancy or gap as a pivotal limit in the realisation of Non-Standard Architecture by

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[19] Melika Aljukic, "Australian Institute of Architects Design Medal," *Architecture Bulletin,* vol. 4.05 (July/August 2005): 45.

[20] Frédéric Migayrou and Camille Lenglois, "Neurons, Simulated Intelligences at Centre Pompidou," produced by Centre Pompidou, *Centre Pompidou*, July 28, 2020, video, https://www.youtube.com/watch?v=GyY5APNyaaI&feature=youtu.be.

[21] Melika Aljukic, "Mutations/Creations, *Architecture Bulletin: Futures*, vol. 76, no. 4 (March 2020): 26–27.

investigating the circumstances – theoretical and technical – that define it.

The conception of Non-Standard explored by the Architectural Association School of Architecture was in the form of an open-source design studio dedicated to various formal experiments exploring new design tools, systems and discourse in architecture and urban design. The phase of mutation was exhibited in the 2002 exhibition *Latent Utopias* through a selection of new materials in the digital media by the Architectural Association such as dynamic interactive components and interfaces that represented a collective process of appropriation rather than the capacity of an individual author.[22] In their *Latent Utopias* project (2002), proponents of Non-Standard Architecture Zaha Hadid and Patrik Schumacher promoted a radically new concept of space that engaged and questioned the needs and demands of contemporary society with a tendency towards architectural autonomy.

The curator of the *Architectures Non Standard* exhibition, Frédéric Migayrou, defined Non-Standard Architecture as an emerging and novel form of architectural investigation, driven by the capacity of computers to generate non-Euclidean formal possibilities within economies of a scale that contested the predominantly orthogonal language and excesses of Modernism. Migayrou suggested that Non-Standard Architecture was related to the dynamic structuralism inherent in René Thom's mathematical modelling of morphogenesis in *Structural Stability and Morphogenesis,* which describes the

[22] Zaha Hadid and Patrik Schumacher eds., *Latent Utopias* (Vienna: Springer, 2002), 8.

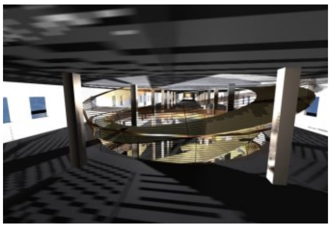
Figure 1.58.
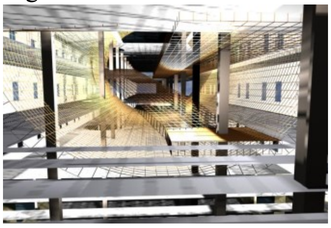
Figure 1.59.

Figures 1.58 and 1.59. Architectural design by Melika Aljukic. *Remote Echo* Exhibition at the University of New South Wales and Jaroslav Fragner Gallery in Prague 11 March – 6 April 2003.

behaviour of forces in space over time resulting from the combination of two or more conflicting forces. The *Architectures Non Standard* exhibition aimed to provide a historical and theoretical framing of emergent digital forms in terms of their mathematical, geometrical and architectural sources, thematics and influences. The exhibition brought the Non-Standard in architecture to the foreground, consolidating its position at the core of contemporary discourse. It defined Non-Standard architectural diagrams on the one hand as "inflection of a hermeneutic capacity and this outside of any contextual sociology (which could be called deconstruction)" and on the other as granting "constructive capacity where the engineering resolves itself in the digital translatability, which hybridises all the tools of production."[23]

The *Remote Echo* exhibition at the University of New South Wales (2002) and the Fragner Gallery at Prague Technical University (2002) featured digital experimentation for adaptive reuse of a factory warehouse project in Karlin. The exhibition featured a variety of novel architectural volumes, structures and unprogrammed spaces that formed a discrete and rarefied moment in the urban fabric[24] (Figures 1.58 and 1.59). The complex geometries of these novel architectural volumes were later further developed in my academic work in computational parametric[25] (Figures 1.60–1.63), working with detailed

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[23] Frédéric Migayrou, "Non-Standard Orders 'NSA-Codes,'" *Future City Experiment and Utopia in Architecture*, ed. Jane Alison et al. (London: Thames & Hudson, 2007), 31.

[24] John Bralic, "Remote Echo," *InDesign*, vol. 13 (2003): 38.

[25] Melika Aljukic, "Unarticulated Topography," *Architectural Review Australia,* vol. 91 (2004): 124.

curved geometries and lightweight structures calculated using an innovative digital platform and materials.[26]

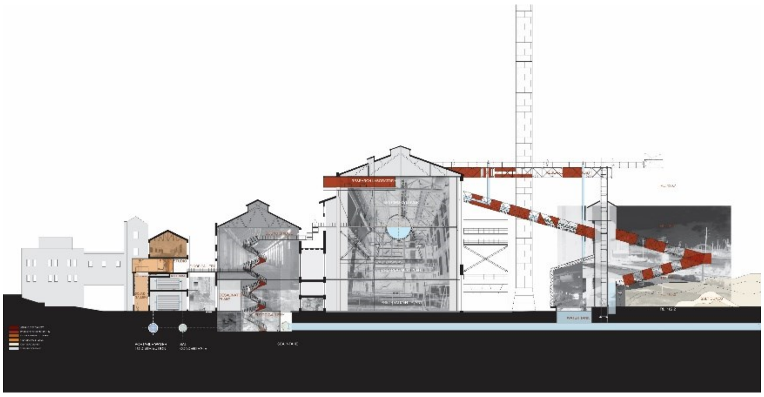
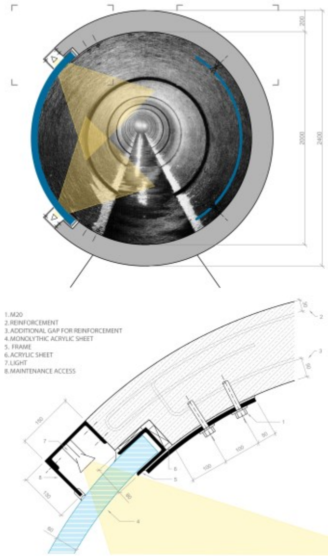


Figure 1.60. *Unarticulated Topography* drawings and bronze model by Melika Aljukic, University of New South Wales. *Perform,* exhibition at the Sydney Town Hall in 2004.



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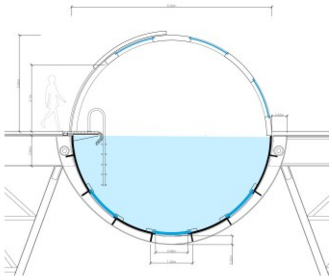

Figure 1.62.

Figure 1.63.

Figures 1.61–1.63. *Unarticulated Topography* drawings and bronze model by Melika Aljukic, University of New South Wales. *Perform,* exhibition at the Sydney Town Hall in 2004.

Non-Standard Architecture initiated a process of design and production radically different from the technical paradigm of the Industrial Revolution in the nineteenth century, which was in turn sublimated into standardisation by architectural Modernism in the twentieth century. In addition, the repetition of identical parts and the question of identicality have persisted in Western architectural history, particularly during the Renaissance. Non-Standard Architecture upgraded assembly lines from mechanical to computer-based technologies, generating customised products without additional cost. Non-Standard production integrated algorithmic continuous functions to deconstruct form into serial production of non-identical parts. Research for this thesis identified the emergence of digital design operations in architecture from the early 1960s, powered by new computer technology that included the de Casteljau

[26] Melika Aljukic, "Flood Gallery Model in Bronze," *Supermodels* (Sydney: St. Margarets and Object Gallery, 2006), 1.

algorithm and continuous functions based on Leibniz's mathematics of continuity and differential calculus. This early phase of the digital revolution in architecture is characterised by smooth and continuous forms and surfaces. Double-curved elements required a spatial computer model to achieve the necessary construction documentation for solid curved structural elements. The thesis finds, that around the late 2000s, significant changes to computer graphics introduced algorithmic design programming into computer-aided design. This shifted identical production to Non-Standard seriality that allowed the emergence of robotics in architecture, thus generating the Second Digital Turn.

1.3.2 The Second Digital Turn of Non-Standard Architecture

The Second Digital Turn of Non-Standard Architecture, identified by this thesis as beginning in 2012, introduced a parametric digital strategy as a collaborative methodology. This computationally advanced digital geometry included engineering logic and physics simulation for form finding and anatomised optimisation processes as part of the design process. Useful precedents include *ARACHN[OL]OIDS* (2013)[27] identified by the thesis as the first Non-Standard architectural robot

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[27] Melika Aljukic et al., *Architectural Association Projects Review 2013: ARACHN[OL]OIDS*, accessed January 17, 2013, http://pr2013.aaschool.ac.uk/DRLPHASE2/Spoon-Benders.

prototype (Figure 1.64) and *Morpheus Hotel* (2019)[28] (Figure 1.65) by Zaha Hadid Architects, which explored Non-Standard parametric forms formulated simultaneously between multiple disciplines and team members. The thesis distinguishes this epoch by formal parametric methodology and the architect's role in understanding the possibilities of computational design, including the making of custom tools for prototyping and production, within the constraints of a mainstream architectural practice. Although the protocol for design and documentation of the *Morpheus* project was a highly digital and integrated parametric data model, fabrication of components had to be realised through a high level of skilled manual work such as pre-bending and welding of aluminium cladding panels by site workers. This thesis contends that fabrication, in practice, remains constrained by technical limits in the standard bases of manufacture and by regulatory limits in the construction industry. These limits impact the implementation of robotic automation for construction. This thesis contends that the gap between the digital architectural codification and the construction can be achieved by fully digitising architecture for automation. This has the potential to increase the quality and precision of architectural construction. Such automation reduces the timeframe for construction by automating the parametric data model during construction and removes the need for supplementary documentation and manual operations.

Following the development of automated construction in Japan from the 1960s, research into

Figure 1.64.

Figure 1.65.

Figure 1.64. First Non-Standard robot prototype. 3D printed shell prototype in polymethyl methacrylate with a rapid prototyping technique. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

Figure 1.65. *Morpheus* architectural typology of the world's first freeform tower exoskeleton by Zaha Hadid Architects, 2013–2019. Photograph by Ivan Dupont. Zaha Hadid Architects, 2019.

[28] Zaha Hadid Architects, *Morpheus Hotel*, accessed September 30, 2020, https://www.zaha-hadid.com/architecture/city-of-dreams-hotel-tower-cotai-macau/.

realising Non-Standard forms in architecture has been undertaken across various universities since 2008. For example, in 2008 Gramazio and Kohler at the Swiss Federal Institute of Technology used a bricklaying robot for Non-Standard assembly. These investigations led to an ecological approach in construction using functionally graded concrete. This method was developed by the Institute for Lightweight Structures and Conceptual Design in Stuttgart. It involved aligning the internal composition of structural components with a specific structural and thermal performance by continuously altering the characteristics of the material throughout the construction process, including its porosity, strength or rigidity, in three spatial dimensions.[29] This process of material optimisation is achieved using a robotic spraying technique. The thesis identifies material grading development such as anatomised functionally graded concrete as part of the Third Digital Turn of Non-Standard Architecture, since the protocol for graded concrete cannot be created manually with unskilled labour, which makes automated construction imperative. This thesis extends contemporary work in functionally graded concrete that is currently limited to linear elements to achieve parametric forms. The methodology integrates material optimisation and efficiency, as well as robotic automation for elaborated form finding.

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[29] Michael Herrmann and Werner Sobek, "Functionally Graded Concrete – Numerical Design Methods and Experimental Tests of Mass-Optimised Structural Components," *Structural Concrete* (Berlin: Ernst & Sohn, 2016), 54.

1.4 Research Questions

Several research questions underpin this investigation. The first question is about the theoretical origins of parametric thinking. The second inquires into the inherent limits of parametric thinking at theoretical, political, technical and implementation levels. If the architectural form is expressed and defined by a limit – geometric, spatial, territorial, and so forth – that limit is a translation, by design, into the figurative or digital and the formal or built. It is generated in the modes of production, aesthetics, geometry lineage and their implementation within a given political, legislative, industrial and manufacturing system or governmentality. The concept of governmentality, coined by Foucault, is defined as the encounter between the technologies of domination of others and those of the self which shift the agenda from questions of how individuals are subjugated by power, to questions of how subjectivity is actively produced. This turns from questions of disciplinary power and its centralised regulatory practices to other forms of ecological governance, to analyse how non-disciplinary apparatuses of power operate, especially those of neoliberalism. The third research question concerns how those limits affect the production of Non-Standard Architecture. The fourth question inquires into the critical differences between Non-Standard Architecture, as originally defined in the Renaissance in the *Statute of Korčula* and *Statute of Dubrovnik*, and the First and the Second Digital Turn as defined by Mario Carpo,[30] Schumacher[31] and the author on parametric form finding and robotics and through a Third Digital Turn of Non-Standard Architecture.

[30] Mario Carpo, *The Second Digital Turn* (Cambridge: MIT Press, 2017), 9–97.

[31] Patrik Schumacher, "Parametricism 2.0," *Architectural Design: Parametricism 2.0*, vol. 86, no. 2 (March/April 2016): 8–17.

1.5 Research Methodology

This thesis research addresses the current limit of codification of Non-Standard Architecture in automation through a series of three case studies on parametric data modelling: the *Morpheus Hotel*, the *ARACHN[OL]OIDS* architectural robot prototype and the development of graded materials to produce Non-Standard elements. The research initiated a process of devising and testing material optimisation to apply concrete material within an automated robotic prototyping process to realise pilot versions of Non-Standard architectural components in ultra-high performance concrete and functionally graded concrete. However, the process encountered several critical challenges, including access to specific optimisation software and interpretation of engineering data from the parametric data model for the fabrication of parametric elements. As a result, the focus of the research and the methodology was reoriented from a focus on prototyping to one that engaged the theoretical bases of the Non-Standard and the conceptual and practical limits that flowed from these bases.

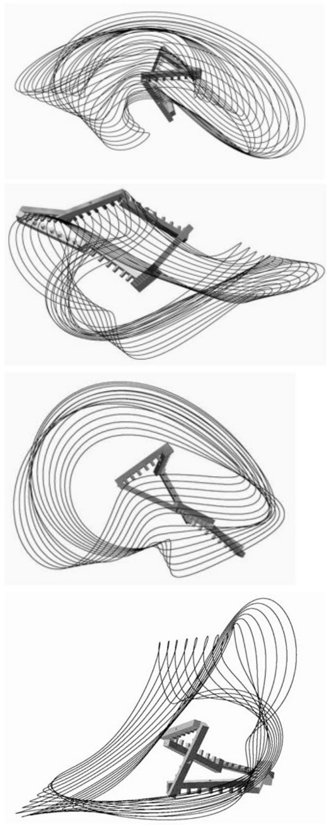

Figure 1.66.

The experimental tests as part of the thesis indicated that geometric optimisation identifying the asymptotic curve generated by automating the first Non-Standard architectural robot can simplify the construction of Non-Standard geometry. Thus, the thesis contends that adopting asymptotic curves could help use innovative geometric systems to achieve Non-Standard Architecture by using straight unrolling and orthogonal nodes which have not previously been applied to load-bearing structures (Figure 1.66). In addition to their theoretical findings, the case studies led to the formulation of the *Statutes of Non-*

Figure 1.66. Asymptotic curves generated by Non-Standard robot 7R Bricard linkage simulated spatial analysis. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

Standard Architecture constraining the realisation of Non-Standard Architecture. The *Statutes of Non-Standard Architecture* eclipses the gap between its principles and the social reality present in practice by conducting a Third Digital Turn of Non-Standard Architecture that can transform implementation of parametric design.

Preliminary research for this thesis established there are foundational limits to how the Non-Standard has been conceptualised in architecture – as non-standard seriality, specifically in its opposite technical paradigm to architectural Modernism. On the one hand, there are parallels between Renaissance, Baroque, Modernist and Non-Standard modes of codification, and their implications and applications to architectural design, production and manufacture. On the other hand, the foundational conception of space used in Non-Standard discourse has remained Euclidean and orthogonal across these different historical phases. At its core, this spatial conception springs from an elemental idea of architecture based on the floor, wall and columns. What resurged as a persistent challenge within the automated Non-Standard Architecture environment of conventional construction means that the Non-Standard must encounter a critical limit preventing it from achieving its key objective of critiquing and challenging geometric production within modern architecture.

To mount this argument, the research draws on the mathematical and philosophical work of Jacques Derrida, Gottfried Wilhelm Leibniz, Albert Lautman Riemann, René Thom, Gilles Deleuze, Felix Guattari, Michel Foucault, Bernard Stiegler and Jacques Lacan to establish a theory on the mathematical algorithm as well as the emergence of the architect and the architectural discipline in an evolutionary process determined by technology (Figure 1.67). Two critical moments are important: the evolution of Jacques Derrida's deconstructive approach that reconceptualised the role of architecture and architectural theory as Deconstruction, and the smooth and continuous forms and surfaces that integrated computer development in late-1990s architecture.

Figure 1.67. Melika Aljukic (right) at the workshop on Jacques Derrida by Architectural Association in Paris, 2018. Photograph by Architectural Association.

1.6 Thesis Structure: The Third Digital Turn of Non-Standard Architecture

Starting with the limits of Non-Standard Architecture, Chapter 1, *The Sovereign Parametrics in Architecture,* situates the Non-Standard within possibilities offered by digital technologies in architectural design and the capacity of the building industry to realise them. The chapter traces the lineage of geometry across architectural epochs and recent precedents to establish a conceptualisation of architectural parametrisation during the Renaissance with the *Statute of Korčula* (1265), the *Statute of Dubrovnik* (1272) and a precursor of Leon Battista Alberti's treatises on architecture. The limit of computation in the First and Second Digital Turns in architecture is identified in the seminal exhibitions including *Remote Echo* (2002)*, Latent Utopias* (2002), *Architectures Non Standard* (2003) and *Perform* (2004) and projects including *Morpheus* (2019), focusing on parametric design and form finding. The chapter also outlines the research questions, the research methodology and the thesis structure.

Chapter 2, *Modern Architectural Authorship and the Parametric Diagram,* analyses the Non-Standard diagram – a key component of Non-Standard architectural thinking – and investigates the constraints and limitations of that diagram and its logics for Non-Standard architectural production. The Second Digital Turn of Non-Standard Architecture is outlined, explaining how architects sought to overcome these limits by implementing meaning and an algorithm in the computation. The chapter identifies sovereign parametrics in architecture developing in two phases: first as the disciplinary and professional territory of architecture beginning with statutory law in Korčula and Dubrovnik and Alberti's theoretical treatises in *De Re Aedificatoria* (*Ten Books on Architecture*), written around 1450; and second, through the diffusion of classical notions of aesthetic theory that introduced modern architectural authorship. Within this context, the first rationalisation of a digitised plan with machinations for identical reproduction in 1430 is analysed, followed by the subsequent evolution of tools into automated robots.

The return of autonomy was identified with Deconstructivist architects, who raised questions about process and meaning by exhibiting deconstructive qualities in contrast to the geometric purity of modern formal composition. In the 1980s, Deconstructivist architecture foregrounded design as experimentation alluding to the open alternation of structure and event. To build critical perspective, the chapter draws on Jacques Derrida's literary interrogation process of 'Deconstruction' and Deleuze and Guattari's form of writing as Abstract Machine. For Derrida, Deconstruction is a criticism of Platonism, defined by the belief that existence is structured in terms of oppositions that are hierarchical, with one side of the opposition being more valuable than the other. This first phase of Deconstruction attempts to reverse Platonic hierarchies. In the second phase of Deconstruction, the inferior term is re-inscribed to re-conceive difference as the emergence of a new 'concept', which divides self-consciousness and renders justice. The shift in architectural practice during the Second Digital Turn consists of a move from sole, analogue authorship by an architect seen as a demiurgic creator harbouring a transcendent, internalised design concept – an idea integral to the conceptualisation of architecture and architects in modernity – to a digitally collaborative, open-ended and emergent authorship.

Chapter 3, *Architectural Autonomy,* investigates the role of mathematical theory in the origins and practices of Non-Standard Architecture. In contrast to formal mathematical language, Non-Standard Architecture introduced open, infinitesimal models that emerged from the Non-Standard analysis in mathematics by Abraham Robinson and the topological theories of René Thom. Robinson's theory of hyperreal numbers interpreted infinitesimals in a manner that completed the calculus hypothesis which began with Gottfried Wilhelm Leibniz. Within this context, Non-Standard Architectural theory elaborated Deleuze and Guattari's reference to Riemann's abstract machines, and to their consequent proposition of smooth and striated space, affirmed through the mathematics of Gaussian theory of the model. Thom's Catastrophe Theory defined topological theory as the behaviour of forces in space over time that result from the combination of two or more conflicting forces. In it, the fold is formulated as a real geometrical entity of elementary catastrophe that describes a change in behaviour from a stable state to an unstable state as a function. The chapter documents the first iteration of Non-Standard architectural design beginning in 2001 as a form of analytical tool that developed various formalised themes, super-surfaces and hyper-surfaces that integrate topological elements of the fold, loop, nodes and layers. However, research indicated that only the Second Digital Turn of Non-Standard Architecture, beginning in 2012, achieved the constructive capacity of the parametric digital model as a new form of communication and collaboration in architecture.

The thesis uses theories by Michael Ostwald (2006), Philippe Potié (2008) and Mario Carpo (2008) to argue that transformations and deformations typical in seventeenth and eighteenth Mannerist and Baroque architecture prefigured the Non-Standard architectural typologies that prevailed throughout the digital turn. For example, folding is explored by Deleuze in philosophy, and by Luigi Moretti, Bernard Cache, Greg Lynn and Frank Gehry in architecture. The thesis differentiates from these theories by identifying sovereign Non-Standard parametric architecture within the Statute in the Renaissance and extends the argument to the algorithmic expression of the Second Digital Turn. Evidence is presented to show parallels between folding as a formal tactic in the Baroque and early 1990s architectural concepts generated through digital platforms, – specifically shifts in facade articulation at the beginning of the sixteenth century.

The fold is a philosophical and tectonic concept pivotal to the Second Digital Turn. Thus, the thesis aims to describe the limits encountered in mathematically defining the fold, and in envisaging and developing production systems and tools that might actualise it in built form. On the evidence of these technological limits – for example, in terms of the productivity and effectiveness of tools and industrially produced materials and components – the thesis highlights a persistent gap between the conception and fabrication of Non-Standard Architecture. Digital printing techniques and file-to-factory production transformed architectural design and construction processes, generating absolute autonomy in the realisations of digital architecture, emphasising its originality and individualism.

Chapter 4, *The Limits of Modern Utopia in Architecture,* traces the imperative of normalisation and standardisation as a pivotal theme of the Enlightenment and its subsequent role during the Industrial Revolution. Standardisation was foundational to Modernity and Modernism in architecture in the eighteenth and nineteenth centuries. The drive to rationalise, classify, codify and quantify to assure the indefinite and efficient reproducibility of stereotypes demanded by mass production found its way into architectural production and eventually transformed architectural thinking. This, in turn, framed the digital revolution with algorithmic design operations powered by new technology at the end of the twentieth century, and was crucial to the emergence of Non-Standard Architecture typologies in architecture. The thesis identifies the difference between two modernities – that of the Enlightenment and the Industrial Revolution – in the characteristic of an opaque architectural object of density and sculptural form supplemented with the transparencies of frame and screen in the nineteenth century. The chapter parallels the interpretation of Colin Rowe and Robert Slutzky of historical change by reference to precedents, comparing the villas of Palladio to those of Le Corbusier. The attempts to correlate or align architecture and language in the post-war period aimed to establish the possibility of architecture as autonomous and heterogeneous, against the modern rhetoric and experience of the anonymous and homogenous building.

Modernism claimed new possibilities through innovations in building technology and new analyses of function, and through the freedom of a design process that was not restricted to the standard vocabulary of historical forms. The introduction of digital technology in the design process of architecture allowed buildings to take on postmodern aspects of formal complexity which could not be encountered in the architecture of late Modernism. The *avant-garde* in Japan and Europe was the final modern movement to raise concerns with nature and flexible architecture that pre-empted the digital revolution. While Metabolist projects integrated prefabrication, advanced technology and industrialisation to create small capsules or living units for private spaces, Archizoom adopted the factory and commercial mall as models for the spatial organisation of civil functions. The logic of the industrial system supporting utopian consumer society was extended to the codification of architecture using typewriters and their orthogonal movement. The thesis identifies the continuity of the orthogonal within the logic of machine in industrial production of robotics.

Chapter 5, *The Second Digital Turn,* surveys and redefines by expanding on recent design systems and technologies, including digital design, and the increasingly robotic manufacturing processes of the past decade. This generation of process-oriented work relates to experiments in automated design processes in the early work of Deconstructivist architecture, the 1990s digital revolution in architecture, the Second Digital Turn and the Third Digital Turn of Non-Standard Architecture proposed by this thesis. In the early work of Deconstructivist architecture, typified in projects by Peter Eisenman, Frank Gehry, Daniel Libeskind, Rem Koolhaas, Zaha Hadid, COOP Himmelb(l)au and Bernard Tschumi, compositional strategies with multiple layers of programmatic and geometric concerns were over mapped into complex format textures. In the 1990s the digital revolution in architecture, characterised in the work of Architectural Association, Zaha Hadid Architects, Greg Lynn and Frank Gehry, introduced new digital design operations with non-uniform rational B-splines and operations like lofting that allowed smooth and continuous forms and surfaces, defined as blobs and topological description of form. Informed by software such as CATIA and Maya, architecture expanded into curvature analysis and the manufacture of materials for complex form. From 2001, Non-Standard Architecture integrated algorithms for digital and computational operations, to produce non-identical parts. From 2012, the Second Digital Turn, typified in projects by Fuksas Architects, Zaha Hadid Architects and Architectural Association Design Research Lab, progressively implemented the algorithmic protocol in the form of the parametric data model. It was a new form of communication and collaboration between architects and engineers and robotics for design and fabrication on Non-Standard parametric components into architectural academia and the profession. The chapter investigates the emergence of digital tool innovation and its influence on design innovation, as well as its role in defining the Second Digital Turn of Non-Standard Architecture.

Chapter 6, *Architectural Automation and Case Studies,* defines the technological apparatus that was an evolutionary tool for the processes of architecture innovation. Tool use and manufacture are defined through both techniques and technology. In *Gesture and Speech*, palaeontologist André Leroi-Gourhan claimed the continuous reinvention of human beings emerged from the advent of technics, evident in the liberation from the genetic constraints of the hand tool.[32] Derrida related this technical

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[32] André Leroi-Gourhan, *Gesture and Speech*, trans. Anna Berger (Cambridge: MIT Press, 1993), 227.

evolution to deconstruction and cybernetics, which he saw as responsible for the decentring of traditional forms of humanism. This thesis analyses Bernard Stiegler's interpretation of Derrida's deconstructive method on existence in the sense of human temporality, constituted in relation to the temporality of technics. Stiegler's interrogation enables detection of structural limits within the technical apparatus of the system, that is, transformation of memory through the technics of writing and the development of industrial temporal objects such as simulation, models and writing. In Stiegler's work, the limits of such technical systems are defined in terms of a process of disorientation within technics: that is, within the technical system itself, as well as in its mode of operation. Stiegler considered this disorientation as producing a time-lag in the system's function of a deferred time which affects the speed of technological development and production. Further, Stiegler considered this deferred time in relation to the industrialisation of collective memory in the form of orthographic writing in history. Stiegler's framing of time, technology, memory and writing enables framing of the Non-Standard in terms of temporal objects where the advent of architecture must be received as a modification, as a difference.

The paradigm shift into the Non-Standard can thus be related to developments of technics in architecture, resulting in architectural elements like double-curved wall panels, facade patterning, structural facades, grading of material, optimisation of form and material and freeform surfaces. Modern architecture in part reflects succeeding generations of design processes, of the procedures and technical systems used by architects to constrain and shape design results. To explore this, a case study of the *Morpheus*

Hotel by Zaha Hadid Architects (2019) investigates the way in which distributed systems function as dynamic processes, developing in altered temporalities and articulating Non-Standard parametric data models and forms.

The chapter further evaluates the development of robotic apparatuses in architecture that began as specialised robotic machinery and automated high-rise construction sites in Japan in the 1960s. Today co-adapting new automation and robotic manufacturing technology has enabled buildings of higher quality and a higher degree of individuality. Notwithstanding, the thesis finds that robotic apparatuses display inherent limits in three ways: the limits of an industrial robot end-effector, that is, the final component of the robotic tool that delivers materials; the programmatic simulation code that instructs and operates a robot; and the robotic axis of freedom (3-, 6- and 7-axis). The Second Digital Turn of Non-Standard Architecture is an attempt to overcome these limitations. In architectural and manufacturing practice, it is distinguished in the thesis through model development as exemplified in the *Morpheus Hotel* by Zaha Hadid Architects. In academia, the thesis identified the first architectural Non-Standard robot *ARACHN[OL]OIDS* developed at the Architectural Association. In reviewing and integrating these contemporary developments, this thesis contributes a novel application for parametric geometry for load-bearing structures by identifying the asymptotic curve generated as part of the geometrical method with a Non-Standard robot prototype. Since asymptotic curves have not been previously applied to load-bearing structures, parametrisation using asymptotic curves with straight unrolling and orthogonal nodes is an advance in the potential realisation of Non-Standard Architecture.

Digital production techniques are documented and reviewed for effectiveness in terms of industrially produced materials and components. Based on analysed experiments, this thesis automates Non-Standard Architecture by generating controlled gradation of concrete for a Non-Standard element with the digital spraying method. The chapter defines the graded manufacturing processes for Non-Standard Architecture with increased performance for Non-Standard form by optimisation, as well as for environmental sustainability. Finally, the thesis proposes the Third Digital Turn of Non-Standard Architecture with a protocol that includes parametric data modelling that has the potential to integrate automation in construction and address the persistent limits that have constrained the full development of parametric possibilities in architecture.

Chapter 7, *The Third Digital Turn of Non-Standard Architecture,* formulates the *Statutes of Non-Standard Architecture* that contribute to the limits of Non-Standard Architecture. The thesis finds that, while the regulatory environment has changed to accommodate geometric and manufacturing innovation, more change is required to fully achieve Non-Standard Architecture. Such change is not technological but regulatory: it requires a fundamental rethinking of the persistent Euclidean bases that continue to frame architectural thinking and industrial manufacturing, material science, construction technologies, tools and practices. The focus must shift from purely formal concerns to the realm of information within contract and law. This includes the process from Non-Standard form finding methodologies of digital tools to print or project documentation and contract documents for transformation into fabrication.

The thesis applies the concept of relationality to the technics of the Second Digital Turn to reposition the project of Non-Standard Architecture. The concept of biodegradability in Derrida's philosophy – a term he uses to refer to the essential iterability of the signifier in deconstruction – is adapted to reframe the notion of re-cycling, re-inscription and re-purposing in a different, architectural context. Derrida advances this hypothesis of biodegradability to the self-destruction of cultural objects that, after being recalled and identified, simply become part of the archive. This has increased with technological advances and with the emergence of digital archives. A computational approach to architectural design and documentation has since integrated the notion of autopoiesis. The thesis evaluates the evolution of Non-Standard design, concurrent with recent work in genetic algorithms, leading to computer programs with feedback capacity that enable machine learning and iterative adjustment, evolution and adaptation. As part of the research, experiments on processes of recursive aggregation, tangent vector algorithm, adaptation and emergence were developed at the Architectural Association and analysed for the production of intelligent materialism and form. The resultant topological space is also an ecological space, since objects generated within it are time and site specific, residing in their relative positions within an inherently complex, dynamic spatio-temporal milieu, whether political, artistic or chemical. In conclusion, the thesis proposes six Statutes of Non-Standard Architecture that could help realise the architecture of ecological governance: Non-Standard planning controls, rationalisation of architecture standards within the contract, the codification of architecture, functionally graded materials for Non-Standard Architecture, automated architecture, and research and implementation of these factors. The conclusion gives an overview of current directions in research and of potential topo/ecological research trajectories that could help overcome the persistent, inherent limits to a full and genuine realisation of Non-Standard Architecture as autonomous.

CHAPTER 2

Modern Architectural Authorship and the Parametric Diagram

The gift of *différance* is technological.[33]

2.1 Introduction: The Emergence of Architectural Authorship

This chapter traces the notion of modern architectural authorship to the Renaissance. It also examines the adaptation of semiology into architecture in the twentieth century and the connected role of the architectural diagram as an autopoietic network of communication with the potential for innovation. Section 2.1 identifies the beginning of parametricism and the codification of city laws in the institutions and governance of the architectural profession during the Renaissance, with the *Statute of Korčula* (1265), the *Statute of Dubrovnik* (1272) and Leon Battista Alberti's seminal text *De Re Aedificatoria* (*Ten Books on Architecture,* ca. 1450). On these bases, formal architectural education was institutionalised in France with the founding of the *Academie Royale d'Architecture* in 1671. Section 2.2 relates the limit of Non-Standard Architecture to this very codification, embodied in the form of guiding principles within theoretical treatises by Alberti. Section 2.3 relates Alberti's machinations for automation in architecture to the evolution of automated robotic devices for the three-

[33] Bernard Stiegler, *Technics and Time 1: The Fault of Epimetheus*, trans. Richard Beardsworth (Stanford: Stanford University Press, 1994), 237.

dimensional simulation of digital codification. From its beginning in the modern period, an autonomous turn in architecture evolved by way of digitalisation emphasising originality and individualism in the translation of design into figurative and formal modes of production, aesthetics, heritage and use. Section 2.4 identifies limits and constraints accompanying the emergence of the architect and the architectural discipline during the Renaissance. Much later, Leroi-Gourhan's and Stiegler's theories on the evolution of human beings as determined by language and technology created a new codex that repositioned architectural authorship within collaborative digitally amendable authorship. Section 2.5 considers the architectural diagram as a means of mechanically negotiating between reality and an abstract system of organisation. The diagram that emerged as Deconstructivist method of graft is traced within the topological space of digital architecture, and further developed its ecological parameters politically defined within a Third Digital Turn of Non-Standard Architecture.

This thesis calibrates the notion of architectural authorship autonomy to Derrida's deconstructive method of thinking and writing of inter-textual weaving, reading one text for the presence of another, dissolving one text into another, or building one text into another. Derrida considers this collage or montage as the primary form of postmodern discourse. It allows both producers and consumers of texts to participate in the production of signification and meaning. The effect is to break or deconstruct the authority and power of the author to impose meanings or offer a continuous narrative. The method of deconstruction "breaks the continuity or the linearity of the discourse and leads necessarily to a double reading: that of the fragment perceived in relation to its text of origin… and incorporated into a new different totality."[34] Thus, the tactic of collage is Derrida's most effective strategy for questioning the illusions of representation. What emerges from this method is *différance* – the term Derrida defines as "the movement of differentiation and deferral, spacing and temporalization which must be thought of as preceding and comprehending any positioning of identifiable differences of oppositions."[35]

In 1985 Peter Eisenman appropriated Derrida's deconstructive method in his project for the *Parc de la Villette,* leading to what became known as Deconstructivist architecture, as well as to the digital revolution in architecture signalled by the Second Digital Turn: a design process integrating computational form finding and optimisation. This topological description of form fundamentally sought to relate matter (building material) and information by emphasising its transformational potential and the many forces at play in creating form. It is through this architectural diagram that the material processes and information associated with architectural practice and design projects are conveyed and transformed.

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[34] Jacques Derrida, *Collages: Revue d'Esthétique*, eds. Group Mu (Paris: Union Generale, 1978), 3–4.

[35] **"**Derrida forges this word at the intersection of the spatial and temporal senses of the verb *différer:* to differ and to defer. The standard spelling of the noun *différance* corresponds only to the first, spatial sense; there is no standard noun formed from the second sense of temporal deferral. The -ance ending conforms to the orthographics of a middle voice: neither active, nor passive, both active and passive (as in resonance). […] Significantly for Derrida's deconstruction of the traditional, philosophical opposition of speech and writing, the difference between *différence* and *différance* is unpronounced.**"** Jacques Derrida, *The Ear of the Other*, trans. Peggy Kamuf, ed. Christie McDonald (Lincoln: University of Nebraska Press, 1985), xii.

The diagram is distinguished from the architectural object first by its emphasis on depicting, in graphic form, the spatial relations between things describing inherently their mobile or dynamic relationships, and second by its emphasis on translating already existing information or organisations into a new conceptual or material relationship.

Such processes rely on increasingly sophisticated digital design tools and programming techniques, as a means for evolving an architectural design. Hence, recent work in genetic algorithms has sought to create programs that have forms of feedback built into their instructions to allow the program to learn or adjust itself to iterative outcomes. The thesis relates the Non-Standard mode of production to digital technology and the advent of industrial prototyping machines that revolutionised the economy of construction and anticipated cultural, political and social transformations. From these, Non-Standard architectural design as an analytical tool developed various formalised themes, super-surfaces and hyper-surfaces that integrate topological elements of the fold, loop, nodes and layers.

2.2 Codex of Architectural Drawing

After the Renaissance, the codex of *De Re Aedificatoria* that emerged as the dissemination of theoretical treatises on the disciplinary and professional territory in architecture institutionalised ideas and evolved into formal education and practice in architecture. With the advent of technology, the algorithmic rationalisation of Non-Standard production in construction documents evidenced a limit between the possibilities of digital architecture and the current capacities of the building industry to realise them. This limit was addressed in the Second and Third Digital Turns of Non-Standard Architecture.

In the Second Digital Turn, parametric thinking elaborated form finding, optimisation and robotic automation. However, these developments further exacerbated earlier limits such as the capacity of the building industry, causing a sustained limitation to the realisation of parametric architecture – that is, the capacity of contemporary technologies to achieve Non-Standard architectural forms. This process of parametrisation and codification of sovereign architecture was identified with the *Statute of Korčula* in 1265 and the *Statute of Dubrovnik* in 1272 as a precursor of treatises on architecture by Alberti that posited language as a measuring tool in architecture. Within this context, the thesis analysed the first rationalisation of a digitised plan with machinations for identical reproduction in 1430. The method of wood construction enabled parametric architecture to be visualised and built. The architectural parametric order is evident in the strictly prescribed city walls and towers, streets, houses and public spaces of Korčula and

Dubrovnik. The Third Digital Turn aimed to overcome the limits of realising Non-Standard Architecture by formulating the Statute for Non-Standard Architecture, which includes revision to the codification of Non-Standard Architecture, ecological governance, rationalisation of Non-Standard Architecture, graded materials for Non-Standard Architecture, automation and implementation of research into academia and practice.

2.2.1 Machinations for Automation of Architecture

The method suggested 570 years ago by Alberti in *Descripto Urbis Romae* represents a substantive positioning of language as a measuring tool, and of the parametric as foundational to architectural design and fabrication. Alberti described a manner of codifying the architectural plan by using a system of polar coordinates (Figure 2.1). The first rationalisation of the digitised plan is evident in Alberti's invention of a method for identical production of architectural images, and the production of a precisely measured, scaled drawing of an urban plan of Rome (Figure 2.2). The codification method integrates a tool that Alberti called *diffinitore* (Figure 2.3), which consisted of a circle, a rotary arm in the centre of the circle and a plumb-line to ensure that the circle was on a vertical level. It allowed readers to recreate pictures by feeding numbers into an instrument similar to today's plotter. The numbers of 'horizon' in *Descripto Urbis Romae* correspond to the numbers on the circle subdivided into forty-eight equal parts called *gradi,* which are further subdivided into four *minuti.*[36] Alberti believed that such digital files based exclusively on numerical data would encapsulate the original details to be recreated by each reader. The thesis suggests that this method of codification pre-empts the emergence of simulation with robotic automation. Following the development of the pointing machine into a triangulation device in the eighteenth century, computation simulated codification with routing machines and robotic automation to reproduce the digital file in plastic, stone and a variety of other materials.

[36] Franco Borsi, *Leon Battista Alberti: Complete Works*, trans. Rudolf Carpanini (New York: Rizzoli, 1989), 212.

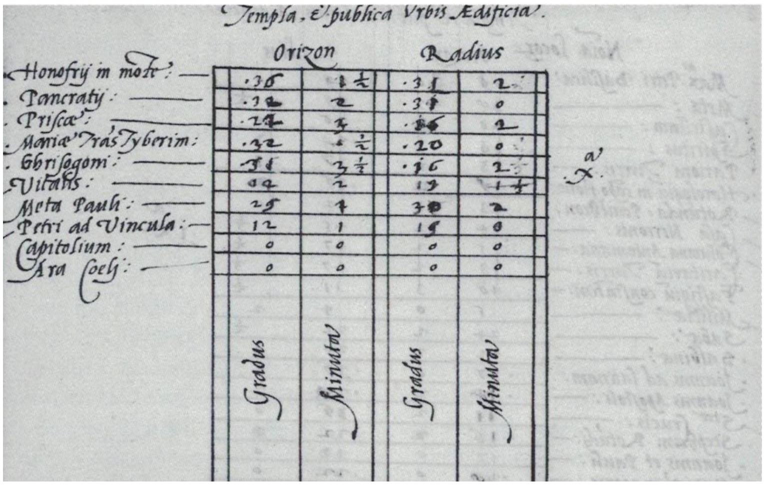

Figure 2.1. In *Descripto Urbis Romae* Alberti lists coordinates that digitise an image, which can then be re-created identically to the original by feeding numbers into the specific instrument, in a similar way to today's plotter. Joseph Rykwert and Anne Engel, *Leon Battista Alberti* (Milano: Electa, 1994), 432.

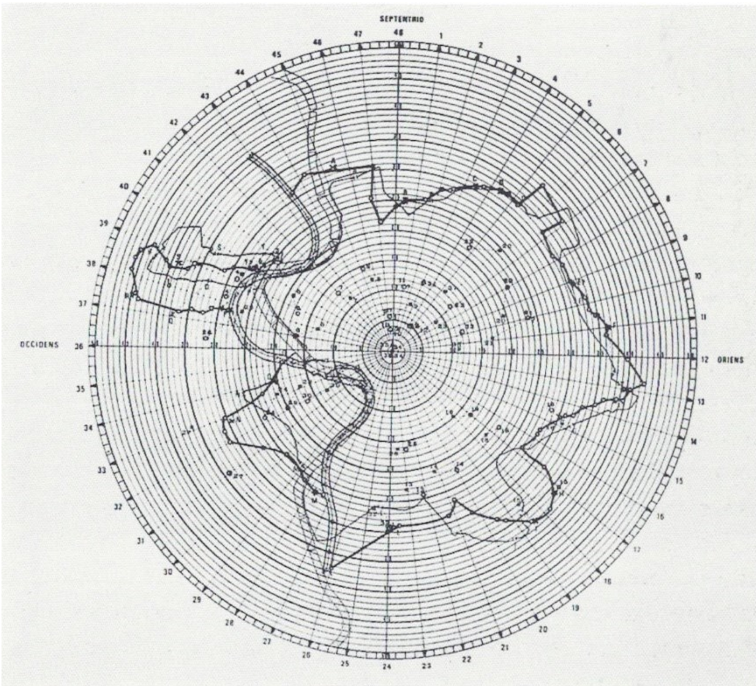

Figure 2.2. *Descripto Urbis Romae,* Diagram of Rome traced according to Alberti's method in ca. 1450, compared to a modern reconstruction of Alberti's by Luigi Vagnetti. Joseph Rykwert and Anne Engel, *Leon Battista Alberti* (Milano: Electa, 1994), 135.

2.2.2 Evolution of Automated Modes of Codification

Figure 2.3.

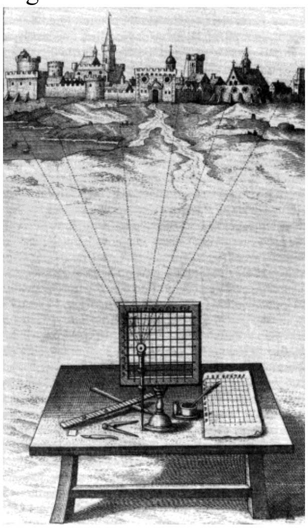

Figure 2.4.

Figure 2.3 Illustration of the *diffinitore* mounted upon a human figure in *De Statua* by Leon Battista Alberti. Leon Battista Alberti, *De Statua* (Livorno: Sillabe, 1999), 28.

Figure 2.4. Perspective frame. Alberti's geometrical exercise on understanding the principles of perspective adopted by Robert Fludd in his conception of the Macrocosm. Leon Battista Alberti, *De Pictura*, trans. Danielle Sonnier (Paris: Editions Allia, 2014), 46.

A similar principle of the *diffinitore* applied to three-dimensional objects by Alberti prefigured the evolution of the tool into automated robots. Alberti's *De Statua* manual introduced a machine, the *diffinitore,* a revolving attachment to the head of the body to be digitised. This innovative tool followed from the treatise by Alberti on painting, *De Pictura,* which presented the mathematics of perspective, introducing the vanishing point, the horizon line and a system by which spatial depth in the form of perspective could be easily constructed on a canvas or wall (Figure 2.4). Development of projective geometry during the Renaissance diverged from Euclidean geometry with the projection of parallel lines on a plane meeting on the point of a horizon. Alberti's window was conceived as a rectilinear frame gridded with a network of strings. His method of replication by numbers was dismissed by scholars until recently as too complex a method. The method required a connection between number scanning and number fabrication processes that Alberti's mechanical technology could not yet provide. The idea of prefabricating parts of an object – in this case, a statue using numbers and machines evokes later development of the proto-industrial system of Taylorism, the assembly line, outsourcing and computer-aided manufacturing.

A later developed measuring device, the *macchinetta,* is most commonly used today in the form of a triangulated instrument with pointing devices (Figure 2.5). In contrast to Alberti's *diffinitore* that locates each point in three axes, the *macchinetta* operates by fixing a point in space relative to three other known points, first on the model, and then in the material that the model is copied into. The measurement is taken by the user locking down the adjustable arm so that the tip of the needle mounted into the arm touches the point on the surface of the plaster cast model. Then the pointing machine is lifted off the cast and placed into its position on the copy in progress, where the needle now indicates the position of that point[37] (Figure 2.6). In the late eighteenth century, the triangulation and pointing machine was eventually developed into automated robotic pointing devices to create three-dimensional digital scans of an original. Such scans were then used to direct routing machines to cut the copy into a material or with three-dimensional printers which replicate digital information by depositing materials in the six-axis robotic apparatus (Figure 2.7).

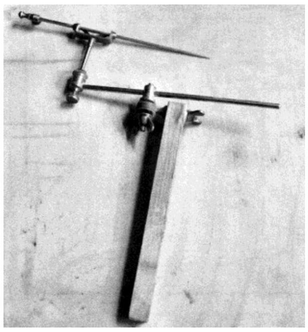

Figure 2.5.

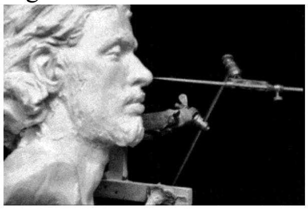

Figure 2.6.

Motion range	
A1	±185 °
A2	-135 ° / 35 °
A3	-120 ° / 158 °
A4	±350 °
A5	±119 °
A6	±350 °
Speed with rated payload	
A1	140 °/s
A2	126 °/s
A3	140 °/s
A4	260 °/s
A5	245 °/s
A6	322 °/s

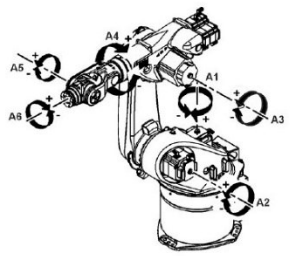

Figure 2.7. Six-axis robot direction of rotation of the robot axes. Kuka Roboter GmbH, *KR60 Specification* (December 2017): 26.

Figure 2.5. The *macchinetta* or pointing machine is a measuring tool for making one-to-one copies of models. Leon Battista Alberti, *On Sculpture*, trans. Jason Arkles (Milton Keynes: Lightning Source Ltd, 2013), 44.

Figure 2.6. The *macchinetta* or pointing machine attached to the croce, is adjusted to touch a small pencil dot made on the tip of the nose. Leon Battista Alberti, *On Sculpture*, trans. Jason Arkles (Milton Keynes: Lightning Source Ltd, 2013), 46.

Today's file-to-factory CAD-CAM technologies integrate the advantages that Alberti had sought into digital formats, where images and three-dimensional objects are recorded, transmitted, manipulated and reproduced by sequences of numbers. The difference between contemporary methods and Alberti's hand-operated digital process is that today, a large amount of digital data is

[37] Leon Battista Alberti, *On Sculpture*, trans. Jason Arkles (Milton Keynes: Lightning Source Ltd, 2013), 45.

automatically processed by electronic machines. For instance, the Microsoft 3D scanner Kinect launched in 2010 is a modern version of Alberti's *De Statua* instrument. Kinect is a camera device where measurement is created with infrared light, like a radar, tracking a beam of light reflection from the body to create a three-dimensional spatial map in front of the device. The device digitises geometries of movements with the scan imported into CAD software. This digital translation of architectural geometry by scanning enabled the development of non-Euclidean or Non-Standard forms.

2.2.3 Non-Standard Architectural Codification

The recent integration of a brainwave reader device in architectural research represents a new method for the architectural codification of spatial definition. The architectural brainwave reader was proposed as part of my research project *ARACHN[OL]OIDS* at the Architectural Association in 2012 (Figure 2.8). It is identified by this thesis as the first Non-Standard automated architectural prototype that addressed the persistent limits between computational architecture and the building industry, in terms of both its design and its construction. The brainwave reader device provides an opportunity for evolution of the architect's interface to codify information for direct spatial movement of the fabrication geometry equipment in real-time.

Figure 2.8. Geometrical definition by the operator that activates the robot equipment through brainwave interface parameters by engaging mental directions and codified facial movements for the prototype. They are transmitted to an automated robot via Bluetooth which delivers material through a series of end-effectors. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

This method integrates Cody's Emokit, which is an open-source library for reading data from the Emotiv EPOC EEG Headset. The device is a brain–computer interface using signals from the brain and facial muscles. Emokit is connected to the device using algorithms, integrated with Arduino programming language for input information parameters. It receives encrypted reports from the device, which are sent in a queue like a rendering interface. The neural interface works with electroencephalography technology, developed initially for medical purposes, notably prosthetics control. Any emitted signal can be captured and converted instantly into a command task. In architecture, functioning as a generator, the method provides an opportunity to evolve architectural codification as preconditioned input. This form of neural interface was envisaged within the parametric data model of the Second Digital Turn, and for the automation of architecture that this thesis identifies as the Third Digital Turn of Non-Standard Architecture produced through a direct human–machine interface.

2.3 Modern Architectural Authorship

The diffusion of classical notions of aesthetic theory by means of writing through the works of Alberti became instrumental in the development of historiography and introduced the notion of modern architectural authorship. Alberti's method of recording and transmitting data with invented mechanical devices to translate images into text pre-empted contemporary digital processes which convert design complexity into algorithms that can rationalise architectural forms, with their correlated architectural drawings as a precondition of manufacture. Whereas Alberti's transmission of drawings into letters and numbers was a reliable method of creating accurate copies, algorithms in digital architectural protocols equally aim to achieve complex geometrical form finding and fabrication. Alberti's rules of parallel projection represent the beginning of geometrically defined standardised, proportional and orthogonal plans.

Alberti's treatise on architecture, *De Re Aedificatoria,* was an in-depth answer to the laborious interpretations of the oldest surviving work on architecture written 1500 years earlier by Vitruvius, *De Architectura* (33 BC). Written in Latin and without illustrations, *De Re Aedificatoria* was not only intended for architects. At first, it was circulated among cultivated patrons of the arts: humanists who needed a selective and reasoned collection of criteria with which to pursue their architectural projects.[38] Alberti developed an original synthesis capable of comparison with models of the past.[39]

A widely disseminated book, *De Re Aedificatoria* was conceived in the form of a codex to enable the copying and transmission of classical architectural forms, together with instruction on the production of building elements and a tectonic, decorative language based on repeatable iterative parts – capitals, entablatures and mouldings. Alberti claimed the effect of architecture on humanity, both public and private, as the first art form capable of combining utility with beauty.[40] Apart from manual codification skills, architects established themselves as professional figures by implementing a method of design and invention through drawing in plan, elevation and section. The design inventions responded to the requirements of contemporary society which were both useful and in harmony with nature, the result of a personal intellectual endeavour. The codification of complexity in design and structural systems implemented by Alberti inaugurates the idea of the code in the architectural lexicon for architectural theory and practice.

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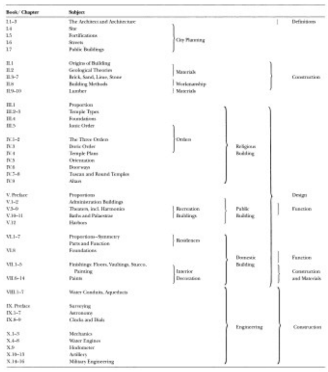
[38] Silvia Beltramo, Flavia Cantatore and Marco Folini, *A Renaissance Architecture of Power: Princely Places in the Italian Quattrocento* (Leiden: Brill, 2016), 60.

[39] Leon Battista Alberti, *Leon Battista Alberti* (Florence: Olschki, 1999), 443.

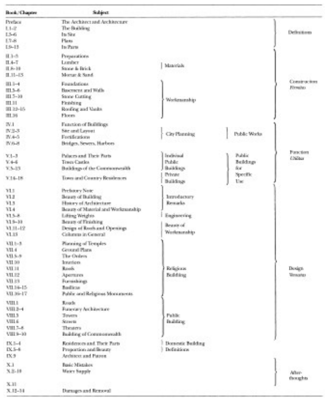
[40] Alberti, *Leon Battista Alberti*, 447–449.

2.3.1 The Ordering Principles of Alberti and Vitruvius



Book/Chapter	Subject			
I.1–3	The Architect and Architecture			Definitions
I.4	Site			
I.5	Fortifications	City Planning		
I.6	Streets			
I.7	Public Buildings			
II.1	Origins of Building			
II.2	Geological Theories	Materials		
II.3–7	Brick, Sand, Lime, Stone			Construction
II.8	Building Methods	Workmanship		
II.9–10	Lumber	Materials		
III.1	Proportion			
III.2–3	Temple Types			
III.4	Foundations			
III.5	Ionic Order			
IV.1–2	The Three Orders	Orders		
IV.3	Doric Order		Religious Building	
IV.4	Temple Plans			
IV.5	Orientation			
IV.6	Doorways			
IV.7–8	Tuscan and Round Temples			
IV.9	Altars			
V. Preface	Proportions			Design
V.1–2	Administration Buildings			
V.3–9	Theaters, incl. Harmonics	Recreation Buildings	Public Building	Function
V.10–11	Baths and Palaestrae			
V.12	Harbors			
VI.1–7	Proportions–Symmetry Parts and Function	Residences		
VI.8	Foundations			
			Domestic Building	Function
VII.1–5	Finishings: Floors, Vaultings, Stucco, Painting	Interior Decoration		Construction and Materials
VII.6–14	Paints			
VIII.1–7	Water Conduits, Aqueducts			
IX. Preface	Surveying			
IX.1–7	Astronomy			
IX.8–9	Clocks and Dials		Engineering	Construction
X.1–3	Mechanics			
X.4–8	Water Engines			
X.9	Hodometer			
X.10–13	Artillery			
X.14–16	Military Engineering			

Figure 2.9.



Book/Chapter	Subject			
Preface	The Architect and Architecture			
I.1–2	The Building			Definitions
I.3–6	Its Site			
I.7–8	Plans			
I.9–13	Its Parts			
II.1–3	Preparations			
II.4–7	Lumber			
II.8–10	Stone & Brick	Materials		
II.11–13	Mortar & Sand			
III.1–4	Foundations			Construction *Firmitas*
III.5–6	Basement and Walls			
III.7–10	Stone Cutting	Workmanship		
III.11	Finishing			
III.12–15	Roofing and Vaults			
III.16	Floors			
IV.1	Function of Buildings			
IV.2–3	Site and Layout	City Planning	Public Works	
IV.4–5	Fortifications			
IV.6–8	Bridges, Sewers, Harbors			
V.1–3	Palaces and Their Parts	Individual Public Buildings	Public Buildings for Specific Use	Function *Utilitas*
V.4–6	Town Castles			
V.5–13	Buildings of the Commonwealth			
V.14–18	Town and Country Residences	Private Buildings		
VI.1	Prefatory Note			
VI.2	Beauty of Building	Introductory Remarks		
VI.3	History of Architecture			
VI.4	Beauty of Material and Workmanship			
VI.5–8	Lifting Weights	Engineering		
VI.9–10	Beauty of Finishing			
VI.11–12	Design of Roofs and Openings	Beauty of Workmanship		
VI.13	Columns in General			
VII.1–3	Planning of Temples			
VII.4	Ground Plans			
VII.5–9	The Orders			
VII.10	Interiors			
VII.11	Roofs	Religious Building		Design *Venustas*
VII.12	Apertures			
VII.13	Furnishings			
VII.14–15	Basilicas			
VII.16–17	Public and Religious Monuments			
VIII.1	Roads			
VIII.2–4	Funerary Architecture			
VIII.5	Towers	Public Building		
VIII.6	Streets			
VIII.7–8	Theaters			
VIII.9–10	Building of Commonwealth			
IX.1–4	Residences and Their Parts	Domestic Building		
IX.5–8	Proportion and Beauty	Definitions		
IX.9	Architect and Patron			
X.1	Basic Mistakes			
X.2–10	Water Supply			After-thoughts
X.11				
X.12–14	Damages and Removal			

Figure 2.10.

Figures 2.9 and 2.10. Comparison of contents of Vitruvius' *De Architectura* and Alberti's *De Re Aedificatoria*. Richard Krautheimer, "Alberti and Vitruvius," *Studies in Western Art: Acts of the XXth International Congress of the History of Art* (New York: Princeton, 1963), 42–52.

Architectural historian Richard Krautheimer compares the ordering principles of Alberti's *De Re Aedificatoria* and Vitruvius' *De Architectura* in an analytical table of related topics (Figures 2.9 and 2.10). Krautheimer claims that, although there are many links between Vitruvius and Alberti including the division into ten books, the title and many references, quotations and paraphrases, Alberti draws on Vitruvius in only four fields: information about historical facts or fancy, technical details, the orders, and Antique building types hardly known in the 1400s such as forums or theatres.[41] Alberti's departure from Vitruvius is evident in major conceptual differences in how the architect and architecture are defined and in the purpose of the documents. Vitruvius' treatise was a manual, a summary of contemporary or obsolete practice, proceeding step by step from subject to subject, without a guiding principle. On the other hand, Alberti approached architecture as 'counsellor at antiquity', trying to discover its principles and parts, and how they can be executed.[42] The Albertian paradigm envisaged building as a mechanical operation of reproduction and variation using codified configurations but then adapting them to the specific circumstances of a project. The principal aim was to materialise an idea in three dimensions at full scale.

[41] Richard Krautheimer, "Alberti and Vitruvius," *Studies in Western Art: Acts of the XXth International Congress of the History of Art, The Renaissance and Mannerism* (New York: Princeton, 1963), 42–52.

[42] Caroline Van Eck, "The Structure of De Re Aedificatoria Reconsidered," *The Journal of the Society of Architectural Historians*, vol. 57, no. 3 (September 1998): 280.

Alberti's documentation of architecture considered region, the building site, platforms and foundations of the building, compartition, walls, roofs, details and ornaments. The treatise initiated the practice of architects prescribing the formal outlines of a building, leaving its construction in the hands of building contractors. Alberti was critical of an interpretation of his work idea that ultimately led to the professionalisation of architecture as a discipline devoted exclusively to design as opposed to implementation. His classicist code provided a historical foundation and replaced the anti-historical code compromised in medieval and gothic architectural languages of the sixteenth century. Apart from written codification, Alberti introduced the variation in the facade, the Roman triumphal arch, while reconsidering the building as an antique temple. Faced with the fundamental problem in the Renaissance of the column as the principal ornament in architecture, Alberti rejected the column creating opposing conceptions of the facade, evident in his *Palazzo Ruccellai* (1446) in Florence (Figure 2.11). Alberti's replacement of the column with a pure expression of the wall, for Rudolf Wittkower, represented a structural understanding of classical antiquity that rendered Alberti as revolutionary.

Figure 2.11.

2.3.2 Digital Architectural Authorship

Modern architectural authorship within the platform of digital technology has made drawing translation easier and opened an architectural practice of reproduction and adaptation, copying and variation as methods for design exploration and innovation. The architectural historian Mario Carpo observes the state of digital innovation today as a fast process where digital simulation generates more

Figure 2.11. *Palazzo Ruccellai* by Leon Battista Alberti, 1446. Scala Archives, Florence.

models than a traditional craftsperson could in a lifetime. Carpo identifies the start of the contemporary practice of producing standardised copies prior to the industrial age, citing Alberti's identical reproduction of images, designs, sculptures and buildings. Computation has made possible the design and accurate representation of an enormous variety of complex structures. For instance, parametric representational techniques with non-uniform rational B-splines function have reduced the distance between the digital object and physical reality with operations like lofting that allow smooth and continuous forms and surfaces. The virtual simulation creates an experience of reality and is used as an experiment to confirm accuracy. With the advent of mass production, architectural production shifted from identical production to Non-Standard seriality. Carpo links the advent of digital technology in the First Digital Turn with the reversal of the Albertian paradigm, in which digital technology has become consistent with the medieval autographic practices of notations by an architect to execute the architectural project. Within this context, authorship becomes anonymous, which contradicts the Albertian model, where authorship is a precondition for the architect's work. Carpo's question is related to changes in design and production into open-ended, interactive and collaborative processes that challenge the classic notion of authorship and authorisation.[43] Although the digital platform has enabled collaboration and created easily amended parameters, it has, at the same time, allowed collective design alteration

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[43] Mario Carpo, *The Alphabet and the Algorithm* (Cambridge: MIT Press, 2017), 43.

that contests single authorship. While the design is a collaboratively open process, the sovereignty of a contract assigns authorial attribution. In contrast, the treatises that began modern architectural authorship by Alberti posit a duality between transmittable public verbal rules and private architectural drawings. Alberti's antiquarian studies, sketches and designs for future buildings were one-offs meant for point-to-point transmission and direct or personal use by their maker or recipient. They were not meant to be seen by anyone else.[44] Consequently, Alberti did not publish architectural drawings. In Alberti's conception, originality remained with the seminal architectural idea embodied in drawing; and a building stood as a copy or translation of the drawing.

2.3.3 Repositioning of Architectural Authorship

Research for this thesis suggests that the collaborative and easily amended parameters of architectural digital authorship emerged in the 1960s with a new conception of subjectivity as autonomous individuality, together with a critique of classical notions of, and relationships between, the author and the reader. Roland Barthes claims for the subject or reader the position of the author, who is produced as a 'modern scriptor' born simultaneously with the text. As Barthes famously contended, the authorship and authority of the reader come at the expense of or the 'death of the author.' The erasure of the author enables the reader to assume a creative role in

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[44] Mario Carpo, "Alberti's Media Lab," *Perspective, Projections and Design*, eds. Mario Carpo and Frederique Lamerle (London: Routledge, 2008), 50.

Figure 2.12.

Figure 2.13.

building their own narrative within the framework established by the writer. Commissioned in 1967 for the *avant-garde* multimedia magazine *Aspen*, Barthes' *The Death of the Author* sets the stage for a recalibrated understanding of authorship[45] (Figures 2.12 and 2.13). Barthes' text orchestrates a play of differences, deferrals and displacements of meaning within a semiotic and linguistic system: a fluid and diverse network of signs, from which meaning takes shape. Barthes' operational and performative methods dissect the canonical codes of dominant bourgeois society into new networks that act by themselves. The meanings fabricated by readers allow them to assert their fundamental nature and absent the writer from the work by disassociating it from existing codes, causes, positions and forms. This allows the preservation and development of architectural authorship, while at the same time enabling both reader and writer, architect and user, to transcend the individualised work of interpretation and understanding into a new, third space of discrete and collective innovation.

Figures 2.12 and 2.13. *Aspen* three-dimensional multimedia magazine at the Bibliothèque Nationale de France special collections. The Minimalist double issue 5+6 edited by Brian O'Doherty published in 1967 has contribution by Roland Barthes of his essay 'The Death of the Author,' commissioned for the magazine. Images by Melika Aljukic.

In Non-Standard Architecture, this reorientation of authorship can be discerned in the delay, or the temporal deferral, between conception and fabrication specific to Non-Standard Architecture. For Bernard Stiegler, there is a "deferred time" that produces disorientation within technics, caused by the resistance encountered in the necessary adjustment between technological evolution and social tradition.[46] While theorists such as Carpo claim

[45] John Logie, "1967: The Birth of 'The Death of the Author,'" *College English,* vol. 75 (May 2013): 493–512.

[46] Bernard Stiegler, *Technics and Time 2* (Stanford: Stanford University Press, 2009), 60.

technical continuity between computer-based design and computer-driven fabrication during the last twenty years,[47] this thesis differentiates with the argument that novel design and consequent fabrication have required the development of new tools in architecture. Carpo defines the Second Digital Turn as the more recent algorithmic ecology focusing on the logic of flat geometric information to the three-dimensional spatial properties introduced by robotics and the accompanying software that replaced the First Digital Turn of digital experimentation of the two-dimensional planar perspective. Nevertheless, this thesis defines the Second Digital Turn with a gap between the possibilities of digital technologies in architecture and the current capacities of the building industries to realise them in robotic automation. The thesis finds the challenge to achieving automation is the limits of the regulatory environment and conservative construction practices. Overcoming the inherent limits requires reconsidering the existing regulations that frame technology and implementing the Third Digital Turn of Non-Standard Architecture.

The First Digital Turn began with customised software such as developed by Frank Gehry for the *Guggenheim Museum* in Bilbao (1997). The Second Digital Turn digital media absorbed design complexity into algorithms, leading to rationalisation and standardisation of plans to produce irregular forms with file-to-factory technologies. The mathematical operativity of digital tools

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[47] Mario Carpo, "Digital Indeterminism: The New Digital Commons and the Dissolution of Architectural Authorship," *Architecture in Formation: On the Nature of Information in Digital Architecture*, eds. Pablo Lorenzo-Eiroa and Aaron Sprecher (New York: Routledge, 2013), 50–51.

forms the basis for a transition from a modern conception of the architectonic object to an algorithmic function that contains an infinite number of different objects. The Non-Standard mode of architecture components production was defined by Bernard Cache in 1996 as part of his practice *Objectile* as no longer designed but calculated by parametric functions that provide two opportunities: the possibility of complex forms that would be difficult to represent by traditional drawing methods; and laying the foundation for a Non-Standard mode of production through modifying calculation parameters that allow the manufacture of a different shape for each object in the same series.[48] The Non-Standard is the philosophical and practical rejection of mass production in a post-industrial society with the potential to create interconnected architectural components. The term Non-Standard Architecture was first initiated by the Centre Pompidou exhibition *Architectures Non Standard* in 2003.

2.3.4 Establishment of the Architectural Profession

The rise of modern architectural authorship originating with the Statute and later Alberti produced an independent tradition, separating architecture from earlier guilds. Enabled by the development of the printing press, architectural treatises triggered the broad dissemination of information on contemporary modes of construction. According to architectural historian James S. Ackerman, there are three periods of development of the architectural profession. The first period represents the transformation of

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[48] Bernard Cache, *Earth Moves* (Cambridge: MIT Press, 1995), 88.

the apprenticed guildsman to building expert. The second period followed Alberti's ca. 1450 treatise *De Re Aedificatoria*, which argued for a clear distinction of architecture from building trades. Following Alberti's invention of modern architectural authorship, the third period, in the late sixteenth century, saw the establishment of academies to train architects and further codify building and form. In this last period, formal education was first institutionalised in France with the founding of the *Academie Royale d'Architecture* in 1671. At the end of the nineteenth century, academic university training became the primary mode of professional architectural training everywhere. Non-Standard Architecture that began with stonemasonry practice during the Renaissance established itself within an architecture profession. Authorship and copyright of the original architectural idea became vested with the architect, represented in design through drawings and models and subsequently produced as a copy in built form. The evolution of the tool by way of interactive variation and optimisation enabled by technology is later associated with the Second Digital Turn of Non-Standard Architecture. The integral algorithms with passwords are implemented within the digital programming language platform to control the authorship of information. On the one hand, this collaborative evolution expands research and form finding, while on the other it implements copyright control through governance, acknowledging the responsibility of authorship. The Third Digital Turn of Non-Standard Architecture identified by this thesis then repositioned authorship with the protocol integrating the Statute of the Non-Standard Architecture, to implement governance for the organisation, automation and customisation of architectural manufacture.

2.4 Semiotic Turn in Architecture

Strategies for analysing and interpreting architecture and the city, using an abstract conception of language, originate in the influence of linguists such as Ferdinand de Saussure and Charles Sanders Peirce who founded the school of thought known as Structuralism to apply linguistic theory to objects and activities other than language. Through semiotic analytical strategies pioneered by de Saussure, the political registers that link a sign, its meaning and its interpretation are highlighted. Peirce developed the science of signs, termed semiotics, by proposing a complex classification of signs by the different relationship between signifier and signified. For Peirce, this notion is a foundation of logic as it exists independently for both reasoning and fact.

A structuralist reading can be interpreted as an inquiry into linguistic codes in the same way that an architectural analysis can be interpreted as an investigation into tectonic codes – those patterns of layout, composition, geometry and form that are foundational to the architectural project. The linguistic revolution of the twentieth century, from de Saussure to contemporary literary theory, proposed that meaning is not merely something communicated, expressed or reflected 'through' language. Rather, language produces meaning; meaning is 'in' language.

2.4.1 Forms of Meaning in Architecture

Although de Saussure's theory was for the historical comparison of languages, it influenced twentieth century architectural theory. By the mid-1950s, the principles of Modernism in architecture had reached a point of crisis for architectural theorists and practitioners. Modernist design methods based on functionality had come to seem prosaic, and its long-accepted aesthetics of abstraction increasingly vacuous. Revisionist thinkers such as Umberto Eco, Roland Barthes and Charles Jencks found intellectual reinvigoration in two bodies of theory outside of architecture: first, by re-theorising functionalism in architecture with operations research that led to systemic design methodology; and second, by adapting theories of 'perception' and 'reception' through an intensified consideration of architecture's audience. This produced a semiotic turn in architecture, typified in the influential work of Charles Jencks. In Jencks' adoption of semiotics, meaning in architecture was derived from the fact that any form in the environment, or any sign in language, is motivated or capable of being motivated.[49] A central component of de Saussurean semiology appropriated into architecture was understanding that a sign, defined as the relationship between a signified (concept) and its signifier (sound-image), is arbitrary; that there is no inherent relationship between a concept and its word-image. Therefore, Jencks implements semiotic theory into architecture by representing a building as a symbol, an understanding of it as a thought, and words as a representation.

The transposition of semiotics as meaning into architecture was pursued in the 1960s by the architectural community including George Baird and Charles Jencks (*Meaning in Architecture,* 1969), Joseph Rykwert

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[49] Charles Jencks, "Semiology and Architecture," *Meaning in Architecture,* eds. Charles Jencks and George Baird (London: Barrie & Jenkins, 1969), 11.

(*Meaning and Building,* 1960), David Crane (*The City Symbolic,* 1960) and Robert Venturi (*Complexity and Contradiction in Architecture,* 1966) amongst others. Theoretical speculations about applying structuralist and semiological ideas in architecture were centred at the Architectural Association in London during the late 1960s. At that time, the Architectural Association journal *ARENA*, with the theme "Meaning in Architecture", evolved into a publication edited by Charles Jencks and George Baird. *Meaning in Architecture* (1969) investigated the application of de Saussurean semiotics in architecture, specifically how semiology, general linguistics, structural anthropology, cybernetics and information theory might be applied to analysis and interpretation in architecture. In his essay "Semiology and Architecture" Charles Jencks presents a model of semiotic analysis for architecture (Figure 2.14). The diagram adapts de Saussurean semiology to describe architecture and its design by three coordinates: symbol, thought and referent. The introduction into architecture of the 'referent' – a term coined by de Saussure to indicate the real or non-linguistic aspect of the sign – recast the creative aspect of architecture and architectural design as acts of communication and representation.

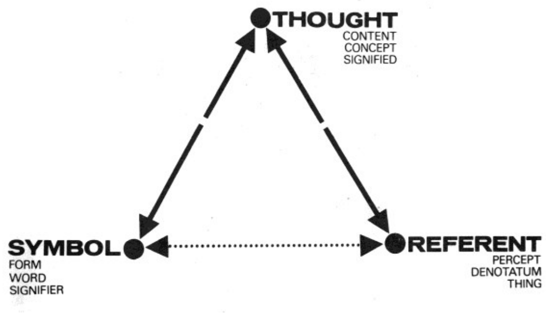

Figure 2.14. *The Semiological Triangle* by Charles Jencks. Charles Jencks, "Semiology and Architecture," *Meaning in Architecture,* eds. Charles Jencks and George Baird (London: Barrie & Jenkins, 1969), 15.

2.4.2 The Absence of Signification: Floating Signifier

While Jencks formally introduced structuralism into architecture and was actively involved in its dissemination and appropriation, Roland Barthes, a pre-eminent structuralist and later deconstructionist, prompted a return to the theories of de Saussure by using *langue* (language) and *parole* (speech) in his writing. Barthes declared the death of the author, based on the claim that authorship was merely the arrangement of structures already present in the language code. While structuralist methodology did not interpret any literary work, it identified a work's characteristics and the structural differences it demonstrated in relation to other works. Barthes' essays on semiology, notably *The Eiffel Tower* (1979), *Empire of Signs* (1970) *and Writing Degree Zero* (1953), triggered the appropriation into the architecture of the motifs of the degree zero – "a still centre, an erotic or lacerating value,"[50] the empty sign and the neutral, irreducible to positive or negative terms and not yet appropriated by myth. The essays prompted an understanding of buildings and cityscapes as communication devices. Yet in his analysis, Barthes moves beyond semiology, reading the modern city, specifically the city of Tokyo in the *Empire of Signs*, in terms of radical difference. The city is occupied by the lacuna of the royal palace, defined around an empty centre: the subways around which the city moves without ever occupying it – an 'empty' or 'floating' signifier that, because of the absence of any codified, agreed or fixed

[50] Roland Barthes, *Camera Lucida: Reflections on Photography*, trans. Richard Howard (New York: Hill and Wang, 1981), 18.

signification, produces an interminable deferral of meaning. This suspension of meaning, and the subsequent play of signification, became a defining register in poststructuralist theory and methodology. Later, it was elaborated by Derrida with the idea that in a floating signifier, "signification adds something, which results in the fact that there is always more, but this addition is a floating one because it performs a vicarious function, to supplement a lack on the part of the signified".[51]

The concept of the floating signifier, and the interminable deferral of meaning, can be linked to the motif of the *flâneur* introduced into literature by Charles Baudelaire in his 1864 essay *The Painter of Modern Life.* This text describes Modernity as a time characterised by historical discontinuity and fragmentation within itself, experienced by the modernist subject as radical suspension, interminable deferral and construction of meaning. Situated on the margin of the city and the bourgeoise, the *avant-garde* figure of the *flâneur* was transposed from literature and linguistic theory to conceptualise the experience of walking and consuming the built environment as spectacle. The peripatetic *flâneur* actualises urban experience as an activity of constructing situations through a technique Guy Debord named *dérive* (drifting).[52] The thesis identifies the

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[51] Jacques Derrida, "Structure, Sign and Play," *The Structuralist Controversy* ed. Richard Macksey and Eugenio Donato (London: The Johns Hopkins University Press, 1972), 260–61.

[52] The first edition of *Situationist International* journal in 1958 defines *dérive* as a mode of experimental behaviour linked to the conditions of urban society: a technique of rapid passage through varied ambiences. The term also designates a specific uninterrupted period of *dériving.* Situationist International, "Definitions," *Situationist International Anthology*, ed. Ken Knabb (Berkeley: Bureau of Public Secrets, 1981), 52.

deferral of the meaning of the *dérive* as an infinite set of trajectories of Non-Standard innovation within a standardised system of architecture. The Situationist International organisation understood this practice as a transformation of Baudelaire's nineteenth century *flâneur*, distinguishing it from classic, premodern notions of journeying and walking. In Baudelaire, the *flâneur* has an ambiguous class position that signals an aristocratic holdover. Through the *dérive,* Debord's *flâneur* suspends class allegiances to enable a heightened receptivity of the 'psychogeographical relief' of the city. Importantly, the *dérive* contributes a sense of "*dépaysement*" or disorientation to the *flâneur's* urban experience, which is not geared to communication and reception of meanings, but a kind of interminable play and reverie.[53] Marcel Proust describes this experience of the search for intellectual truth as the violent effect of a sign, which forces the mind to seek the sign's meaning. The search for truth as an essential relation to time is interpreted through the development of the sign in itself, the distinction between time lost, and time regained.[54] Intelligence alone is capable of supplying the effort of thought, or of interpreting the sign, within lost time. Deleuze sees this Proustian search not only as an instrument but as a machine, because of its essential productive and implementational work of resolving the contradiction between regained and lost time. This machinic process from fragmentation into intelligence

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[53] Tom McDonough, "Situationist Space," *Guy Debord and the Situationist International*, ed. Tom McDonough (Cambridge: MIT Press, 2002), 257.

[54] Gilles Deleuze, *Proust and Signs*, trans. Richard Howard (London: The Athlone Press, 2000), 23.

reflects the algorithmic parametric data modelling in Non-Standard Architecture, where conceptual analysis and design are generated from digital information within a project-specific timeframe. The manual version of urban mapping, *The Naked City* map (Figure 2.15), credited to Guy Debord, represents the concerns of *Situationist International*, particularly in the construction and perception of urban space. The fundamental principle of the psychogeographic map, composed of nineteen cut-out sections or 'unity of atmosphere' of Paris and linked by directional arrows in red, is the construction of the narrative rather than a tool of universal knowledge. Debord describes the production of the psychogeographical map as a sum of ambient urban possibilities that a citizen could experience.

Figure 2.15. *The Naked City* by Guy Debord, 1957. Tom McDonough ed., *Guy Debord and the Situationist International* (Cambridge: MIT Press, 2002), 242.

2.4.3 The Spectacle of Autonomous Movement

Debord's *The Society of Spectacle* (1967) is a collection of 211 theses that critique the spectacle as "the autocratic reign of the market economy which had acceded to an irresponsible sovereignty, and the totality of new techniques of government which accompanied this reign."[55] For Debord, this reified realm of society's commodity accumulation and its reorganised production begins in 1927, and represents an appropriate designation of the latter half of the twentieth century. His critique of the spectacle applies and develops Karl Marx's concepts of commodity fetishism and alienation for the film, advertising and television age. For Debord, the image is the final mode of the commodity; and a spectacle is a tool that drives society, in the era of late capitalism, to valorise image consciousness and appearance rather than production. Spectacle brings together and explains a wide range of apparently disparate phenomena. However, Debord defines the spectacle based on the image-object over the real world of production as the spectacle of autonomous movement of non-life where primary human needs are replaced by "the pseudo-need for the reign of an autonomous economy to continue."[56] Another direction of strategies developed into highly politicised behaviour with the May 1968 student revolution in Paris that physically integrated into the city with barricades, graffiti and the diversion of entire city streets (Figures 2.16 and 2.17). Generated in the universities and

Figure 2.16.

Figure 2.17.

Figure 2.16. General dissatisfaction on May 13, 1968. Image from Rues Des Archives/AGIP. *Le Monde: 68 Les Jours Qui Ebranlerent La France* (April 2018): 7.

Figure 2.17. Rue Gay-Lussac, May 10, 1968. Libero Andreotti, "Architecture and Play," *Guy Debord and the Situationist International*, ed. Tom McDonough (Cambridge: MIT Press, 2002), 236.

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[55] Guy Debord, *Comments on the Society of Spectacle*, trans. Malcolm Imrie (London: Verso, 1998), 2.

[56] Guy Debord, *The Society of the Spectacle*, trans. Donald Nicholson-Smith (New York: Zone Books, 1995), 34.

Figure 2.18.

Figure 2.19.

art institutes, and on the cultural fringe of city life, the movement transformed into a street rebellion including factory workers in Paris, evolving into the global turbulence of 1968. The global movement of resistance to the dominant high modernist movement subsequently pre-empted a postmodernist turn, emerging between 1968 and 1972.

The year up to the event of May 1968 was prolific with literary production including Guy Debord's *The Society of Spectacle*, Michel Foucault's *Of Other Spaces: Utopias and Heterotopias* and Ronald Barthes' "The Death of the Author", while Jacques Derrida published three major books: *Speech and Phenomena, Writing and Difference* and *Of Grammatology*. *Tel Quel* (1960–1983), the French *avant-garde* literary magazine founded by Philippe Solers and Jean-Edern Hallier, published discourses by Lacan, Derrida, Foucault and Barthes amongst others, working towards post-structuralism and deconstruction. The moment of *Tel Quel's* theoretical proliferation coincides with the moment that appears as anti-theoretical in its spontaneity: the events of May 1968. The time of theory became extremely tense, resulting from the contrasting pull of different temporalities. The situation of May 1968 influenced the emergence of the political on to the scene of theory, and it also moved from the "orthodox, but crucial, frame of theoretical Marxism towards a more popular, less abstruse language, to the point of its breakdown."[57] The period was a prelude to the formulation of a new vision and is still part of the discussion around aspects of the Third Digital Turn of Non-Standard

Figure 2.18. *Couple D'Etudiants Dans Une Salle de L'Ecole Des Beaux-Arts*. May 1968. Photograph by Édouard Boubat.

Figure 2.19. *Intérieur de L'Atelier Populaire de Sérigraphie,* Ecole des Beaux-Arts de Paris, May 1968. Photograph by Ewa Rudling.

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[57] Patrick Ffrench, *The Time of Theory: A History of Tel Quel* (Oxford: Clarendon Press, 1995), 106.

Architecture on theories of space, the identification of the subject and the role of automation in the construction of the architecture (Figures 2.18 and 2.19).

2.4.4 Postmodernism: New Directions in Architecture

Codifiable systems of meaning by Umberto Eco and Noam Chomsky distinguished semiotic mechanism in the form of the primary function of a functional object, and the secondary function of a symbolic object. Within this semiotic framework, the sign is characterised only by the "codified meaning that in a given cultural context is attributed to the sign vehicle" rather than on "either behaviour that it stimulates or actual objects that would verify its meaning."[58] The interpretation of architecture in terms of linguistic structures, influenced by the work of Umberto Eco, diversified into technical, syntactic and semantic studies, evident in architecture as a system of codes. This led to design-oriented approaches concerned with typology, morphology and generative structures as promoted by Non-Standard Architecture. Robert Venturi's approach to architecture as an apparatus for popular culture represented a threshold of what would become Postmodernism, that emerged from a re-examination of the canon of architectural history, formalised in *Complexity and Contradiction*.[59]

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[58] Umberto Eco, "Function and Sign: Semiotics of Architecture," *The City and the Sign: An Introduction to Urban Semiotics*, eds. Mark Gottdiener and Alexandros Lagopoulos (New York: Columbia University Press, 1986), 59.

[59] Robert Venturi, *Complexity and Contradiction in Architecture* (New York: The Museum of Modern Art, 1966), 16.

Figure 2.20.

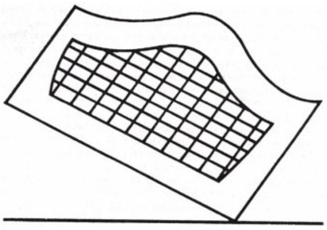

Figure 2.21.

Figure 2.20. *Parc de la Villette* by Bernard Tschumi. Jacques Derrida and Anthony Vidler, *Tschumi Parc de la Villette* (London: Artifice Press, 2014), 69.

Figure 2.21. Sketch by Jacques Derrida of a chora object for *Choral Works*, 1986. Geoffrey Bennington and Jacques Derrida, *Jacques Derrida* (London: University of Chicago Press, 1993), 406.

Polemical counterattacks on Postmodernism by the *neoavant-garde*, with Peter Eisenman as a prominent representative, turned away from Chomsky, favouring instead the philosophies of Jacques Derrida. Collaboration between Derrida and Eisenman on a section of the *Parc de la Villette* at the instigation of Bernard Tschumi generated a design process that advanced the notion of decomposition in architecture. This was explored through the defragmentation of classical, Euclidean and Cartesian geometries that governed modern architecture. Derrida's influence on architects such as Eisenman and Tschumi led to a transposition of deconstruction, as primarily a literary and analytical technique, into a formal, representational and stylistic technique in architecture. The representation of deconstruction came to be pursued through design based on the manipulation of two- and three-dimensional geometric configurations so that the "forms themselves are infiltrated with the characteristic skewed geometry, and distorted."[60] However, this representational approach misread Derrida profoundly. In his writing on and about architecture, Derrida claims that buildings are fundamentally event-sites, situations for things to happen, to take place. Rejecting the architecture of "the trial of the monumental moment," Derrida proposes buildings as sites of happenings – not only in the sense of the event of construction but as an event that continues to occur, to be "the imminence of that which happens now."[61] Derrida finds such practice in *Parc de la Villette*, where follies fold-out in place, forming a number

[60] Philip Johnson and Mark Wigley, *Deconstructivist Architecture*, (New York: Museum of Modern Art, 1988), 16.

[61] Jacques Derrida, "Point de folie – Maintenant l'architecture," *AA Files*, no. 12 (Summer 1986): 65–75.

of unexpected combinations and activities or events (Figure 2.20). Derrida implies the spatiality and forms in a diagram for *Parc de la Villette* in 1986 (Figure 2.21) to describe the '*chora*' concept used by Plato to describe space with potential and capacity.

The graft is an example of Derrida's textual mechanism of cutting, marking and incision in language, accompanied by *différance*, trace and supplement, for a new concept of writing over the logocentric. Derrida's graft or montage can be related to deconstructivist collage elements as a system of signs that created an operation of absence and systemic play of differences which opposed the modernist mechanic–organic formal processes associated with standardised forms. However, the paper collage semiotic recombinations have limits compared to digital architecture as they appropriated the pre-digital method. The montage technique was challenged, and the criteria for the new architecture emerged with neo-modern theorists, who sought to contribute to a non-hierarchical, heterogenous political space as opposed to postmodernist and deconstructivist architecture. One contributing factor in the search for a new architecture was the exhaustion of collage as the prevailing paradigm of architectural heterogeneity.[62] The graft thesis relates to the topological space of digital architecture which has formulated parameters in the Third Digital Turn that propose governance for organisation, optimisation and customisation of the process of automation in architecture.

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[62] Jeffrey Kipnis, "Towards New Architecture," *Architectural Design: Folding in Architecture*, ed. Greg Lynn (London: Wiley, 2004), 58.

2.5 Diagram as Architectural Machine

The digital revolution in architecture emerged as a transition from concepts of Deconstructivism. The seminal exhibition *Deconstructivist Architecture* at the Museum of Modern Art in New York in 1988 curated by Philip Johnson and Mark Wigley foregrounded the adaptation, through experimental design, of what was a tactic of literary criticism and philosophy into a novel design method and a distinctive style of architecture. Style and method revealed possibilities and potentialities of articulating disorder within normative modernist formal programs and systems. The deconstructivist architect was defined as "one who locates the inherent dilemmas within buildings," through defaulting to "formal strategies developed by the Russian *avant-garde* early in the twentieth century."[63] Deconstructivist architecture drew from constructivism yet radically deviated from it by employing formal strategies of disruption, dislocation, deflection, deviation and distortion.

Deconstructivist architecture was linked to the theories of Jacques Derrida (1930–2004) and presupposed that if architecture were a language capable of communicating meaning, it could be subject to linguistic philosophy and analysis. At the same time, this contention raised difficulties for Stanford Kwinter and Greg Lynn who found it arguable that late twentieth century and early twenty-first century architecture had any genuine claims to be a language, with its attendant grammar, syntax and vocabulary. The architectural appropriation of Derrida's

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[63] Philip Johnson and Mark Wigley, *Deconstructivist Architecture* (New York: Museum of Modern Art, 1988), 11.

deconstructive project aimed to disrupt the normative representational character of architectural systems by proposing that meaning is not a presence but rather the effect of a generalised absence: a *différance* alluding to the open alternation of events.

Research for this thesis pointed to a theoretical shift from an architecture of deconstruction, influenced by Derrida, towards discourses on mathematical models, influenced by Deleuze, Foucault, Lacan and Luhmann, leading to what came to be known as Non-Standard Architecture. The shift was represented by a digital revolution, powered by the new computer technology that emerged in the late 1990s with new digital design operations. Associated software capability included the algorithmic generation of continuous functions based on Leibniz's mathematics of continuity and de Casteljau's algorithm. Consequently, the digital revolution of the 1990s was characterised by smooth and continuous forms and surfaces, defined as blobs, and topological descriptions of form. An ethical dimension emerged, prompted by the concept of the fold drawn from Gilles Deleuze's *The Fold: Leibniz and the Baroque* (1988). Deleuze's definition of Non-Standard variability is related to the work of Leibniz, philosopher of the Baroque, and entails a system of deviation from a norm into the mathematics of continuity and differential calculus. Deleuze uses Leibniz's mathematics and modulation to propose a new theory and status of the object as a 'temporal modulation'. This in turn, shifted the focus on architecture from static buildings and forms to dynamic systems, processes and events that could be described algorithmically. The spatial and geometric recasting of form paralleled an equivalent linguistic methodology, characterising digital discourse in the 1990s with smooth and continuous forms and surfaces. They were configured with a spatial computer model into double-curved elements and proclaimed into Non-Standard Architecture by Centre Pompidou in 2003.

Figure 2.22.

2.5.1 Second Digital Turn of Non-Standard Architecture

Non-Standard Architecture theory shifts the parameters that determine architectural form from classical and industrial systems of standardisation to another idea of architectural identity. One characteristic strategy of the Second Digital Turn of the Non-Standard was the integration of robotic technology and algorithmic protocols for design and fabrication. Another was a shift into achieving large-scale Non-Standard architectural forms based on the serial production of non-identical non-linear components. The process of constructing Non-Standard Architecture was fundamentally interdisciplinary, deploying knowledge and tactics from biology, topology, parametric design and new technologies of fabrication.

This Non-Standard necessitated a non-hierarchical, non-orthogonal, non-Euclidean space, characterised by heterogeneity, and by the capacity for continuous variation. This was conceptualised by Deleuze and Guattari as smooth space, not the striated space of modernity, figuratively represented by the Riemann abstract machine[64] (Figure 2.22). Deleuze and Guattari affirm Riemann geometry as a revolutionary move into a "geometry of sufficient reason, a

Figure 2.22. Riemann surface models from the Henri Poincaré Institute. Image from Cedric Villani and Jean-Philippe Uzan, *Objects Mathematiques* (Paris: CNRS Editions, 2017), 95.

[64] Gilles Deleuze and Felix Guattari, *A Thousand Plateaus,* trans. Brian Massumi (Minneapolis: University of Minnesota Press, 1987), 485–6.

Riemannian-type differential geometry which tends to give rise to discontinuity on the basis of continuity, or to ground solutions in the conditions of the problems."[65] The concept of the abstract machine in architecture is related to the virtual enabled by technological processes that allow "operations of smoothing within an architectural form."[66] Such an organisation or formation is defined as ecological and autonomous. Hanjo Berressem argues that the position of the abstract machine as an architectural site is that of an actual rhizome. To produce a difference, Deleuze and Guattari argue, is to understand signs as rhizomes, as sign regimes, rather than in terms of human semantics and linguistic models. The development of rhizomatic principles in Non-Standard Architecture has limits with concepts based on the logocentric (Derrida) and arboreal (Deleuze and Guattari). The logocentric views all differences as ultimately derivative and recuperable while the arborescent structure has a centre from which elements branch off. These principles establish a rhizomatic digital platform of the parametric data model.

Stanford Kwinter made an analogy between Deleuze's diagram of a set of relations between forces and Kant's schema categorised with time, as machines or counterpoints performing as devices that generate space to relate a perceptible reality to the formal organisation system. This agency of schema or diagram is not merely the representation of a static assemblage or pattern but rather an active force, negotiated mechanically between reality

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[65] Gilles Deleuze, *Difference and Repetition,* trans. Paul Patton (New York: Columbia University Press, 1994), 162.

[66] Hanjo Berressem, *Felix Guattari's Schizoanalytic Ecology* (Edinburgh: Edinburgh University Press, 2020), 368.

and its abstract system of organisation. Kwinter argues that the diagram occurs through a contraction, which folds the object allowing it to traverse the process and unfold within the system as topologised schema.[67] These parameters distinguish the Second Digital Turn, which implemented a parametric digital model geared towards innovative formal possibilities through interlocking ways, as the distribution of forces produced in relation to time.

The aim of the Second Digital Turn of Non-Standard Architecture*,* while integrating nonlinear geometry, was directed to formal rather than in-formal ends. That is, it was geared to the computational documentation of a design, expressed as an algorithm, to produce parametric data models for construction. The current integration of digital technology in architectural and engineering processes has necessitated digital prototyping, with architects becoming directly involved in the fabrication processes as they create information that is translated by fabricators directly into the control data that drives digital fabrication equipment.[68] The new digital processes of production of complex geometries imply that the constructability of architecture becomes a direct function of computability.

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[67] Stanford Kwinter, "The Genealogy of Models. The Hammer and the Song," *ANY: Diagram Work*, no. 23 (1988): 58.

[68] Branko Kolarevic ed., *Architecture in the Digital Age: Design and Manufacture* (New York: Taylor & Francis, 2009), 33.

2.5.2 Third Digital Turn of Non-Standard Architecture

Rethinking the tool conceptualised the notion of the algorithm in architectural design and fabrication processes. This notion was developed within architectural theory and design as a tooling device in a series of embedded instructions for geometry, structural efficiency and optimisation. The Second Digital Turn of Non-Standard Architecture emphasised process over representation and the primacy of algorithms within a file-to-factory fabrication system. This radical homogenisation of design data and automated fabrication generates simulation processes as a tool. The aim of achieving industrial-scale multiplicity and efficiency as well as individual specificity and singularity has led to the potential of mass customisation in the digital environment where mass production and customisation coexist.

The Third Digital Turn then introduced governance to organise, optimise and customise the process of automation in architecture regulating Non-Standard Architecture quantification of writing and the measure of parametricism. The Third Digital Turn of Non-Standard Architecture answers the questions to overcome limits of realisation by implementing autonomous architecture for the automated Non-Standard Architecture environment.

2.6 Conclusion: The Limits of Architectural Codification

This chapter reviewed poststructuralist philosophy to trace codification in architecture and its development into the Second Digital Turn of Non-Standard Architecture as an evolutionary process for spatial practice. The codex that emerged as the dissemination of theoretical treatises on the disciplinary and professional territory in architecture is evident in the *Statute of Korčula* and *Statute of Dubrovnik* as well as Alberti's treatises on architecture. Their codex is Platonic with variation based on a model that each coded version repeats. Codex remains hierarchical with the copy subservient to the form or idea. From this codex, formal education and practice in architecture evolved. For Derrida and Deleuze, repetition is not the return of the same but the production of difference. In such differentiated production, variation is not tied to a transcendent model that it reproduces or represents. The copy and simulacrum are genuine means of diversification and innovation; innovation contests and deterritorialises.

The Second Digital Turn of Non-Standard Architecture privileges differentiation and diversification made possible by the topological schema. The Non-Standard contests mechanical paradigms of production by integrating algorithmic functions for the serial manufacture of non-identical parts. The formulation of codification in architecture is a method orientated towards difference, realised in the Second Digital Turn through parametric data models and custom robot prototyping. However, this system of robotic production and digital infrastructure remains bound to the Platonic and Euclidean notions of regularity and the orthogonal, as well as to the mimetic apparatus of manufacturing sameness, rather than to non-Euclidean possibilities of differentiation by deregulation and deterritorialisation. Hence, the Second Digital Turn of Non-Standard Architecture is foundationally obstructed or limited by conservative construction practices that are radically different from its digital capability.

This thesis recognises the Third Digital Turn of Non-Standard Architecture in the possibilities of contesting the Second Digital Turn with the *Statute for Non-Standard Architecture*. The thesis contends that achieving autonomous robotic automation can contribute to quality and precision in realisations of digital architecture, emphasising its originality and individualism.

CHAPTER 3

Architectural Autonomy

Autonomy of the will is the sole principle of all moral laws and of duties in keeping with them; heteronomy of choice, on the other hand, not only does not ground any obligation at all but is instead opposed to the principle of obligation and to all the morality of the will.[69]

3.1 Introduction: The Language of Autonomy in Architecture

This chapter examines the development of the Non-Standard as an autonomous discipline of architecture from its conception in the sixteenth century to its integration into digital architecture. Since the Renaissance, the practice of apprenticeship has been allied with the theoretical articulation of architecture's distinct disciplinary and professional territory. The quest for an autonomous code of architecture discipline emerged together with the dissemination of architectural theory in Alberti's *De Re Aedificatoria,* eventually becoming institutionalised as the architectural profession. This chapter examines the notion of architectural autonomy as it developed through the formal grammar of the Non-Standard. Section 3.1 identifies autonomy as a concept in contemporary debate. Section 3.2 reviews the emergence of parametrisation as pivotal to the formation of Non-Standard Architecture. Section 3.3 argues for the constructive capacity of the Non-Standard protocol by tracing the emergence of its first digital iterations as an

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[69] Immanuel Kant, *Critique of Practical Reason,* trans. Lewis White Beck, in *Kant's Critique of Practical Reason and Other Writings in Moral Philosophy* (Chicago: University of Chicago Press, 1949), 33.

analytical tool to develop various formal possibilities. Section 3.4 argues for the transformation and deformation of Mannerist and Baroque architecture into Non-Standard Architecture enabled by digital possibilities. The chapter extends the work of Michael Ostwald, Philippe Potié and Mario Carpo by looking at the manifestation of Non-Standard Architecture and its sources in Mannerist and Baroque architecture. Section 3.5 traces autonomous governance of architecture codification into absolute autonomy with the realisation of automated architecture.

Architectural autonomy, as exploration and transformation of its language, emerged in the modern period, introducing ethical and political issues in debates about architecture. It first appeared as a concern for classifying and taxonomically defining the universal qualities of architectural form, as a challenge to the stylism dominating architectural production, and as a means of safeguarding the status and role of the architect in an increasingly specialised profession.[70] In 1933, Emil Kaufmann associated the analysis of historical architecture with Kant's philosophical position under the phrase 'architectural autonomy'. In *Von Ledoux bis Le Corbusier*, Kaufmann's analyses drew on Kant's concept of autonomy based on morality to argue that the shift from Baroque to Neoclassicism initiates autonomous architecture. Most explicitly characterised in the work of Ledoux, autonomous architecture is marked by the isolation of buildings from their context. Kaufmann argued that this quality is foundational for Modernism through the geometric

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[70] Anthony Vidler, "The Leddoux Effect: Emil Kaufmann and the Claims of Kantian Autonomy," *Perspecta*, vol. 33 (2002): 16.

rationalisation of the plan. Architectural geometry was a fundamental tool for generating autonomous architecture. This thesis investigates the evolution of architecture in terms of aesthetic progress and the reflection of the social conditions that prompted innovation in formal expression. The language of autonomy in architecture has been debated most recently by Aldo Rossi, Robert Venturi, Peter Eisenman and Patrik Schumacher.

3.2 Non-Standard Geometry

In Kant's essay *What is Orientation of Thinking?* (1786) he makes an analogy between geographical orientation and the orientation in thinking to characterise the starting point and difficulties of philosophical inquiry. In illuminating eternal moral truths and therefore, humanity's progress toward rationality and enlightenment, Kant implements mathematics to transform the terms of his analogy. He compares reason to a sphere, the radius determined from the curvature of the arch of the surface.[71] His argument is oriented in practical thought such as the history of cosmology that overlapped with the history of human thought to establish a mathematical base. The origin of Riemannian geometry is indispensable to the description of the universal space as a generalised curved space. As in Euclidean geometry, Riemannian geometry assumes that the measurements of figures and objects do not depend on their position (Figure 3.1). In Euclidean geometry figures are freely movable only on a plane (on which they may slide and rotate), while Riemann geometry extends to any surface, including the surface of a sphere. This new non-Euclidean perspective of measures as a process of parametric quantification, using Riemann's concept of a point as an undefined entity determined by its coordinates, was the basis for Non-Standard geometry, then for Non-Standard Architecture.

Figure 3.1.

Figure 3.1. Riemann surface. Gerd Fischer ed., *Mathematical Models* (Braunshweig: Vieweg & Sohn, 1986), 122.

Both Newtown and Leibniz revolutionised mathematics at the end of the seventeenth century by

[71] Immanuel Kant, *Critique of Pure Reason*, trans. Norman Kemp Smith (London: Macmillan and Co, 1929), 608.

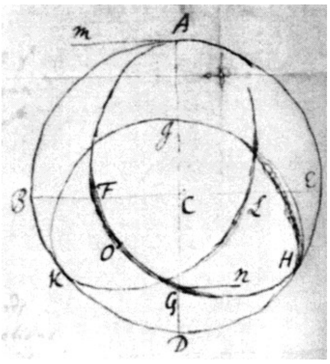

Figure 3.2.

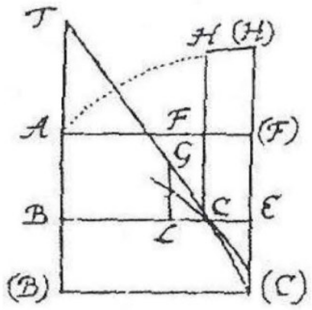

Figure 3.3.

independently developing notations that express the ideas of calculus. While Newton developed the method of computing curvature in 1664 (Figure 3.2), Leibniz developed curve geometry and area calculations with infinitesimal methods in 1674 (Figure 3.3). Later development by Abraham Robinson using methods of mathematical logic incorporated Leibniz's infinitesimals into Non-Standard analysis. Here, the structure of real numbers is "enlarged" to a field containing (arithmetic) infinitesimals and infinities in the form of Non-Standard models that preserve the usual algebraic properties of a real number. Apart from calculus, Non-Standard analysis was introduced into branches of mathematics, including topology and differential geometry. These advances on continuous functions based on Leibniz's mathematics were integrated into digital design operations for algorithms. Consequently, the digital revolution of the 1990s was characterised by smooth and continuous forms and surfaces, defined as blobs, and topological descriptions of form. The digital design protocols that integrate infinitesimal models from 'Non-Standard analysis' in mathematics by Robinson are integral to the geometric strategies of Non-Standard Architecture.

3.2.1 The Principles of Forming Curved Surfaces

The principles of a curved surface resolve computation of Non-Standard forms as precisely described and measured for codification and automation. The principles for forming curved surfaces are in the spatial analysis of geometric transformation. In 1964 Frei Otto founded the Institute for Lightweight Structures and Conceptual Design (ILEK) in Stuttgart, which became

Figure 3.2. Isaac Newton's diagram for the orbit of a body in a constant central field reveals the state of development of dynamics in 1679. Michael Nauenberg, "Newton's Early Computational Method for Dynamics," *Archive for History of Exact Sciences,* vol. 46, no. 3 (1994): 221–252.

Figure 3.3. Theorem of calculus. Gottfried Wilhelm Leibniz, *Acta Eruditorum* (Hildesheim: Georg Olms, 1682).

renowned for revolutionary research on lightweight constructions. The research merged architectural subject areas of design and form with the engineering fields of analysis, construction and material science. The Institute for Lightweight Structures developed physical analogue design and working models in a wide range of materials for the architectural design process and tension distribution in membranes. During the development process, the form was optimised, meaning that the form improved in specific criteria for the transmission of forces compared to its original form.

Early manifestations of form finding methods included the soap film machine developed in 1964 by the Institute for Lightweight Structures and Conceptual Design. This machine integrated the geometrical registration and measurement of the models produced (Figure 3.4). The physical analogue models developed were design and working models in a wide range of materials for the architectural design process and tension distribution in membranes. (Figure 3.5). The optimised structure, as defined by Frei Otto, is the "improved form of an object as compared to the original form [...] even if proof cannot be established in each individual case that this optimum is absolute and cannot be improved further."[72] Non-uniform rational B-splines have advanced digital design of lightweight structures through isogeometric analysis that combines the design and optimisation model.

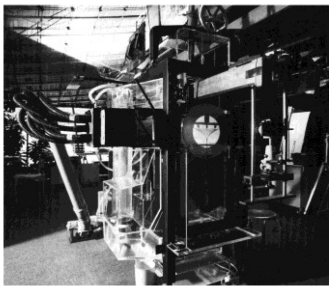

Figure 3.4.

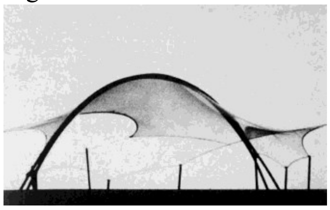

Figure 3.5.

Figure 3.4. Soap film machine, climatic chamber and photographic apparatus at ILEK. Frei Otto and Bodo Rasch, *Finding Form* (Fellbach: Edition Axel Menges, 1995), 58.

Figure 3.5. Soap film model of an arch tent – experimentally developed membrane and roof structures at ILEK. Frei Otto, "Architecture Nature," *Detail: Frei Otto, A Life of Research Construction and Inspiration*, eds. Irene Meissner and Eberhard Moller (Berlin: De Gruyter, 2015), 25.

[72] Frei Otto and Wolfgang Weidlich, *Form, Force, Mass 5: Experiments* (Stuttgart: University of Stuttgart, 1990), 15.

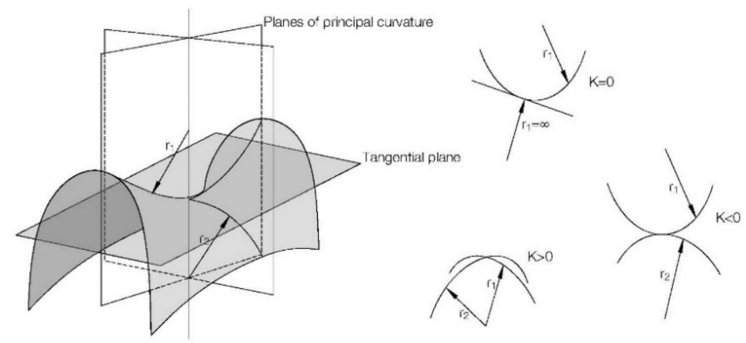

Figure 3.6. Principal curvatures r_1 and r_2, and Gaussian curvature K of curved surfaces. Jan Knippers et al., *Detail: Construction Manual for Polymers + Membranes* (Basel: Birkhauser, 2011), 136.

Surface curvature can be described by two different parameters: principal curvature and Gaussian curvature (Figure 3.6). Gaussian surfaces allow a resolution of the problem of surface developability in fabrication and can be applied to the task of form finding in Non-Standard geometry and architecture. Combining Gaussian curvature (K) with the principal curvatures (k_1 and k_2) defines the curvature of a surface. Positive or synclastic curvature ($K>0$) results from two principal curvatures located on the same side of a surface. This type of curvature applies to domes and pneumatically prestressed membranes. Negative or anticlastic curvature ($K<0$) results from two principal curvatures located on different sides of a surface. This type of curvature characterises saddle-shaped surfaces in mechanically prestressed membranes.

The formation of curved surfaces to carry loads axially is generally distinguished between free, geometrical and structural optimisation methods (Figure 3.7). Freeform surfaces are generated with a high degree of control curvature produced by non-uniform rational B-splines (NURBS). These surfaces or curves are calculated by changing parameters of order, control points and knot vectors within the spline.

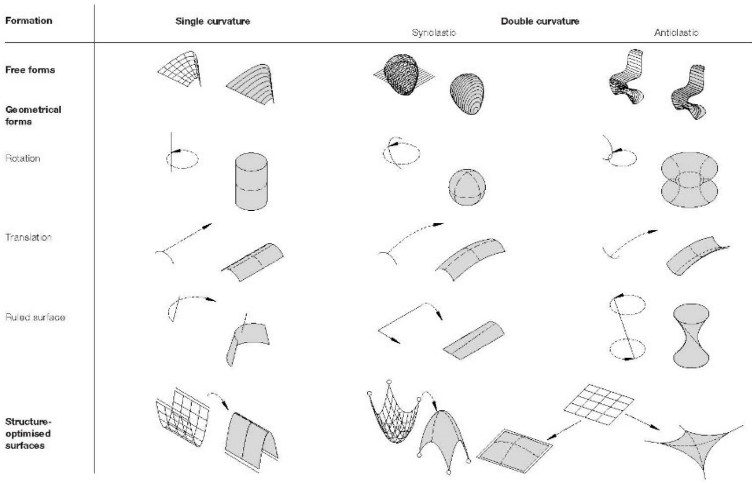

Figure 3.7. Generating curved surfaces. Jan Knippers et al., *Detail: Construction Manual for Polymers + Membranes* (Basel: Birkhauser, 2011), 136.

With the invention of parametric curves and surfaces by Paul de Casteljau in 1958,[73] digital spline-modelling was developed at Citroen as part of computer graphics for three-dimensional surface modelling system to guide numerically controlled machine tools. Generalised as non-uniform rational B-splines, today, they are the most common notation for freeform curves in all branches of digital design and manufacturing.

Geometrical surfaces are generated through the operations of revolution, translation and ruled surfaces. A surface of revolution is created by rotating a curve (the generatrix) around an axis of rotation. If the generatrix is concave with respect to the axis, the form is synclastic, or domical, while a convex generatrix with respect to the axis generates an anticlastic or saddle-shaped surface. A

[73] Paul de Casteljau, *Shape Mathematics and CAD* (London: Kogan Page, 1985), 10.

translation surface is generated through the parallel translation of a generatrix along a directrix line of parabola. A ruled surface is created through the movement of a straight line in space along curves of any form. Formatting of parametric surfaces with geometrical definitions is useful for fabrication and construction because of the translatability of quantifiable geometrical laws such as defined curvature, developability or the option of achieving a curved surface out of flat squares or rectangles that can be mass-customised.[74]

3.2.2 Digital Optimisation Methods

Structural optimisation is an inverse process in which parameters are indirectly optimised to find the geometry of a structure by *sizing*, *shape optimisation* and *topology optimisation*. The *sizing* is measured by element thickness. *Shape optimisation* changes the external shape of a continuum structure without changing the topology of the structure. *Topology optimisation* is a method of distributing material in an innovative way and in accordance with the structure. The methodology for structural optimisation in Non-Standard geometry under a form load is developed either by experimental or computer-based methods. Digital optimisation is a numerical method characterised by high precision, flexibility and speed. Isogeometric analysis uses complex non-uniform rational B-splines geometry (the basis of most CAD packages) in the finite element analysis application directly. This allows models to be designed,

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[74] Jan Knippers et al., *Detail: Construction Manual for Polymers + Membranes* (Basel: Birkhauser, 2011), 137.

tested and adjusted in one go, using a common data set. The method avoids converting the model to a polygonal mesh and achieves the parametrisation by NURBS during the simulation model from the geometric design in CAD.[75] These digital methods have replaced analogue experimental form finding typified by the work of Frei Otto in the 1950s.

Today, advanced digital tools are capable of performing optimisation on meshes and modelling minimal surfaces virtually, using software including RhinoVault, Surface Evolver, Kangaroo-Soap Film and Rhino-plugin TeDa. For membrane structures, form finding is a complex iterative procedure calibrated to material, form and load-bearing behaviour. This advanced digital design optimisation method has been developing in line with the continuous evolution of software algorithms. Typical current optimisation methods are the finite element method, the force density method and dynamic relaxation. The finite element method subdivides (discretises) the entire structure into elements joined together by nodes. The force density model is based on the equilibrium of forces at the nodes of the mesh. Dynamic relaxation involves prestressing a discretionary initial mesh that induces oscillations. These numerical optimisation methods allow increased complexity and efficiency in the design of structures. Consequently, finite element method software allows calculation of nonlinear structures and new methodologies

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[75] Austin Cottrell, Thomas Hughes, and Yuri Bazilevs, *Isogeometric Analysis: Toward Integration of CAD and FEA* (Chichester: John Wiley & Sons Ltd, 2009), xi.

in the computation of parametric design.[76] Dassault Systèmes Abaqus is a suite of engineering simulation programs, based on the finite element method, that can solve problems ranging from relatively simple linear analyses to the most challenging nonlinear simulations.

3.2.3 Topology: Transformational Events

The potential of the topology through transformation events has been applied to Non-Standard Architecture. In *Structural Stability and Morphogenesis* (1972), René Thom notes that catastrophe theory is one method to describe the evolution of forms in nature through the behaviour of forces in space over time. It is a topological theory that describes the behaviour of forces in space over time resulting from the combination of two or more conflicting forces. The fundamental importance of perturbations in nature is that they can be studied to extract parameters that can be applied to perturbation in Non-Standard structures, which are characterised by changes in geometry and form. The technique has been extended to real-world phenomena such as the forming of tools, the capsizing of ships, embryology and psychology.

René Thom's theorem classifies seven different types of elementary catastrophes: fold, cusp, swallowtail, butterfly, elliptic umbilic, hyperbolic umbilic and parabolic umbilic. They are characterised according to their universal

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[76] Nonlinear analysis in Abaqus is one in which the structure's stiffness changes as it deforms. Each load case is defined and solved as a separate analysis. There are three sources of nonlinearity in structural mechanics simulations: material nonlinearity, boundary nonlinearity and geometric nonlinearity. Dassault Systèmes Simulia, Abaqus Manual (Providence: Dassault Systèmes, 2013).

unfolding based on their effects involving one or two coordinate variables (x and y). The fold, as a simple figure of catastrophe, describes a change in behaviour from a stable state to an unstable state as a function of the control parameter (x)[77] (Figure 3.8). The cusp surface is a two-dimensional projection of the three-dimensional event-form unfolding as a catastrophe on the event surface above it (Figure 3.9). It describes two stable states of behaviour. The change between these two stable states of behaviour in the cusp is a function of two control parameters, asymmetry and bifurcation.[78] This catastrophe set is an example of a virtual form that established a differential model for the processes of Non-Standard Architecture.

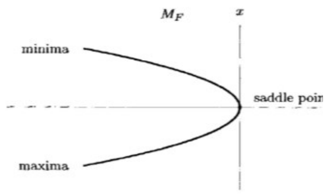

Figure 3.8.

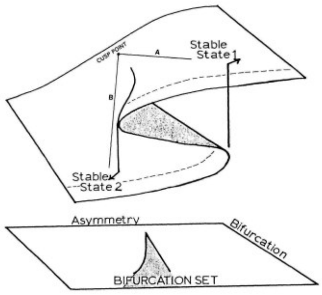

Figure 3.9.

René Thom's catastrophe theory derived partly from the writing of Conrad Hal Waddington on ideas of 'chreod' and 'epigenetic landscape'.[79] In 1939, Waddington introduced an intermediary space between the genotype and the phenotype in embryology, which he called an epigenetic landscape.[80] Waddington termed the stable pathways of change within this landscape 'chreods'. The epigenetic landscape model contains a set of developmental choices faced by a differentiating cell in the embryo. The process of development was described diagrammatically by way of a model, featuring a ball rolling down a landscape surface marked with several valleys. Waddington claimed that the

Figure 3.8. The fold catastrophe. Domenico Casteligiano and Sandra Hayes, *Catastrophe Theory* (Boca Raton: CRC Press, 2004), 37.

Figure 3.9. The cusp catastrophe response surface (upper) and bifurcation set (lower). Stephen Guastello, *Chaos, Catastrophe, and Human Affairs* (Mahwah: Lawrence Erlbaum Associates, 1995), 36.

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[77] Domenico Casteligiano and Sandra Hayes, *Catastrophe Theory* (Boca Raton: CRC Press, 2004), 37.

[78] Stanford Kwinter, "Landscapes of Change: Boccioni's Stati d'animo as a General Theory of Models," *Assemblage*, no. 19 (1992): 61.

[79] René Thom, "Topological Models in Biology," *Topology*, vol. 8 (1969): 321.

[80] Conrad Waddington, *An Introduction to Modern Genetics* (New York: Routledge, 2016), 155.

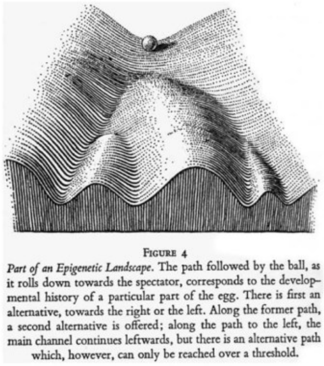

Figure 3.10.

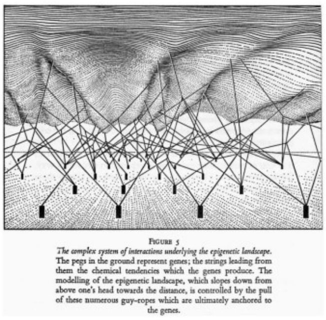

Figure 3.11.

Figure 3.10. Epigenetic landscape. Conrad Hal Waddington, *Strategy of the Genes* (New York: Macmillan, 1957), 29.

Figure 3.11. The complex system of interactions underlying the epigenetic landscape. Conrad Hal Waddington, *Strategy of the Genes* (New York: Macmillan, 1957), 36.

canalising or buffering of paths against perturbations is a critical element in morphogenesis (Figure 3.10).[81] A later version of an epigenetic landscape demonstrated how complexes of genes affect the course of any developmental pathway (Figure 3.11). Consequently, René Thom saw the Waddington model topologically, with the potential landscape as the catastrophic surface of a vast underlying complex continuity of biological metabolism, and the bifurcation points between pathways as the non-generic catastrophe points of the surface.[82] This process is related to the topological optimisation of design and material in Non-Standard Architecture through the distribution of forces within the parametric architectural digital model. Thom also found that catastrophe theory could inform parts of theoretical biology by providing biology with qualitative mathematical models and morphological concepts like chreod, canalisation, landscape and branching point that could function across both biochemistry and genetics. This research has led to work in genetic algorithms where programs with inbuilt feedback allow learning or adjustment to iterative outcomes, evolution and adaptation.

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[81] Jan Baedke, "The Epigenetic Landscape in the Course of Time: Conrad Hal Waddington's Methodological Impact on the Life Sciences," *Studies in History and Philosophy of Biological and Biomedical Sciences*, vol. 44 (August 2013): 756–773.

[82] Peer Bundgaard and Frederik Stjernfelt, "René Thom's Semiotics and Its Sources," *Semiosis and Catastrophes*, eds. Wolfgang Wildgen and Per Aage Brandt (Bern: Peter Lang, 2010), 47.

3.2.4 The Notion of the Schema

Waddington's epigenetic landscape is a complex multiplicity of conditions in constant interaction. It is also an emergent landscape, an enabling landscape, whose interactions give rise to novel events and unpredictable outcomes. This multiplicity is constructive for the concept of Non-Standard analysis. Deleuze's notion of the schemata is a philosophical figure capable of dividing and differentiating a concept, enabling it to diversify and assume different valencies and agencies.[83] It is a pivotal tactic in critical analyses of architectural concepts enabled through parametric data models. Deleuze and Guattari extended the concept of multiplicity into the full potential of Riemann's mathematical developments. They distinguished the 'virtual' and the 'possible', from their respective relations to the real. The rules of actualisation of the virtual, by contrast, are "not those of resemblance and limitation, but those of difference or divergence and of creation."[84] On the other hand, the kind of standard geometry outlined by Plato is based on two types of image-making: copy and simulacrum or representation. The copy of a paradigmatic model – Plato's *eidos* or form – is created by altering its dimensions to respect the correct measure of the paradigm so that any variation or similitude preserves both angles and proportions, while in the simulacrum, proportions are intentionally distorted to make the copy appear correct to viewers, in spite of it resulting in a

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[83] Gilles Deleuze, *Difference and Repetition,* trans. Paul Patton (New York: Columbia University Press, 1994), 218.

[84] Gilles Deleuze, *Bergsonism* (New York: Zone Books, 1991), 97.

malformed entity.[85] The parameters of the object became resolved with the Non-Standard digital platform of the Second Digital Turn capable of automating its fabrication.

These geometric qualities are defined as a virtual concept by Plato rooted in the idea of form, defined by moral values, axioms, physical properties and relations. This approach to motion analysis of the three-dimensional object implemented a measure of space, motion and velocity by the object's speed, size and its relation to other objects in velocity, defining motion as abstract conception and timeless syntax. Compared to the Non-Standard conceptualisation of form, formulated by a swept outline moving in space, Platonic form relates to the identical movement of its rotation around the centre of the geometrical element where rotating invariant measurements are preserved. Philosophical tropes developed by Edmund Husserl in *Formal and Transcendental Logic* and by Henri Bergson in *Matter and Memory* characterise multiplicity more specifically as a space of duration and imply that a built form is closely linked to a conception of all matter and experience such that the optimisation process is inherently dynamic, connected and interactive.

Likewise, Deleuze views simulacra as challenging the *eidos* or ideal form because, in them, multiplicity results from the different relationships entertained by the principle so that a resulting system can have no prior identity or internal resemblance. The comparison between Deleuze's tracing and mapping of the diagram and Kant's converting through subsumption empirical objects of intuition of

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[85] Plato, *Republic*, 396b10.

schema focuses both concepts on the space. Deleuze described the diagram as the abstract function of the "panoptic mechanism" through which trajectories of power can be mapped "in every relation from one point to another."[86] In comparison, Kant wrote that the schema is "a hidden art in the depths of the human soul, whose true operations we can divine from nature and lay unveiled before our eyes only with difficulty."[87] In turn, the schema gives the diagram an antecedent in the history of philosophy through elements that become part of the mechanism of thought organised between various systems.

[86] Gilles Deleuze, *Foucault,* trans. Sean Hand (Minneapolis: Minnesota University Press, 1995), 36.

[87] Immanuel Kant, *The Critique of Pure Reason*, trans. and ed. Paul Guyer and Allen Wood (Cambridge: Cambridge University Press, 1998), A141/B180–181.

3.3 Non-Standard Protocol

This thesis investigates the Non-Standard protocol of the Third Digital Turn – the deconstruction of parametric form and its potential for automated construction, characterised by parametric automated architecture and grading of material, made possible by the evolution of digital design and new technologies. Parametric design is concerned with fabricating concrete material objects through automation which Non-Standard graphic software never intended to calculate.[88] Non-Standard Architecture claimed geometric and volumetric invention, challenging Euclidean bases of architectural form. It developed out of novel interpretations of geometric possibilities, with a lineage stretching from the seminal work of Alberti in the Renaissance, through to Baroque and Modernist spatial theories and practices. While extending Baroque experimentation with spatial and formal turbulence that contested the orthogonal hegemony of the Renaissance, and extending turn of the century concerns for the dynamics of form, the Non-Standard was largely made possible by the capacities of digital technologies and new materials to realise innovative structural forms. Apart from generating new processes of design and construction, Non-Standard design expanded the architectural horizon.[89] The concepts of space question the needs and demands of contemporary society by introducing the reproduction of new materials

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[88] Bernard Cache, "Towards a Non-Standard Mode of Production," *Projectiles* (London: AA Publications, 2011), 61.

[89] Urs Hischbert, Daniel Gethmann, Ingrid Bock and Herald Kloft eds., "Theory and Debate," *Nonstandard Structures* (Graz: Graz Architecture Magazine, 2009), 13.

such as dynamic interactive components and interfaces, and a collective process rather than an individual author. A key characteristic of Non-Standard Architecture is an interest in complex surface curvatures and folded forms. One of its key aims was to integrate algorithmic continuous functions for the serial production of non-identical parts.

3.3.1 Conceptions of Non-Standard Architecture

The conception of Non-Standard was introduced by the Architectural Association as an open-source design studio dedicated to the systematic exploration of new design tools, systems and discourses for design innovation in architecture and urbanism. The studio was a platform for generating and testing ideas and aimed to advance digital design methods, applying them to real world urban and architectural challenges.[90] The phase of mutation through selection and reproduction of material as a collective process was shown in the 2002 exhibition *Latent Utopias.* The studio projects were undertaken in a collective process, investigating new ways "in which built assemblies can evolve across distributed design systems and perform as intelligent, adaptive, architectural spaces."[91] Concepts ranged from static composition through to dynamic and interactive components and surfaces. Design, structure and material were guided by digital media integrating sensors, controllers and feedback mechanisms. The project was a form of autonomous open research emphasising particular

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[90] Patrik Schumacher, "Digital," *AA Files*, no. 76 (June 2019): 52.

[91] Brett Steele, "AA Design Research Lab," *Latent Utopias,* eds. Zaha Hadid and Patrik Schumacher (Vienna: Springer, 2002), 94.

Figure 3.12.

forms of practice and communication between designers, collaborators and clients, which can be considered in terms of contemporary design systems related to historical precedents within modern architectural discourse.

While the Non-Standard projects introduced a new phase of digital mutation, they faced distinct technological limitation in the digital model's capacity to integrate and simulate real data. The Second Digital Turn of Non-Standard Architecture that followed sought to overcome these limits by implementing algorithms in computation and custom automation. The project followed a proto-design research agenda to investigate computation or systemic design applications that are scenario- and time-based.[92] A distinctive prototype of the Second Digital Turn is *ARACHN[OL]OIDS* (Figure 3.12) identified by this thesis as the first Non-Standard architectural robot and developed as part of my previous academic research at the Architectural Association in London during 2011–13.[93] The project achieved parametrisation by sinusoidal inversion of a custom seven-axis robot prototype by integrating kinematics embedded in the kaleidocycle geometry. The Third Digital Turn introduced by this thesis implements governance for organising, optimising and customising the process of automation as a threshold between concept design and construction.

Figure 3.12. Shell prototype generated by the first Non-Standard architectural robot. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

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[92] Architectural Association, *Design Research Lab*, produced by Architectural Association, June 10, 2014, video, https://www.youtube.com/watch?v=B8p_2fmLWfs.

[93] Architectural Association, *AADRL 2013 Phase 2 Reel*, produced by Architectural Association, June 21, 2013, video, https://vimeo.com/68853170.

Latent Utopias was exhibited at the Landesmuseum Joanneum in Graz (26 October 2002 – 2 March 2003) and foregrounded the realisation of Non-Standard Architecture projects. The curators of the exhibition, Zaha Hadid and Patrik Schumacher, provided exposure to academic research at the Architectural Association and twenty international practices, including Zaha Hadid Architects, COOP Himmelb(l)au, MVRDV, Foreign Office Architects, Sadar Vuga, Greg Lynn, NOX, UN Studio and Riser & Umemoto. Their production was assimilated with the artistic protocol that addressed the complex social process from which proto-architecture emerged. The discourse of the architectural *avant-garde* showed the transition from dominant concepts like de-construction, dis-location, de-coding and de-territorialisation into concepts of "plurality, multiplicity, heterogeneity, and virtuality" that challenge concepts of modernity and signal the end of universality, predictability and any notion of a future order.[94]

Figure 3.13.

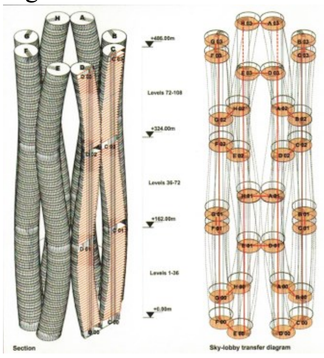

Figure 3.14.

Zaha Hadid Architects' radical architectural concepts in their *Contemporary Art Centre* (2010) in Rome subverted vectors of circulation into ways of gathering, moving and communicating in the public domain (Figure 3.13). Critical here was moving away from the object, towards fields of multiple associations anticipating the inevitable necessity of change. Also pivotal was an idea of architecture as emerging from directional drifts of geometry and distributions of densities, rather than from key points. Foreign Office Architects proposed a new high-rise typology that operated with building massing rather than

Figure 3.13. *Contemporary Art Centre* in Rome by Zaha Hadid Architects, 2010. MAXXI, *Zaha Hadid Architects*, accessed June 2, 2020, https://www.zaha-hadid.com/architecture/maxxi

Figure 3.14. The *Bundle Tower* in New York by Foreign Office Architects. Zaha Hadid and Patrik Schumacher eds., *Latent Utopias* (Vienna: Springer, 2002), 144.

[94] Zaha Hadid and Patrik Schumacher, "Latent Utopias," *Latent Utopias,* eds. Zaha Hadid and Patrik Schumacher (Vienna: Springer, 2002), 7.

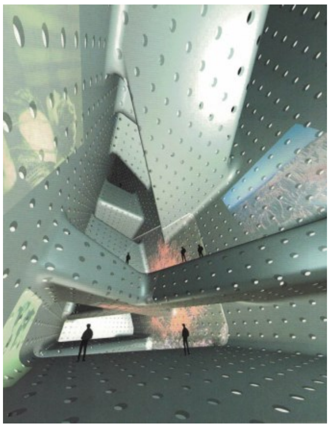
Figure 3.15.

just distribution of structure. Their *Bundle Tower* (2002) is a concept for interconnecting towers based on program data like rental workspace floor size and services zones (Figure 3.14). The tubular structure with a circular profile of eighteen metres aims to maximise the ratio between floor area and perimeter and to improve the structural performance of the building. The structural contribution includes the geometry of tubes that bend vertically to buttress each other, reducing the bending length of the towers. Seeking optimum design parameters, MVRDV introduced *Functionmixer* software (Figure 3.15). The model responded to planning controls by integrating complex data, including invisible factors like noise and economic factors. The optimisation method was applied to the urban and building scale with different parameters rendered as a virtual reality three-dimensional model. These radical projects of *Latent Utopias* remain a catalyst for design, however their resolution to assimilate site and design elements was not equivalent to modern algorithmic data models.

In his article "Non-Standard orders: 'NSA codes'", Frédéric Migayrou identified the non-Euclidean basis of Non-Standard Architecture with the concept of 'Non-Standard' in the work of mathematician Abraham Robinson.[95] The first iteration of Non-Standard architectural design functioned as an analytical tool to develop various formal possibilities featuring super-surfaces, and hyper-surfaces that integrate topological elements of the fold, loop, nodes and layers. The exhibition

Figure 3.15. *Eyebeam Institute* in New York by MVRDV. Zaha Hadid and Patrik Schumacher eds., *Latent Utopias* (Vienna: Springer, 2002), 180.

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[95] Frédéric Migayrou, "Non-Standard Orders 'NSA-Codes,'" *Future City Experiment and Utopia in Architecture*, eds. Frédéric Migayrou et al. (London: Thames & Hudson, 2007), 17.

Architectures Non Standard in 2003 aimed to situate Non-Standard developments as a consequence of recent architectural innovations within a historical and theoretical context. Exhibitors of work included Asymptote, dECOI, Architects, DR_D, Greg Lynn FORM, KOL/MAC Studio, Kovac Architecture, NOX, Objectile, Oosterhuis.nl, R&Sie, Servo and UN Studio. The work was organised under eleven themes: biomorphism, shells, imprints, figures, forms, helicoidals, inflections, lines, ribbons, sequences and mathematical objects. Here, the design of architectural form becomes fundamentally a question of software animation, since the form is defined through a morphogenetic approach and in a state of perpetual evolution. However, while the Non-Standard protocol envisaged novel geometric and formal possibilities, it was not able to realise the constructive capacity of the parametric data model.

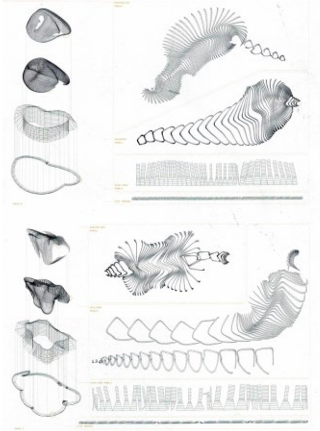

Figure 3.16.

Nevertheless, there are significant differences between techniques within Non-Standard projects. The first technique concerns material realisation and its depiction using techniques of diagramming. The second technique involves the use of Non-Standard analysis to contest a normative approach to program functionality. In the first approach, for material realisation, a distinction can be drawn between the form finding approaches of Greg Lynn and NOX (Lars Spuybroek). While Greg Lynn's *Embryological House* is internal to software, the work of NOX is a formal investigation of the potentiality of materials. The work of NOX is based on Frei Otto's analogue modelling techniques. The digital process for NOX begins and ends with materials. On the other hand, Lynn's is not a material practice. His prototype house relies on animation software commonly used in the automobile

Figure 3.16. *Embryological House,* Greg Lynn. Frédéric Migayrou ed., *Architectures Non Standard* (Paris: Centre Pompidou, 2003), 137.

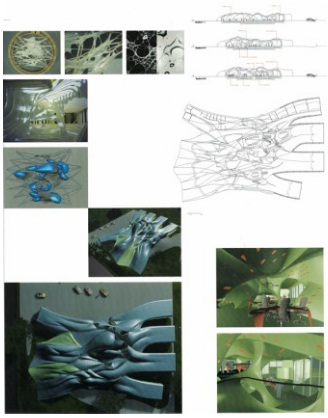
Figure 3.17.

and aeronautics industries to generate infinite variations of unique products (Figure 3.16). The form of the house is developed out of a strategy of double-curved aluminium surfaces that vary with each iteration. Within the same number of panels, the house configuration can be indefinitely diversified. By contrast, NOX uses "self-generative design techniques" where empirical research of existing forms is a process through "a mobilization of its topologically connected components, which consolidate and take on a form, first as a design and then as a building."[96] NOX's 2000 project *Soft Office* is a highly procedural form generation process according to the search for porosity. The concept is inspired by the optimised path system experiments of Frei Otto (Figure 3.17). Topological porosity is generated with an analogue machining technique comprising a three-dimensional system that combines a varnishing technique and the wool-water technique. The varnish technique is a "surface-to-line-technique" based on the effects that varnish or lacquer have highly viscous properties to dry up and store information.[97] Here, the analogue machine is used to stretch lacquer surfaces into different directions, which break into interconnected threads of lacquer. During the drying process, the viscous lacquer locates the structural forces of distribution. In contrast, the wool-water technique is a line-to-surface-technique where the wool thread geometry provided is fixed and dipped underwater which generates merging of threads. Within these analogue computing techniques, matter and

Figure 3.17. *Soft Office* by NOX, 2000. Frédéric Migayrou ed., *Architectures Non Standard* (Paris: Centre Pompidou, 2003), 137.

[96] Lars Spuybroek, "Machining Architecture," *NOX* (London: Thames & Hudson, 2004), 10.

[97] Branko Kolarevic and Ali Malkawi eds., *Performative Architecture: Beyond Instrumentality* (London: Spon Press, 2005), 167–68.

form are not separate but simultaneously evolving: liquid becomes substance and form in a morphogenetic process of emergent configuration.

Projects driven by programmatic concerns are equally challenged in the Non-Standard where design involves strategic operations to "undo the strict oppositions between the public and the private."[98] The Non-Standard mode of analysis allows different ways of form finding of the forms of continuity. Work undertaken equally at the urban and the building scale includes projects by UN Studio (Ben van Berkel) and DR_D (Dagmar Richter). In the design process, the continuities of geometric flow allow individual elements to emerge. The concept of continuity implemented by UN Studio into built form for the *Mercedes-Benz Museum* in Stuttgart was showcased at the *Architectures Non Standard* exhibition (Figure 3.18). Here, structural repetition and curvilinear geometry are created with "three overlapping circles" in the plan as a variation of the mathematical model "belonging to the field of knot theory on which the Mobius strip and its three-dimensional variant, the Klein Bottle, are based."[99] The concept of topology integrates building movement and orientation.

At the building scale, public and private are explored by DR_D's *Maison Dom-In(f)o.* DR_D's concept integrates computational processes to digitise modernist standard frameworks for mass production, such as in the *Maison Domino* by Le Corbusier, to generate continuity

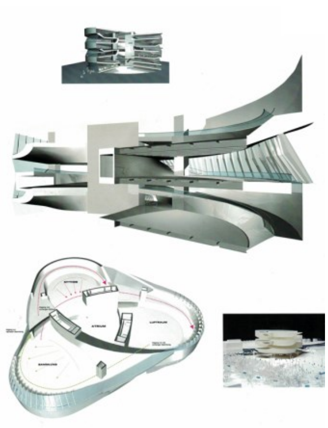

Figure 3.18.

Figure 3.18. *Mercedes-Benz Museum* by UN Studio, 2002–2006. Frédéric Migayrou ed., *Architectures Non Standard* (Paris: Centre Pompidou, 2003), 193.

[98] Andrew Benjamin, "The Standards of the Non-Standard," *Writing Art and Architecture* (Melbourne: re.press, 2010), 81.

[99] Ben van Berkel and Caroline Bos, "Everything is Curved," *Architectural Design: Elegance,* eds. Ali Rahim and Hina Jamelle, vol. 77, no. 1 (January/February 2007): 36.

Figure 3.19.

from which different discontinuous elements emerge (Figure 3.19). The new organisation of structure and an alternative way of industrial production are based on the new performance criteria of a system integrating atmosphere, humidity, temperature, light, recycling, supply and waste. The project identified contemporary housing needs to reformulate surfaces for a new prototype that uses novel technologies to improve their performance. The library of prototypical surface constructions attempts to provide an expanded vocabulary of known properties and textures by using digital design and rapid prototyping.[100] Compared to the automobile industry, the concept seeks customisation of the prototype as Non-Standard production that reveals a new topology for life.

3.3.2 Non-Standard Fabrications

Compared to building in the last five centuries in the West, the Non-Standard represents a challenge to the logic of mechanical reproduction, whose aim had been the industrial mass reproduction of identical, invariable units. Distinguishing between the classical definition of architecture and Non-Standard Architecture, Bernard Cache argued that digital technology provides an opportunity to cross a threshold into new territory, from proportional invariants into sophisticated invariants, both projective and topological. Cache's approach provided alternative topologies to neo-Platonist modes of proportional reproducible models, characterised by

Figure 3.19. *Maison Dom-in(f)o* by DR_D Office, 2002–2003. Frédéric Migayrou ed., *Architectures Non Standard* (Paris: Centre Pompidou, 2003), 82.

[100] Dagmar Richter, "Camouflage as Aesthetic Sustainability," *Architectural Design: Architextiles,* ed. Mark Garcia, vol. 76, no. 6 (November/December 2006): 68.

complex and Non-Standard building components.[101] He separated four types of invariants found in architecture – isometric, homothetic, projective and topological – that can be challenged and developed into more sophisticated invariants using new technologies such as a mathematically-driven three-dimensional modelling software with numerically controlled machines. For Cache, architecture is better able to order the diversity of space when all its invariants are in play, "deterritoralising their traditional field of application – the isometry of the central plan, the projectivity of complex solids, and the topology of intertwining ornaments."[102] Projects produced entirely on the computer from the early conceptual phase through schematic design, design development and working drawings provide a smooth interface of shared information between consultants and subcontractors. To situate Non-Standard Architecture as a true social reality, Cache's approach is through fabrication that resolves Non-Standard using the normative methods of postindustrial fabrication. He promotes the idea of 'associativeness' to integrate the architect into a process stretching between conceptualisation to prefabrication of components. One of the difficulties identified by Cache in the fabrication process is the quantity of Non-Standard data transfer, rather than the cost. For Cache, an architecture based on variable invariants provides an alternative approach to topology compared with the neo-Platonist mode of identical reproduction. However, with the Second Digital Turn of the

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[101] Branko Kolarevic ed., *Architecture in the Digital Age: Design and Manufacture* (New York: Taylor & Francis, 2009), 172.

[102] Bernard Cache, *Projectiles* (London: AA Publications, 2011), 67.

Non-Standard the process became limited to highly specialised, industrial applications of robotic automation with specific tools. Architectural computation is used to analyse and simulate building performance, including information about materials, tectonics and the parameters of production machinery.

3.4 Digital Turn in Baroque

This thesis suggests that the transformation and deformation typical in seventeenth and eighteenth century Mannerist and Baroque architecture prefigured the digital turn that prevailed in Non-Standard Architecture. The link between Baroque and Deconstructivist architecture was made by Robert Harbison specifically between the work of Borromini, Frank Gehry and COOP Himmelb(l)au. Within this architectural transformation, Harbison finds "fixation on movement and spatial illusions and their need to subvert conventional forms."[103] In the Baroque, novel geometries such as the interlacing wave, variable curves or folds were realised through new conceptual tools such as projective geometry, replacing earlier models and diagrams characterised by Euclidean geometry. For Deleuze, contemporary movements in art and science could already be read in Baroque aesthetics as well as in the philosophical writings of Gottfried Wilhelm Leibniz, who defined Baroque mathematics in terms of radical diversification, and the search for "a 'new affection' of variable sizes, which is variation itself."[104] The historical and epistemological contexts of the Baroque indicate a collapse of epistemologies based on reason and a transition exemplified by Leibniz towards the reconsideration and reconstruction of classical reason. Similarly, Lacan argues that the Baroque is transitional yet exceptional in a contradictory attempt to cope with a sixteenth century that

[103] Robert Harbison, *Reflections on Baroque* (London: Reaktion Books Ltd, 2000), x.

[104] Gilles Deleuze, *The Fold: Leibniz and the Baroque* (London: Continuum, 1993), 18.

witnessed the crisis of classical *episteme*[105] and its influence on medieval Christian theology, as well as the rise of modern science.[106] Deleuze's argument elaborates on the influence of Leibniz on the curvilinear shapes of Baroque architecture, characterised by the aesthetic and formal qualities of folding. He describes an activity that folds, unfolds and refolds matter, space and time; and the epistemological response of this event as a self-enclosed unity that also contained the entire world. In addition to Leibniz's metaphysical register for the fold of the world where each substance acts according to its law of unfolding, and that of the mind unfolding in accordance with laws of the corporeal machine, the idea also involved a material register: that of the pleat. Deleuze relates the material register of the fold to Bernini's folds of clothing in the marble sculpture of Santa Teresa.[107] Three hundred years later, we find parallel thinking on folding in architecture, investigated through complex curvatures on digital platforms. Positioned within the geometry of Non-Standard, the fold obtains mathematical definition fundamental to its conception and fabrication. The fundamental principle of Non-Standard analysis is to allow differences and discontinuities to coexist with forms of continuity, a procedure that fundamentally rethinks actual architectural geometry within the digital. The first freeform

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[105] Jacques Lacan, *The Seminar of Jacques Lacan, Book XX: Encore* (London: W. W. Norton, 1998), 36.

[106] Lorenzo Chiesa, "Exalted Obscenity and the Lawyer of God: Lacan, Deleuze and the Baroque," *Lacan and Deleuze: A Disjunctive Synthesis*, eds. Bostjan Nedoh and Andreja Zevnik (Edinburgh: Edinburgh University Press, 2017), 151.

[107] Gilles Deleuze, *The Fold: Leibniz and the Baroque* (London: Continuum, 1993), 124.

digital surface for the *Guggenheim Museum* (1997) in Bilbao by Frank Gehry was developed and constructed using computer aided three-dimensional interactive application software intended for the design and manufacture of aeroplanes.[108]

3.4.1 Baroque Hybridisation of Geometry

The Baroque conception of space developed through the mutation and hybridisation of at least two geometrical shapes into classical architecture: cone and centred plane on which the volume was supported. The Baroque construction method weaved the cone into the surface of the horizontal form until the latter was no longer identifiable, producing an interlacing wave[109] (Figures 3.20 and 3.23). Baroque hybridisation of geometrical shapes transformed one geometric form into another (Figure 3.21). The metamorphosis in the shift from circle to ellipse symbolically marked the Baroque turn. In architecture, the domes constructed by Borromini demonstrate the use of ellipses to create the type of oval that reflects an elongated circle. Andrea Palladio provides another instance of spirals showing creativity of stereotomy at *Santa Maria della Carità* (1561) in Venice (Figure 3.22). In Deleuze's terminology, Baroque space is deterritorialised by the indefinite variegations of the forms that define it according to the operation of the fold. Basing his diagram on Heinrich

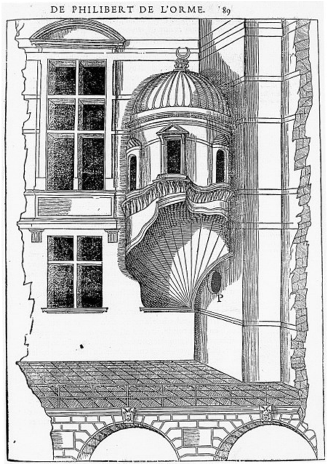

Figure 3.20.

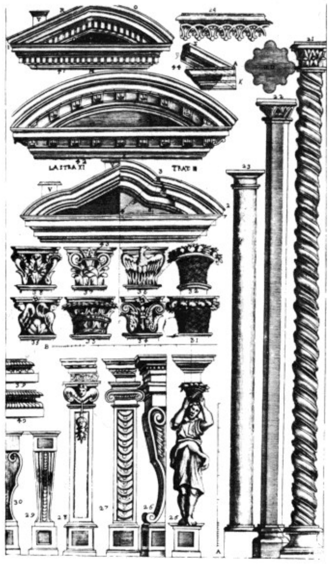

Figure 3.21.

Figure 3.20. *Trompe d'Anet*. Philibert de L´Orme, *Le premier tome de L´Architecture* (Paris: Federic Morel, 1567), 89.

Figure 3.21. Architectural details. Guarino Guarini, *Architettura Civile* (Turin: Mairesse, 1737).

[108] Branko Kolarevic ed., *Architecture in the Digital Age: Design and Manufacture* (New York: Taylor & Francis, 2009), 31.

[109] Philippe Potié, "Sophisticated Geometry, Baroque Composition," *Perspective, Projections & Design*, eds. Mario Carpo and Frederique Lemerle (London: Routledge, 2008), 112.

Figure 3.22.

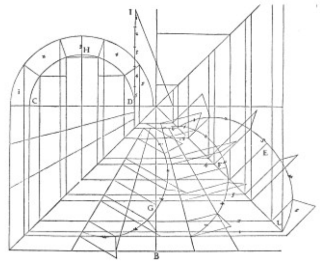

Figure 3.23.

Figure 3.22. Spiral staircase (*a chiocciola*) with a void in the centre in *Santa Maria della Carità* (1561) by Andrea Palladio, Venice. Tracey Cooper, *Palladio's Venice* (London: Yale University Press, 2005), 159.

Figure 3.23. Drawing of the spiral stairs of the *Vis Saint Gilles Quarrée*. Philibert de L´Orme, *Le premier tome de L´Architecture* (Paris: Federic Morel, 1567), 127.

Wölfflin's reading of *Santa Caterina dei Furnari's* Baroque facade designed by Giacomo Della Porta (Figure 3.24), Deleuze draws the two floors of the *Baroque House*[110] (Figure 3.25). He outlines six categories of the Baroque: the fold, the inside and outside, the high and the low, the unfold, textures, and the paradigm. This form that emerged in Baroque was parametrised with the introduction of the parametric data model in the Second Digital Turn.

Similarly, in Derrida's concept of *différance*, original thought is subject, through deconstructive critique, to "a structure and a movement" of differentiation that disturbs the possibility of meaning.[111] In this movement, both form and thought are delayed in their transformation. In *Specters of Marx,* Derrida defines the nature of the fold, in terms of the uncanny *(unheimlich),* as the difference, both decisive and insubstantial at the same time that separates being from appearing. The appearing of being, as such, as phenomenality of its phenomenon, is not the being that appears; that is, the fold of the '*unheimlich.*'[112]

3.4.2 Codification of Baroque Architecture

Compared to the modern and classical notion of codification, where the method of drawing only uses ground plan and elevation, in Non-Standard Architecture, the conception of the object changed profoundly, moving

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[110] Gilles Deleuze, "The Fold," *Yale French Studies: Baroque Topographies*, trans. Jonathan Strauss, vol. 80 (1991): 229.

[111] Jacques Derrida, *Positions*, trans. Alan Bass (London: Routledge, 1978), 27.

[112] Jacques Derrida, *Spectres of Marx: The State of the Debt, the Work of Mourning and the New International* (London: Routledge, 1994), 181–82.

from geometries of variable curvature defined by points and centres to vectors of curvature or splines. In the Non-Standard, the digital platform absorbed Baroque complexity and vectorised architectural form into parametric surfaces. As Tafuri noted, “to operate critically with the instrument of architecture implies a deformation of architecture itself.”[113] To inform the kinds of comparative architectural codification arising in modern architecture at this time, different arguments have been advanced.

Based on methods for drawing architectural plans, Philippe Potié in *Perspective, Projections and Design* distinguished between two methods of modern architectural design. The first, simple method involves an organic relationship between the ground plan and the elevation, characteristic of classical architecture during the seventeenth century through to modern twentieth-century architecture. The second, complex method of projection develops irregularly curved shapes and is characteristic in the Baroque and in Non-Standard Architecture of computer-generated digital design.[114] A contrasting view by historian Pierre Charpentrat argues that Baroque is a living style that has changed and evolved since the seventeenth century. Drawing spatial parallels in the works of modernist (Walter Gropius, Le Corbusier and Mies van de Rohe) and Baroque architects (Giovanni Lorenzo Bernini, Johann Balthasar Neumann and Francesco Borromini), Charpentrat argues that each uses geometry to

Figure 3.24.

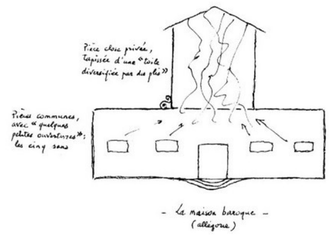

Figure 3.25.

Figure 3.24. Baroque facade of *Santa Caterina dei Furnari* in Rome by Giacomo Della Porta, 1564. Image from Heinrich Wölfflin, *Renaissance and Baroque*, trans. Kathrin Simon (New York: Cornell University Press, 1966), 34.

Figure 3.25. *La Maison Baroque* (allegory). Gilles Deleuze, *The Fold* (London: Continuum, 2006), 5.

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[113] Manfredo Tafuri, *Theories and History of Architecture* (New York: Harper & Row, 1817), 110.

[114] Philippe Potié, “Sophisticated Geometry, Baroque Composition,” *Perspective, Projections & Design*, eds. Mario Carpo and Frederique Lemerle (London: Routledge, 2008), 105.

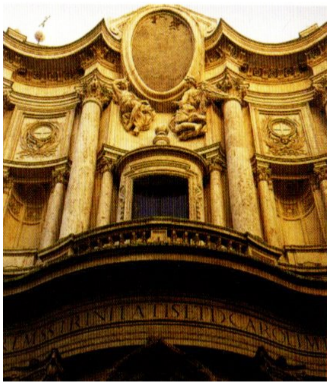


Figure 3.26.

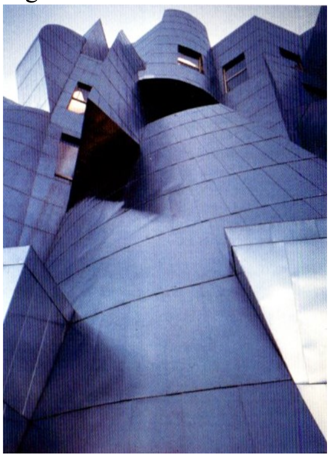


Figure 3.27.

Figure 3.26. The wall translated into undulating movement in *San Carlo alle Quattro Fontane* by Borromini in Rome. Rolf Toman ed., *Baroque: Architecture, Sculpture, Painting* (Konigswinter: Konemann, 2007).

Figure 3.27. *Weisman Art and Technology Museum*, Frank Gehry. "Weisman Art Museum," Wikipedia, accessed July 3, 2019, https://en.wikipedia.org/wiki/Weisman_Art_Museum.

achieve similar goals, where the "ellipses of Bernini and Neumann and the triangles of Borromini are equivalent to the cuboid forms of the modernists."[115]

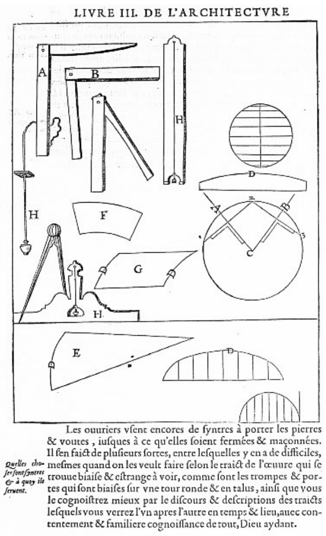
Following Potié's perspective, Michael Ostwald in *Architecture of the New Baroque* investigates similarities between the historical Baroque architecture of the 1600s and its revival in the 1800s to works of contemporary architecture which he calls the 'new Baroque'. For Ostwald, the 'new Baroque' constitutes a continuation or revival of the historical Baroque by correlating the concepts of the seventeenth century (Figure 3.26) with Modernism's static sculptural forms and the dynamics in digital architecture (Figure 3.27). Drawing on Harbison, he identifies four strategies associated with the idea of infinity, which he believes is evident across these periods: curvature and perspective devices of the wall; proportional and formal relationships of Baroque unity; the blurring of boundaries; and the use of naturalistic forms and decoration.[116] While Harbison, Ostwald and Potié addressed the emergence of aspects between Non-Standard Architecture and its sources in Mannerism and Baroque within the digital platform, their analyses did not extend into aspects of parametric data modelling and automation of Non-Standard architecture and construction.

[115] Pierre Charpentrat, "The Message of the Baroque," *Living Architecture: Baroque Italy and Central Europe* (London: Oldbourne, 1967), 108.

[116] Michael Ostwald, *The Architecture of the New Baroque* (Singapore: Global Arts Affiliated Press, 2006), 49.

3.4.3 Baroque Stereotomy

The introduction of perspective drawings and the printing press in the fifteenth century changed the design of the construction process and the role of the architect. Following developments in the Renaissance, the complexity of Baroque architecture increased. Baroque architects were preoccupied with the possibility of making two-dimensional objects which are three-dimensional, attempting to unfold them on paper (Figure 3.28). Stereotomy, on the basis of projection, implied a symmetrical correspondence between drawings and architecture, which was a major concern for architects since architectural correspondence of ceilings and vaults was difficult to achieve and only became resolved three-dimensionally within the Non-Standard digital model. This thesis contends that the geometric systems in the Baroque show the limitations of the simple tools of chisels and masons' mallets then available, whose orthogonal logic of production persisted in later Non-Standard geometric systems, in the age of technical reproducibility. While the Second Digital Turn resolved digital design and construction collectively with the parametric data model, its construction method remained conservative. The complexity of stereotomy sought in the late Renaissance and Baroque could not be handled or realised with two-dimensional drawing, given the imperatives of standardisation during the Industrial Revolution. Any means of production and tooling that needed constant resetting and the development of new apparatuses to achieve the geometric complexity that was more easily done by the human hand with hand tools was a higher cost


LIVRE III. DE L'ARCHITECTVRE

Les ouuriers vsent encores de syntres à porter les pierres & voutes, iusques à ce qu'elles soient fermées & maçonnées. Il s'en faict de plusieurs sortes, entre lesquelles y en a de difficiles, mesmes quand on les veult faire selon le traict de l'œuure qui se trouue biaise & estrange à voir, comme sont les trompes & portes qui sont biaises sur vne tour ronde & en talus, ainsi que vous le cognoistrez mieux par le discours & descriptions des traicts lesquels vous verrez l'vn apres l'autre en temps & lieu, auec contentement & familiere cognoissance de tout, Dieu aydant.

Quelles choses sont syntres & à quoy ils seruent.

Figure 3.28.

Figure 3.28. Stonecutting tools. Philibert de L´Orme, *Le premier tome de L´Architecture* (Paris: Federic Morel, 1567), 57.

to the building sector, which rationalised production in the form of plan, section and elevation.

The digital turn with file-to-factory production is even more significant since it affected the practice of architecture and the construction industry. The computer as a tool replaced the technical connection between human hand and eye, between architects and their skills in setting out ideas in the plan, section and elevation. Nicholas Negroponte promoted the computer as a tool to liberate people from market constraints and empower the individual within an individually-controlled environment. 'Soft' technology began as a new concept of architecture that could fulfil the radical goals of Modernism to create new forms. Nevertheless, modernist architecture remained tied to industrialisation, standardisation and uniformity as a result of products of modernity. In the mid-1970s, a revolution in computational hardware and software with microcomputers and colour graphics enabled dynamic CAD tools that shifted the perspective to new ways of generating design.

Design computing allowed the complex manipulation of graphic elements that could account for and integrate the complexity of architectonic language in ways that enthusiasts underestimated or failed to appreciate. Non-regular architecture remained hard to define within the standard register of classical culture during Modernism and early digital design. In turn, later developments in digital media, in particular, the Second Digital Turn, absorbed the system of projective geometries into algorithms, allowing rationalisation or standardisation of plans in an automated mode, and this again enabled the production of irregular form. However, the limit still exists in the Second Digital Turn as the implementation of the parametric data model for robotic automation on construction sites. This gap, produced by the regulatory environment and incapacity of conventional construction to handle Non-Standard robotic automation, has meant that complex geometries in the infrastructure, systems, techniques and machinery of industrial scale contemporary construction have not yet been implemented.

3.4.4 Algorithmic Explorations of Parametric Architecture

The publication *Space* (1950–53), founded by Luigi Moretti, investigated the continuity of parametric systems across the Baroque and Modernism. Moretti brings Baroque to the present during Modernism with the discussion on parametric architecture formulated between 1940 and 1942, which developed over the subsequent decade with mathematicians and physicists. This characteristic of Moretti's work led to his inclusion in Robert Venturi's *Complexity and Contradiction in Architecture*, which made him a precursor of Postmodernism. The coincidence, in architectural form, of structure, function and expression, termed an algorithm by Moretti, defined the complex relationship of architecture.[117] This algorithm was extended to the more complex geometries of digital parametric data models exploited in the Second Digital Turn of Non-Standard Architecture. Thus, Moretti's claim about parametric architecture did not extend to the digital

[117] Marco Mulazzani, "Luigi Moretti: Forms in Space," eds. Frederico Bucci and Marco Mulazzani, *Luigi Moretti; Works and Writings*, trans. Marina de Conciliis (New York: Princeton Architectural Press, 2002), 20.

production of the algorithm to fabricate Non-Standard forms. However, he did envisage the kinds of curvature that would feature in later technological software developments, for example, with models and graphic images of structures for sport and spectacle, determined through studies of curvature. These developments were staged in a parallel drawn between Moretti and Zaha Hadid in a 2010 exhibition for the opening of the new *Museo Nazionale delle Arti del XXI secolo (MAXXI)* in Rome (Figure 3.29).

Figure 3.29. "Luigi Moretti: From Rationalism to Informalism" exhibition in July 2010 for the opening of MAXXI by Zaha Hadid Architects in Rome. Rowan Moore, "Luigi Moretti: From Rationalism to Informalism," *The Architectural Review* (July 2010): 92–93.

Exhibition curators Bruno Reichlin and Maristella Casciato consider that Hadid's designs represent less a step change in architecture than a point on a wave that began to swell in the 1950s.[118] The exhibition of six thematic categories aimed to foreground Moretti's work within historical and cultural contexts, and to situate it within contemporary

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[118] Sebastiano Brandolini, "Luigi Moretti from Rationalism to Informalism," *Blueprint*, no. 293 (August 2010): 72.

architectural practice and theory. The comparative study showed shared interests in dynamic urbanism, though pursued through different sensibilities.[119] The exhibition situated Moretti as a link between Baroque, modern and deconstructivist architectures: a protagonist who continued the representational qualities of curved space. However, achieving curvature in built form has taken until 2010 and even later for Non-Standard architecture seriality. The Second Digital Turn of Non-Standard Architecture gave new possibilities for parametric architecture by defining algorithms with the novel technology of the computer and programming language as a digital notation that combined Moretti's analogue elements of structure, function and expression digitally in a parametric data model.

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[119] Rowan Moore, "Luigi Moretti: From Rationalism to Informalism," *The Architectural Review* (July 2010): 92–93.

3.5 The Autonomous Code in Architecture

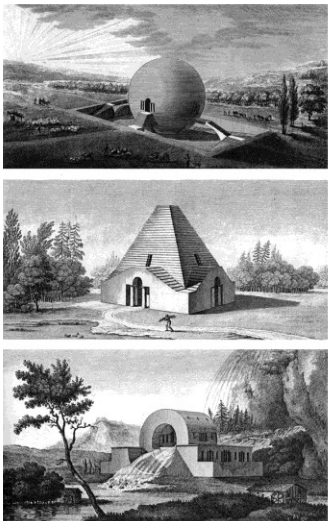

Figure 3.30.

Critics dispute attributions of autonomy in architecture. The first acknowledgement of autonomy in architecture was in 1933 by Emil Kaufmann, who imported the idea of autonomy from the arts, emphasising individuality and self-expression. Kaufmann's conception of architectural autonomy relies primarily on Kant's idea of the freedom of the human will as the supreme principle of ethics. Kaufmann's architectural autonomy is metaphorical and based on geometry; the autonomy of the urban villa from its environment; the freedom from necessity and architectural precedent. In *Von Ledoux bis Le Corbusier* (1933), Kaufmann credits the autonomy of architecture to Claude-Nicolas Ledoux and Le Corbusier's architectural system. In Kaufmann's analysis, initial rationalisation starts with Ledoux's principles that break away from the aesthetic principles of building proportion, order, harmony and symmetry into separate volumes according to function and geometry (Figure 3.30).

The autonomous approach to volume and material decomposition in the Baroque creates new possibilities for vertical circulation and design in the architectural section. Similarly, Le Corbusier is credited with creativity and compositional and formal introduction of new architectural elements. Kaufmann situates the start of modernity at the end of the eighteenth century and considers that the idea of autonomy had significant influence in the United States, in particular, with ideas of pure geometry referenced, for example, in Philip Johnson's *Glass House* in New Canaan. The reception of Modernism as a style in the United States was the result of the 1932 *Modern Architecture – International Style* exhibition at the Museum of Modern Art

Figure 3.30. The primacy of geometrical forms in the architecture of Claude-Nicolas Ledoux. *Top*, House of the Agricultural Guards of Maupertuis. *Middle*, Workshop of the Charcoal Burners. *Bottom,* House of the Surveyors of the Loue River. Emil Kaufmann, *De Ledoux à le Corbusier* (Vienne: Editions de La Villette, 2016), 53–54.

in New York, the related catalogue and the influences of Henry-Russel Hitchcock, Alfred Barr and Philip Johnson.

3.5.1 Invention of an Architectural Type

The autonomy of architecture introduced novel architectural typologies. Claude-Nicolas Ledoux inherited his academic orthodoxy from Jacques-Francois Blondel, who earlier reinforced the pivotal role of social hierarchy in architecture and developed a series of models as standard, codified and reproducible solutions. Architectural education in the second half of the eighteenth century involved the calculation of entire buildings: deposition of the general masses, the choice of forms and a sustained style. In addition to decoration, the building character was defined by the use of different orders, the nature of emblems and attributes, the 'movement of the plan,' and the massing of building in three dimensions.[120] Blondel, the founder of the new school of architecture Ecole des Arts, begins the hierarchy of character in architecture in accordance with the hierarchy of programs set by their place in the social order. Beginning in the early 1760s, Ledoux's designs reflect the strict hierarchical system promoted by Blondel, while rationalising architectural types and classification whose ultimate purpose was to influence social tastes.

In the 1770s, Ledoux's work exhibited a radical break with academic conventions, such as in his design for the *Saline de Chaux*. This project's industrial character brings together different functions of the salt production

[120] Anthony Vidler, *Claude-Nicholas Ledoux: Architecture and Social Reform at the End of the Ancient Regime* (Cambridge: MIT Press, 1990), 19.

process within a unifying geometry that is guided by a sense of management and community. Ledoux uses a semi-circular plan in his theatre of production, with an inherent analogy to the antique theatre described by Vitruvius (Figure 3.31). The semicircular geometry facilitates ‘surveillance’ addressing the concerns of oversight and economy by a director centrally positioned so that his lines of sight radiate to the workers, clustered in groups around the periphery (Figure 3.32). The relation between geometry and visual control by Ledoux anticipates Jeremy Bentham’s *Panopticon* of 1791. Michel Foucault refers to Ledoux’s plan as the possibility of constructing a ‘perfect disciplinary apparatus’ that makes possible a constant single gaze:

> A central point would be both the source of light illuminating everything, and a locus of convergence for everything that must be known: a perfect eye that nothing would escape and a centre towards which all gazes would be turned. This is what Ledoux had imagined when he built Arc-et-Senans.[121]

A similar strategy for circular and semicircular plans followed after the 1770s for institutes including hospitals, prisons and factories with the nature of surveillance varying in each project. In addition to semicircular plans, Ledoux used the iconography of pyramids in his project for saline furnaces and the motif of rusticated columns adapted from Palladio and Serlio. *Saline de Chaux* was envisaged by Ledoux as the industrial nucleus of a new town. The project incorporated ideas of hygiene and functionality with separate pavilions around its perimeter and along its

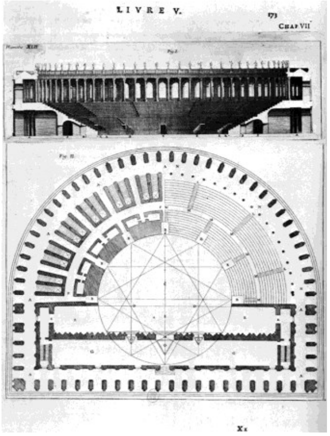

Figure 3.31.

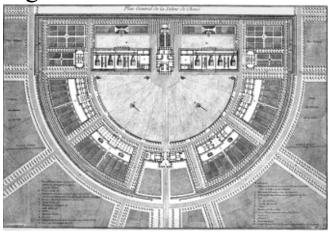

Figure 3.32.

Figure 3.31. Reconstruction of Roman theatre as described by Vitruvius by Claude Perrault in 1684. Anthony Vidler, *Claude-Nicholas Ledoux: Architecture and Social Reform at the End of the Ancient Regime* (Cambridge: MIT Press, 1990), 98.

Figure 3.32. The second project for Saline de Chaux by Claude-Nicholas Ledoux, 1774–78. Anthony Vidler, *Claude-Nicholas Ledoux: Architecture and Social Reform at the End of the Ancient Regime* (Cambridge: MIT Press, 1990), 97.

[121] Michel Foucault, *Discipline and Punishment: The Birth of the Prison*, trans. Alan Sheridan (New York: Vintage Books, 1995), 173.

diameter. The planning incorporates the idea of the city of the winds by Vitruvius and the city planning as codified in the *Statute of Korčula* from 1265 to take advantage of breezes from different directions and to circulate air through the city and render its inhabitants healthier.

3.5.2 The Principles of Systemisation in Architecture

A later exponent of Neoclassicism, Jean-Nicolas-Louis Durand, affirmed Ledoux's concept of an autonomous architecture in his lectures at the French engineering school, the *École Polythechnique*, which were published between 1802 and 1805. Durand's scientific method aimed to systematise and rationalise architecture by rejecting "both personal expression and the appeal to any transcendental authorities such as Nature, divine proportions, ideal prototypes, or absolute standards of beauty."[122] His collection of building types from different eras in architecture was compiled in *Précis des leçons d'architecture données à l'École Polytechnique* (1794) to codify universal architectural types, patterns and rules. The method reduced architecture to discrete, autonomous constructional elements of column, wall and vault, with plan configurations for vestibules, porticos and courts. Drawing is proposed here as a method to assure a high degree of systematisation in the early stages of design. However, his instructions were intended to assist the design

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[122] Robert Bruegmann, "The Pencil and the Electronic Sketchboard: Architectural Representation and the Computer," *Architecture and Its Image*, eds. Eve Blau and Edward Kaufman (Cambridge: MIT Press, 1989), 141.

process, rather than to propose complete formal architectural solutions.

Durand's new methods of analysis and synthesis emerged during the second half of the eighteenth century when there was transformation in the patterns of patronage of architecture. On the one hand, there was a move to rationalise public commissions of architecture, while on the other to diversify private ones. In the first instance, public rationalisation took the form, and the notion of the monument was replaced by facility, *l'equipment.* Schools, courthouses, bourses and markets were facilities with functional objectives that soon took over from the monumental imperatives of the assertion of sovereignty.[123] The scope of architects' private work diversified and took two forms: programs such as great townhouses or hotels for aristocratic or bourgeois clients became more and more complex (Figure 3.33), undermining the traditional hierarchies of architecture, their planning underwent a process of refinement, confronting architects with new problems.[124] Also, there was a proliferation of speculative programs in private work, including the first buildings designed specifically for rental (Figure 3.34).

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[123] Antonie Picton, "From 'Poetry of Art' to Method," Jean-Nicolas-Louis Durand, *Précis des leçons d'architecture données à l'École polytechnique* (Paris: L'Auteur, 1825), 16.

[124] Monique Eleb-Vidal and Anne Debarre-Blanchard, *Architectures de la vie Privée: Maisons et mentalités, XVII-XIX siècles* (Brussels: Archives d'Architecture Moderne, 1989).

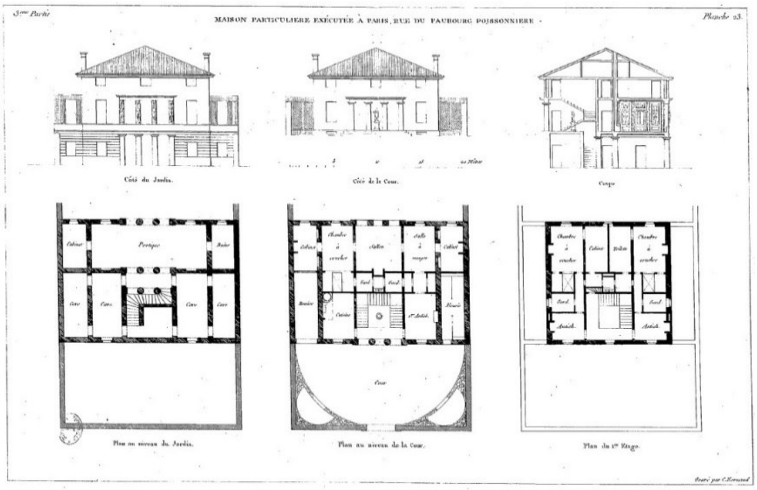

Figure 3.33. Principles of architectural composition in the plans for a private house by Durand. Jean-Nicolas-Louis Durand, *Précis des leçons d'architecture données à l'École polytechnique* (Paris: L'Auteur, 1825), 23.

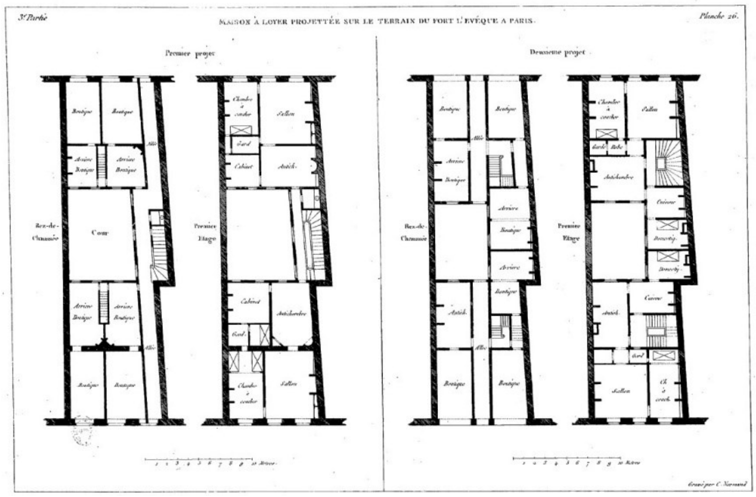

Figure 3.34. Principles of architectural composition in the plans for a rented house by Durand. Jean-Nicolas-Louis Durand, *Précis des leçons d'architecture données à l'École polytechnique* (Paris: L'Auteur, 1825), 26.

Antonie Picton notes that Durand is challenged to develop other ways of working in response to constitutive transformations in the nature of commissions in architecture and the relationship of the architect to the clients founded on the recognition of his professional competence.

Guided by the two principles of architecture, fitness for purpose and economy of means, Durand created an anti-aristocratic approach that reduced the increasing complexity in the architect's work, as a result of the high cost of the contractors and workers. This instigated the emergence of a desire for tighter control on the building production process where rules of art and their application on site were no longer negotiable.[125] Durand's new compositional and graphic technique for integrating the form of a regular orthogonal grid inscribed within a square a double function, regulatory and generative. Furthermore, Durand's prototypical designs for libraries, justice ministries, museums, colleges and hospitals appear to be an extension of Blondel's building characterisation in their manner of introducing standardisation into architectural plans.

Both Kaufmann and Durand argue for the principle of systemisation as a means of architectural composition.[126] This approach was developed more significantly after the

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[125] Antonie Picon, "From 'Poetry of Art' to Method," *Précis of the Lectures on Architecture*, Jean-Nicholas-Louis Durand, trans. David Britt (Los Angeles: Getty Research Institute, 2000), 16–17.

[126] Emil Kaufmann, "Claude-Nicolas Ledoux, Inaugurator of a New Architectural System," *Journal of the American Society of Architectural Historians*, vol. 3, no. 3 (July 1943): 13.

peak of the Industrial Revolution in the nineteenth century, where mechanical mass production delivered economies of scale based on identical products. The experimentation of architectural plan can be seen to emerge with the urban reform through rationalising the tenement building to pursue production, construction and material efficiency. For instance, in 1811 the New York State Commissioners' Plan proposed a gridiron of 2,000 blocks subdivided into 25x100 foot lots to rationalise and improve access to services, sanitation, light and air (Figure 3.35). With the definition of standards for building construction in New York City (1866) and the *Tenement House Act* (1867), there was early experimentation in the configuration of the tenements across these lots. Nelson Derby's proposal in 1877 organised a building around a larger internal courtyard by combining air shafts, providing solar access and ventilation (Figure 3.36). Series of plans emerged during the late nineteenth century that applied this reasoning at the city scale. Alan Colquhoun argues that the superblock, and with it the concepts of the 'designed whole', is a fact of the modern capitalist state. He references its evolution from the representative buildings of the Renaissance that gradually superseded the system where small plots were designed within a metonymic set.[127] Colquhoun argued that, by 1970, architects relied either on a cybernetic model or randomness or invented a vocabulary that referred to the traditional language of architecture.

[127] Alan Colquhoun, *Essays in Architectural Criticism: Modern Architecture and Historical Change* (Cambridge: MIT Press, 1981), 102.

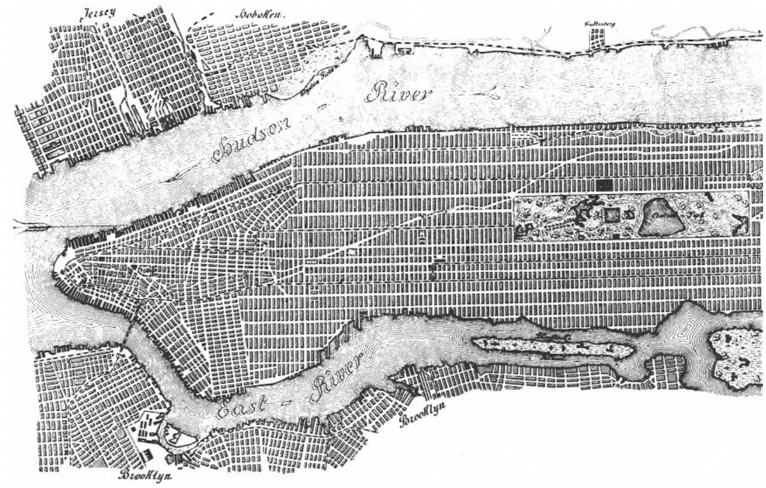

Figure 3.35. 1811 Commissioners Grid of New York with Central Park. Richard Plunz, *A History of Housing in New York City: Dwelling Type and Social Change in the American Metropolis* (New York: Columbia University Press, 1990), 12.

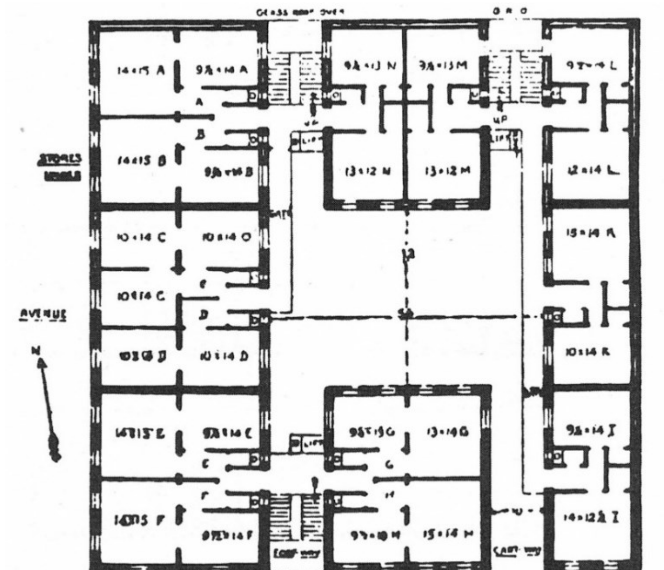

Figure 3.36. Proposal for a tenement made by consolidating four lots by Nelson Derby. *American Architect and Building News,* vol. 2, no. 56 (January 20 1877): 19.

Early experimentations of the architectural plan are traced in the Venetian rental house which emerged from the double house in the sixteenth century and became the pattern of residential buildings for the next two centuries and more. The need to provide as many dwellings as possible for all social classes and the very high prices of building land led to the emergence of compact apartment buildings and row houses, for whose design Venice evolved trend-setting solutions.[128] Row houses often adjoined a street or a courtyard on two sides. Their unified planning led to serial repetitions in their ground plans and elevations but allowed the blocks to be closed off from the outside (Figures 3.37 and 3.38). The new concept of construction separated floors, one above the other, to form independent flats with scissor stairs (Figure 3.39). Another feature of the dwelling was an internal cistern fed by clay pipes enclosed in the walls collecting rainwater from the roof gutters.

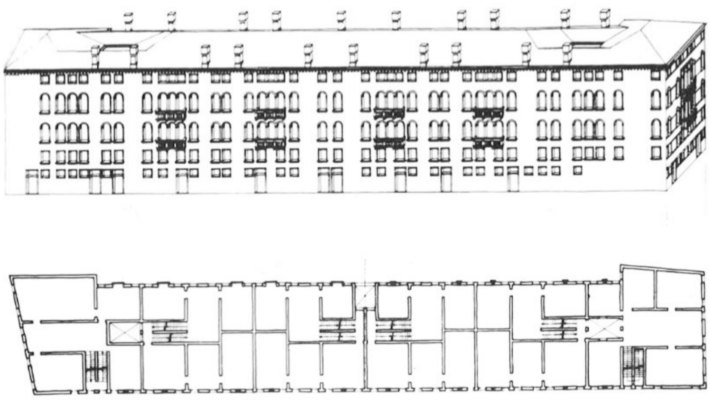

Figure 3.37. Residential buildings on the Calle Contariana on the Rio Marin in Venice, XVII. Norbert Huse and Wolfgang Wolters, *The Art of Venice: Architecture, Sculpture, and Painting, 1460–1590* (Chicago: The University of Chicago Press, 1990), 18.

Figure 3.38.

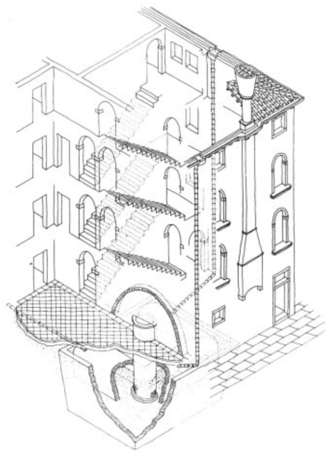

Figure 3.39.

Figure 3.38. Residential buildings on the Calle Contariana on the Rio Marin, Venice. Norbert Huse and Wolfgang Wolters, *The Art of Venice: Architecture, Sculpture, and Painting, 1460–1590* (Chicago: The University of Chicago Press, 1990), 18.

Figure 3.39. Axonometric view of *Capello* houses at Santa Maria Maggiore, Venice. Egle Trincanato, *Venezia Minore* (Milano: Edizioni del Milione, 1948), 303.

128 Norbert Huse and Wolfgang Wolters, *The Art of Venice: Architecture, Sculpture, and Painting, 1460–1590* (Chicago: The University of Chicago Press, 1990), 18.

Book 1 of Palladio's *I Quattro Libri dell' Architettura*, published in Venice in 1570, examines two varieties of the double staircase. The first example derived from the converging flight staircase at *Santo Apostolo* in Rome. The second double staircase referenced by Palladio is a four-flight spiral staircase design by Leonardo da Vinci at *Chambord Castle* in France (Figure 3.40).

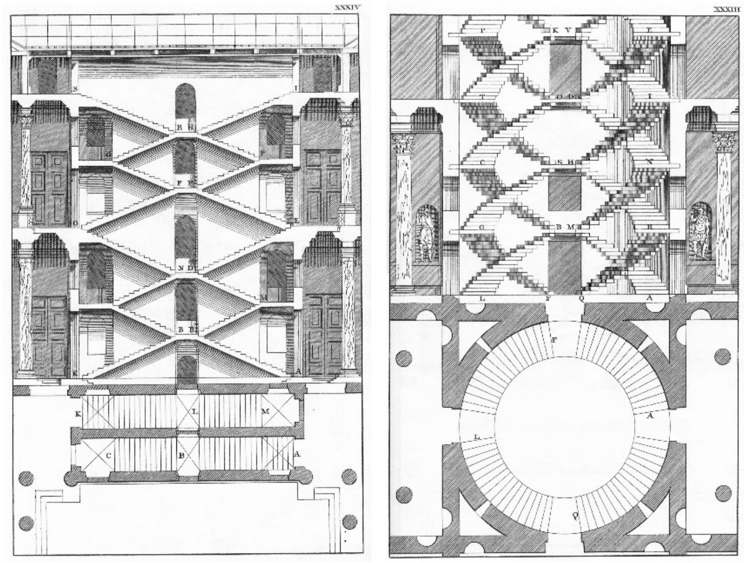

Figure 3.40. *Left.* Andrea Palladio's diagram of the *Santo Apostolo* staircase. *Right.* Palladio's diagram of the staircase at *Chambord Castle*. Andrea Palladio, *The Four Books of Architecture* (New York: Dover Publications, 1965), Book 1, Chap. XXVIII.

Sketches by Palladio show that he was working on a problem with a serial building for a given site. Palladio made several proposals in the *I Quattro Libri dell' Architettura* for specific sites in Venice, demonstrating that the triangular project was also destined for the city due to the long, narrow, irregular site, tripartite arrangements, and water door (Figures 3.41–3.43).

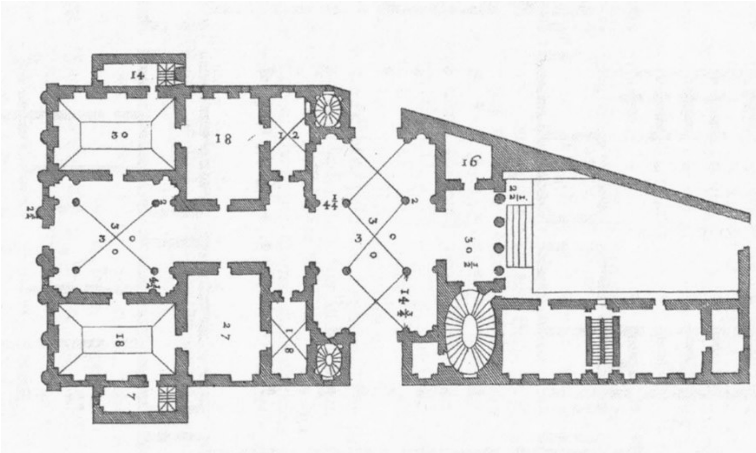

Figure 3.41. Design for a palace on the Grand Canal. Andrea Palladio, *The Four Books of Architecture* (New York: Dover Publications, 1965), Book 2, Chap. XVII.

Figure 3.43.

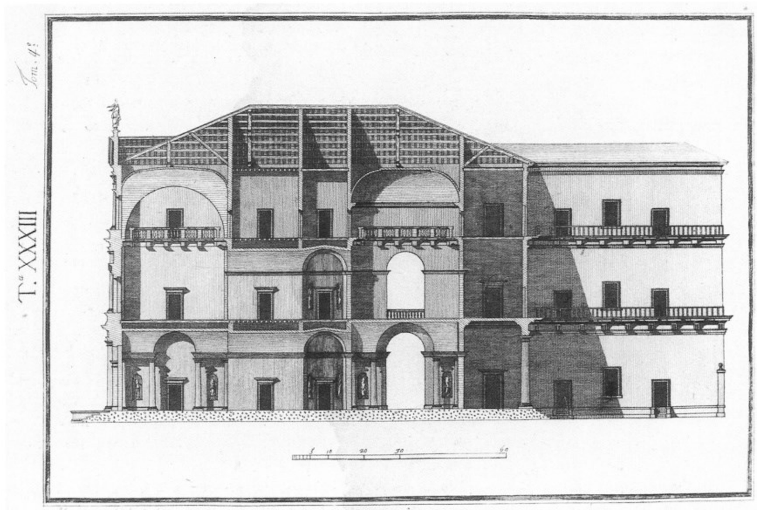

Figure 3.42. Reconstruction of Palladio's design for a palace on the Grand Canal. Bertotti Sacamozzi, *Le Fabbriche e i disegni* (Vicenza: Per Francesco Modena, 1776).

Since the Renaissance, the search for complexity in architecture during the 1990s challenged the logic of standardised mechanical reproduction, and Non-Standard Architecture aimed to engage that complexity by using computational design software to economically mass produce a series of non-identical parts.

Figure 3.43 Palazzo Bellavite on the Campo Maurizio. Norbert Huse and Wolfgang Wolters, *The Art of Venice: Architecture, Sculpture, and Painting, 1460–1590* (Chicago: The University of Chicago Press, 1990), 65.

3.5.3 Repositioning Architectural Autonomy

In 1987, Anthony Vidler revisited Kaufmann's perspective in his book *The Writings of the Walls: Architectural Theory in the Late Enlightenment.* Vidler claimed that the Age of Reason initiated a practice of codifying architectural knowledge and form. He saw the institutional reform at the time as a response to social and political necessity and traced the implications of reform in architectural historiography. Both institutional reform and historiography were concerned with the visual codes and symbols by which architecture represented its social purposes through a "language of monuments."[129] In sum, Vidler identified autonomous architecture, and its codification through taxonomies, as a kind of quest for origins, linking it to Laugier's archetype of the primitive hut and Rousseau's natural society theories – an argument that vindicates Kaufmann's Kantian thesis. The concept that integrates natural aesthetics into architectural design constitutes a departure from the Baroque and demarcates a new field of development for architecture, together with a distinct set of principles and practices. They include the notion of autonomy with the values of the Enlightenment through the centuries leading to the ahistorical Enlightenment. Formulation of autonomy became absolute with the digital architecture that deployed autonomous computational field enabling Non-Standard Architecture.

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[129] Anthony Vidler, *The Writing of the Walls* (New York: Princeton Architectural Press, 1987), 2.

In the 1960s, Manfredo Tafuri identified architectural autonomy in relation to urban design. In contrast to Kaufmann, Tafuri argued that the implementation of the city grid in the eighteenth century transformed the urban villa as an expression of autonomy. Compared to Europe, the implementation of a regular grid for urban development in the United States allowed absolute freedom to insert single architectural fragments within, a neutral spatial and geometric context that was not formally conditioned by it.[130] Following Tafuri, Aldo Rossi redefined the notion of autonomy in *The Architecture of the City.* Associated with the Tendenza group, Rossi's notion of autonomy was based on universal architectural types. In contrast to Kaufmann's idea of autonomy as individualism, Rossi's autonomy concentrated on the discipline itself of rational architecture characterised by language derived from former architectures and form and role in the city as a product of a historical urban structure as of social or political concerns.[131] Colin Rowe's interest in taxonomy and universal types disseminates the idea of architectural autonomy as a discipline in itself. In *The Mathematics of the Ideal Villa*, Rowe formally analyses Le Corbusier's *Villa Stein* (Figure 3.44) in relation to Palladio's *Villa Malcontenta* (Figure 3.45). The comparison suggests that the elements of Corbusier's villas articulate such generic types. Rowe identified similarity in the proportional system and a relationship to a mathematical order between the

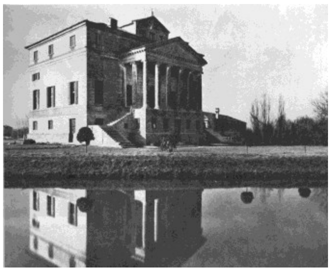

Figure 3.44.

Figure 3.45.

Figure 3.44. Andrea Palladio's *Villa Malcontenta*, 1550–60. Colin Rowe, *The Mathematics of the Ideal Villa and Other Essays* (Cambridge: MIT Press, 1976), 21.

Figure 3.45. Le Corbusier's *Villa Stein*, 1927. Colin Rowe, *The Mathematics of the Ideal Villa and Other Essays* (Cambridge: MIT Press, 1976), 51.

[130] Manfredo Tafuri, "Toward a Critique of Architectural Ideology," *Architecture Theory Since 1968*, ed. Michael Hays (Cambridge: MIT Press, 2000), 13.

[131] Anthony Vidler, *Histories of the Immediate Present* (Cambridge: MIT Press, 2008), 55.

villas, corresponding to parallel volumetric and spatial systems of the subdivision.

During the 1970s autonomous architectural language was constructed from a different perspective. Transcendental typologies and internal disciplinary processes explored by a *neoavant-garde*, including Aldo Rossi, Robert Venturi and Peter Eisenman, transformed architecture into the autonomous movement of Deconstruction, which questioned process and meaning in architecture by contesting the geometric purity of formal composition. The realisation of autonomous Deconstructivist architecture in the 1980s and early 1990s was reflected by originality and individualism in built form. In turn, autonomous architecture formalised its own constrained conditions and became internal to the discipline of architecture. The autonomous turn developed absolute autonomy by the realisations of digital architecture, emphasising originality and individualism in its translation of the design. In the 1990s, digital experimentations in architecture shifted into autonomous realisations by appropriating software used to design and manufacture aeroplanes to achieve design development and structural analysis of architectural autonomous designs. The introduction of algorithmic design programming into computer-aided design shifted identical production to Non-Standard seriality allowing codification of robotics in architecture. This thesis generates the most recent proliferation of autonomy in the parametric architecture of Non-Standard Architecture prompted as the Statute of the Third Digital Turn of Non-Standard Architecture.

3.6 Conclusion: Development of Absolute Autonomy in Architecture

The introduction of autonomous architecture by Emil Kaufmann in *Von Ledoux bis Le Corbusier* (1933) identified architectural principles and taxonomies that promoted a departure from the Baroque, and from the classical tradition of the eighteenth century. Kaufmann argued that the twentieth century *avant-garde* was influenced by Ledoux's system, which sought to breach architecture's dependence on style. Kaufmann considered the pure geometrical forms of Le Corbusier's architecture as an extension of Ledoux's autonomous aspect into the twentieth century. His attribution of autonomy in modern architecture was criticised by contemporary historians, as a formalist assumption which disregarded cultural or historical context. The rise of functionalism, which contradicted various formalist concepts, determined Kaufmann's system. However, the International Style was credited by Ledoux for Mies van der Rohe's iconic *Glass House* (1940) which Vidler considered an instance of 'classical Modernism.' Architectural autonomy resurfaced in the 1970s and 1980s through Aldo Rossi and Peter Eisenman's aim to legitimise the architectural position in society. The latter propagated autonomy by shifting the emphasis from utility and production into individual autonomy. The realisations of digital architecture projects in the 1990s then developed what might be called absolute autonomy through individual expression by digital media that used software to realise architecture in a radically decontextualised computational field. The monumentalisation of the architectural object achieved integrated and customised manufacturing of complex three-dimensional geometries. The digital revolution in architecture transformed into the Second Digital Turn with algorithmic programming developing Non-Standard seriality of architecture with the comprehensive digitalisation of data for parametric models through collaborative communication.

CHAPTER 4

The Limits of Modern Utopia in Architecture

Architecture or Revolution.
Revolution can be avoided.[132]

4.1 Introduction: Concepts of Modernism

Modernity is an autonomous project characterised by historical discontinuity and internal fragmentations so that, as an epistemological, political and aesthetic category, it is both autonomous in the history of ideas and internally contested. The *avant-garde*, as Renato Poggioli and Peter Burger note, had a vital role in the history of Modernism by interrupting the sense of continuity with the flow of history through radical surges, recuperations and repressions into the discovery of new rational experience. Although the contemporary term *avant-garde* has an ancient history, the project of Modernity developed during the eighteenth century through objective science, universal morality and law, and autonomous art according to an inner logic to release their cognitive potentials and set them free from their esoteric forms.[133] The development of rational forms of social organisation and rational models of thought promised liberation from the arbitrary use of power. In this chapter, Alain Touraine read Modernity as an attempt to

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[132] Le Corbusier, *Towards a New Architecture* (New York: Dover Publications, 1986), 289.

[133] Reinhart Koselleck, *Critique and Crisis: Enlightenment and the Pathogenesis of Modern Society* (Cambridge: MIT Press, 1988), 141–43.

move "from a recognition of the essential role of rationalisation to the broader idea of a rational society in which reason would take control of not only scientific and technical activity but also of the government of human beings as well as the government of things."[134] Section 4.2 identifies the idea of standardisation and its prevailing difference between the modernities of the Enlightenment and the Industrial Revolution. It traces architectonic possibilities in Modernism enabled by the mathematical ordering systems of the Renaissance and Mannerism. Section 4.3 reviews the potentials of prefabrication from the Industrial Revolution to the autonomous formation processes investigated by Frei Otto. Section 4.4 traces new design solutions of the *avant-garde* in Japan and Europe that pre-empted the digital turn.

Modernism exhibited linear progress and rational planning under the standardisation of knowledge and production. While the Modernism that resulted was "positivistic, technocentric, and rationalistic," at the same time it was proposed and practised by an elite *avant-garde* of planners, architects, critics and other guardians of high taste.[135] To contest these developments, various anti-modernist movements emerged in the 1960s such as Postmodernism and Deconstructivism. This counterculture explored the realms of individualised self-realisation through a distinctive new left politics which exhibited anti-authoritarian gestures, iconoclastic habits and a critique of everyday life. Generated in the universities, art institutes

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[134] Alain Touraine, *Critique of Modernity*, trans. David Macey (Oxford: Blackwell, 1995), 21.

[135] David Harvey, *The Condition of Postmodernity* (Oxford: Blackwell, 1990), 35.

and on the cultural fringe of city life, these movements developed into widespread turbulence and street rebellions around 1968 across Berlin, Chicago, Madrid, Mexico City, Paris, Prague and Tokyo. They pre-empted a postmodernist turn, emerging between 1968 and 1972, which sought to establish itself against a cultural background in its own right. What followed was the Deconstructivist movement in architecture as a new style exhibiting deconstructive qualities of irregular geometry as a structural condition in contrast to the geometric purity of formal modernist composition.

4.2 Modernity of Enlightenment and the Industrial Revolution

The idea of the 'modern' in architecture is a contested one. Likewise, the differences in meaning between modernity, modernism and modernisation are persistently undervalued in architectural discourse. Modernity refers to a cluster of social, economic and political systems that originated in the West around the eighteenth century including the processes of the modern capitalist industrial state. Modernity is characterised by certain typical features of what was considered modern or contemporary at the time; and the experience of these features by an individual undergoing a continuous process of evolution. It implies a progressive economic and administrative rationalisation and differentiation of the social world, where differentiation means, for example, the separation of fact from value, of the ethical from the theoretical. Modernism comprises a collection of visions and values oriented to the future and to progress. Modernisation refers to the stages of social development which are based on industrialisation generated by scientific and technological discoveries and innovations, industrial upheavals, population movements, urbanisation, the formation of national states and mass political movements, all driven by the expanding capitalist world market.

This thesis traces the idea of standardisation as pivotal to the Enlightenment and the Industrial Revolution. Arguably, modern architectural authorship began with Alberti's revolutionary codification system in the fifteenth century. Modernity beginning in the eighteen century onwards was defined in relation to antiquity. In the nineteenth century, driven by the *avant-garde* and antibourgeois attitudes, modernity introduced rationalisation and standardisation. In *Five Faces of Modernity*, Matei Calinescu described the intrinsic cultural split during the first half of the nineteenth century that emerged within Modernity as "a product of scientific and technological progress, of the industrial revolution, of the sweeping economic and social changes brought about by capitalism – and modernity as an aesthetic concept."[136] Jurgen Habermas also saw a fundamental split in the eighteenth century concept of Modernity where modernity is an incomplete project characterised on the one hand by the desire for autonomy in the arts and sciences, and on the other by distinctive practical and geopolitical imperatives.

In *The Order of Things,* Michel Foucault considered history as a series of reinterpretations across three historical periods – the Renaissance, Classicism and the Modern. For Foucault, the idea of history as a linear succession of models of interpretation compelled a re-evaluation of the emergence of human sciences from the Renaissance and Classical thinking to the threshold of modernity in the early nineteenth century.[137] Foucault argued that modern episteme began with 'non-representable realities': things, like the force of labour or the power of speech, perceived as having an internal organisation, but which did not correspond to the order of representation characterising classical episteme. In turn, modern *episteme* marks the introduction of a concept of architectural space where relations are determined by function in the early nineteenth

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[136] Matei Calinescu, *Five Faces of Modernity* (Durham: Duke University Press, 1987), 41.

[137] Michel Foucault, *Power/Knowledge: Selected Interviews and Other Writings* ed. Colin Gordon (Brighton: The Harvester Press, 1980), 74.

century. Non-Standard further elaborates on the gesture of modernisation and evidences the same disassociation with history through a digital revolution in architecture and parametric modelling reflecting the virtual structure of prototyping with all elements assigned and tested in a virtual environment.

4.2.1 Differences Between Modernities of the Enlightenment and the Industrial Revolution

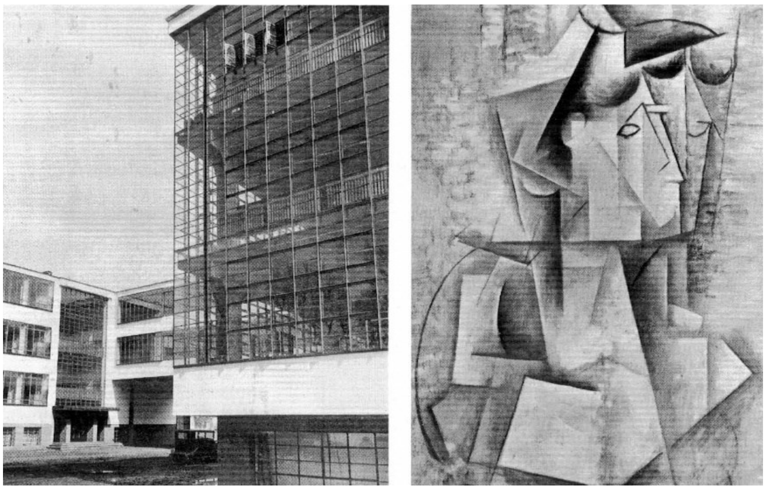

Figure 4.1. Simultaneity and transparency of overlapping planes that dematerialise the corners in Picasso's L'Arlesienne and Gropius's Bauhaus. Sigfried Giedion, *Space, Time and Architecture* (Cambridge: Harvard University Press, 2008), 494–495.

Research for this thesis highlighted a pivotal difference in the concept of Modernity between the Enlightenment and the Industrial Revolution, suggesting that each era was characterised by a distinct kind of Modernity. The difference can be gleaned in the tectonic qualities and characteristics of the architectural object produced by each period. During the Industrial Revolution of the nineteenth century, architecture responded to political and societal changes that valorised universal language by exploiting the tectonic quality of transparency through the possibilities offered by technological innovation such as the dematerialisation of the wall made possible by steel and the curtain wall. This eclipsed the contemporaneous or 'modern' architecture of the time, based on classical tectonics of formal and material opacity.[138]

These ideas of pure visibility dominated in the work of influential theorists such as Sigfried Giedion and Bruno Zevi. Giedion's text attempted to explain the way architecture is perceived through the introduction of a 'time–space' conception in modern architecture based on simultaneity and movement, while Zevi attempted to restructure the categorisation of architectural styles by taking the focus away from the stylised form. In *Space, Time and Architecture* Giedion argued that transparency in the form of a universal glass curtain was a literal and visual symbol of social democracy, functioning by displaying open society from outside to inside[139] (Figure 4.1). Zevi coincided modern architecture with a new way by restoring its historicity.

In *Transparency: Literal and Phenomenal,* Colin Rowe and Robert Slutzky distinguish between literal and phenomenal transparency in the work of Le Corbusier compared to Walter Gropius. Literal transparency is defined as physical translucence inherent in a material or structure, as in a glass curtain wall, or an inherent quality in an organisation.[140] Conversely, phenomenal transparency is

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[138] Colin Rowe and Robert Slutzky, "Transparency: Literal and Phenomenal," *Transparency* (Basel: Birkhauser, 1997), 33–53.

[139] Anthony Vidler, "Transparency: Literal and Phenomenal," *Journal of Architectural Education* (March 2013): 6–7.

[140] Colin Rowe and Robert Slutzky, "Transparency: Literal and Phenomenal," *Transparency* (Basel: Birkhauser 1997), 23.

a function of historical change, which Rowe evidenced comparatively with reference to the villas of Palladio and Le Corbusier. Rowe's analyses show how layers of space divide building volumes through the use of multiple overlaid grids that together produce continuous fluctuations of interpretation. Rowe and Slutzky read the formalism of modern architectural elements in relation to cubism, gestalt and the 'free facade'. Phenomenal transparency is considered at a perceptual level, in relation to gestalt psychology which, in its analysis of perception, seems to have been preoccupied with the questions central to their examination. The gestalt phrases include configuration, figure-ground, field, common contour and proximity, among others.[141] In the Third Digital Turn of Non-Standard Architecture, the opacity can be translated into architectural form finding and material grading material corresponding to porosity.

The introduction of digital technology in architectural design around 1990 enabled much more complex and intricate investigations of the kinds of formal articulations foregrounded by Rowe – articulations that were not possible through the analogue tactics of late Modernism. This drive to complexity, typical of the postmodern disposition, was also directed to architectural autonomy through formal computational grammars. For instance, the *Embryological House* (1998) by Greg Lynn incorporates redefined digital design methods with a complexity excluded by Rowe's aesthetic framework. Lynn's use of digital operations such as shearing, shifting

[141] Colin Rowe and Robert Slutzky, "Transparency: Literal and Phenomenal…Part II," *Perspecta*, vol. 1, no. 13/14 (1971): 298.

and rotating superimposes static forms. These tactics imply a temporal dimension since, as was the case in cubism, the various configurations represent different perspectives, captured at different times, in relation to the same formal program. They also suggest movement between different frames or moments, within a static architectonic entity.[142] The intervals between superimpositions generate a destabilising effect in the image representation. The method demonstrates how conceptual architectural simulation was made possible in digital space by the advent of computational tools.

4.2.2 Modernity and Modernism

Starting with the idea of the *tabula rasa,* modern architecture contested the classical tradition of historical continuity, thereby producing an inherently fractured relationship with the past (Figure 4.2).

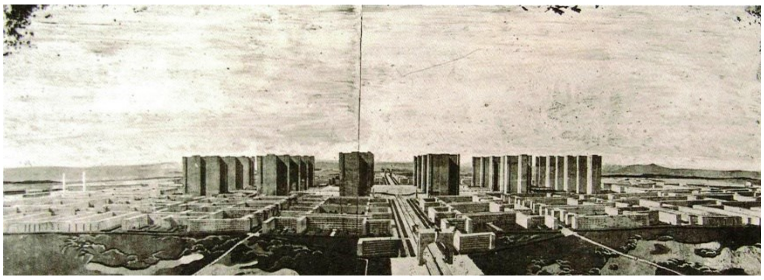

Figure 4.2. Diorama of the contemporary city for three million inhabitants by Le Corbusier. Tim Benton*, The Rhetoric of Modernism: Le Corbusier as a Lecturer* (Basel: Birkhauser, 2009), 11.

[142] Greg Lynn, *Animate Form* (New York: Princeton Architectural Press, 1999), 12.

This fracture – a necessary condition of rationalisation and standardisation – eventuated in the destruction of traditional social bonds, customs and beliefs. Modernisation was the achievement of science, technology and education. The concept of difference defined a new direction for modern architecture and its formal structure. As David Harvey noted in *The Condition of Postmodernity*, pivotal to deconstruction was the commodification and commercialisation of a market for cultural products during the nineteenth century that forced cultural producers into market competition that reinforced the process of creative deconstruction within the aesthetic field itself.[143] Accordingly, Le Corbusier proposed orthogonal geometry as a means of ordering and correcting architectural elements. This mode of expression was an integral part of his architectural creativity as "[t]he necessity of order. The regulating line is a guarantee against wilfulness. It brings satisfaction to the understanding."[144] The regulating line for Le Corbusier constituted a tool which he applied systematically to all his villa projects during the 1920s. The architectural expression gained a universal language with the Industrial Revolution. The modernist form was sought in the manipulation of pure volumetrics essentially directed to the functionality of productive standardisation developed by the Industrial Revolution.

Such functionalist architecture looked to the machinery of industrialisation, mass production, and engineering, which it eventually aestheticised through its

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143 David Harvey, *The Condition of Postmodernity* (Oxford: Blackwell, 1990), 22.

144 Le Corbusier, *Towards a New Architecture* (New York: Dover Publications, 1986), 67.

eclectic predilections for structures such as ships, aeroplanes and motor cars. But as Reyner Banham noted, this was directed more to the emulation of appearances of technological and scientific concepts than to what it claimed for itself in terms of 'honesty' and 'truth' in architecture.[145] In the 1960s, Banham's call for *'une architecture autre'* reframed the architectural discourse through technology and social needs.[146] For Banham, topology became dominant over geometry as a guiding force in design. This could be seen in contemporary movements such as New Brutalism (1950s–1970s), descended from modernist architecture but pursuing movement through angular, quick and economical construction characterised by precast concrete slabs, rough, unfinished surfaces, exposed steel beams and large sculptural shapes. Banham characterised New Brutalism with the memorability of an image, clear exhibition of structure and valuation of materials as found.[147] The notion of image ascribed by Banham was through topology that moved architecture through form finding beyond the technical exploration. The neologisms of New Brutalism, topology and image established the protagonist's position in the Modernist movement in architecture.

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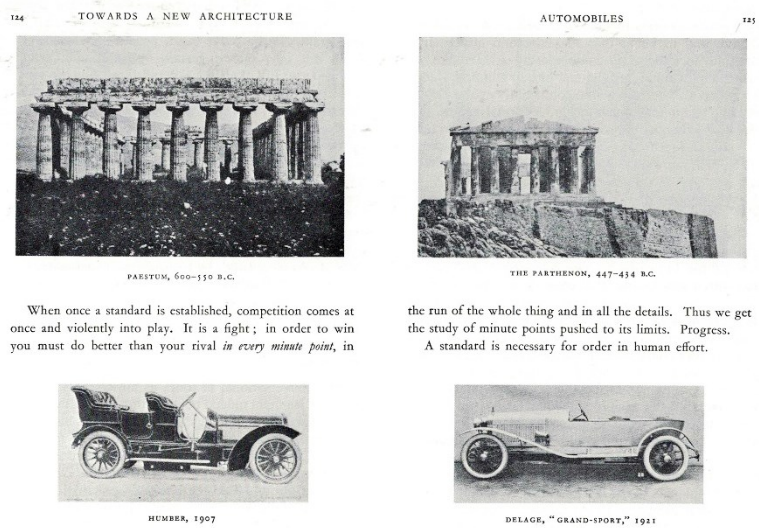
[145] Reyner Banham, "The Science Side: Weapons Systems, Computers, Human Sciences," *Architectural Review,* vol. 127, no. 757 (March 1960): 183.

[146] Reyner Banham's definition of '*une architecture autre'* is a call for an architecture that technologically overcomes all previous architectures but possesses an expressive form. As he stated in relation to Archigram's neo-futuristic Plug-in Computerised City, form does not have to follow function into oblivion. See Nigel Whiteley, *Reyner Banham: A Historian of the Immediate Future* (Cambridge: MIT Press, 2000), 176–178.

[147] Reyner Banham, "New Brutalism," *Architectural Review,* vol. 118, no. 108 (December 1955): 361.

4.2.3 Formalising the Morphology of Modernism

The applications of new scientific media technology prompted a re-evaluation of codification in architecture. For Le Corbusier, the universal value of architecture is demonstrated through technological contexts such as the machine and is necessary for architectural fabrication because of the imperative of logic verified by experimentation. Le Corbusier appealed to industrial and engineering logic, and to the rational norms and standards mobilised in manufacturing by juxtaposing the Parthenon with a racing car (Figure 4.3).


124 TOWARDS A NEW ARCHITECTURE

AUTOMOBILES 125

PAESTUM, 600–550 B.C.

THE PARTHENON, 447–434 B.C.

When once a standard is established, competition comes at once and violently into play. It is a fight; in order to win you must do better than your rival *in every minute point*, in the run of the whole thing and in all the details. Thus we get the study of minute points pushed to its limits. Progress.

A standard is necessary for order in human effort.

HUMBER, 1907

DELAGE, "GRAND-SPORT," 1921

Figure 4.3. *The Parthenon* (447 B.C.), *Paestum* (600–550 B.C.) and automobiles (1921). Le Corbusier, *Towards a New Architecture* (New York: Dover Publications, 1986), 134–135.

Le Corbusier's analogy between classical principles of geometry and form and the logic of modern technology sought to foreground invariable normative principles that transcend historical or chronological conditions over changing style. He aimed to codify such regularities in order to build an architectural language with an intrinsic grammar and syntax, with a distinctive morphology equal to what he saw as the heroic task of the contemporaneous or the 'modern'.

4.2.4 Mannerism and Modern Architecture

Rudolf Wittkower's analyses of Renaissance architecture had a profound influence on modernist understandings of geometry, modularity, pattern, proportion, the function of the diagram, the role of perspective and the concept of ideal form.[148] In his approach to the notion of the paradigm, Wittkower firstly deals with the question of symbolism, the appropriation of form by reinterpreting history as the syntax and reinventing Classicism as a system. Secondly, he investigates the question of taxonomy and the development of building types. Within this frame of thinking, Wittkower defined Mannerism as a new inherently conflictual architectonic conception giving the impression of unstable movement. He contended that Michelangelo's *Biblioteca Laurenziana* deals with particular conflicts that introduce 'difference' within the architecture.[149] He reads the main stair as an unstable element, differentiated into three separated flights of varying dimensions and rhythms within the one assembly (Figures 4.4 and 4.5). Thus, the law of double function and double meaning expressed in different degrees of a static or a dynamic structure in the form of Mannerist architecture is distinguishable from the statics of Renaissance architecture

Figure 4.4.

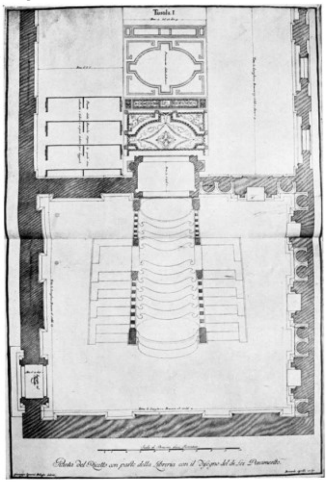


Figure 4.5.

Figure 4.4. Staircase of the *Laurentian Library* by Michelangelo Buonarroti in Florence, 1571. Image from Rudolf Wittkower, "Michelangelo's Biblioteca Laurenziana," *The Art Bulletin*, vol. 16, no. 2 (June 1934): 173.

Figure 4.5. Plan of staircase at the *Laurentian Library*. Image from Rudolf Wittkower, "Michelangelo's Biblioteca Laurenziana," *The Art Bulletin*, vol. 16, no. 2 (June 1934): 164.

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[148] Rudolf Wittkower, *Architectural Principles in the Age of Humanism* (New York: Norton & Company, 1971), 73.

[149] Rudolf Wittkower, "Michelangelo's Biblioteca Laurenziana," *Art Bulletin*, vol. 16, no. 2 (June 1934): 149.

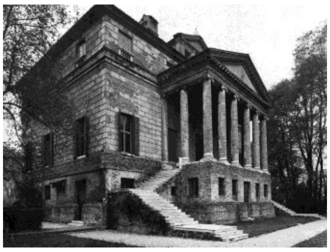

Figure 4.6.

and the dynamic structure of the Baroque.[150] Many Baroque palaces included grand staircases imposing different movement. With the function of the vestibule in the palace, the stairway splits into a pair of double ramps that converge at the centre of the *piano noble* (Figure 4.6).

In his article *Mannerism and Modern Architecture*, Colin Rowe formulates a theory for contemporary architecture based on the relationship between mannerism and modern architecture.[151] Rowe argues that modern architecture may contain elements analogous to mannerism, though reinterpreted due to nineteenth-century demands for structural integrity. Rowe identifies, in the Renaissance, a move to codify form. During this period, basic architectonic elements and invariable principles of architecture were investigated, using functional and visual frames of reference. Based on Wittkower's text Rowe established a comparison between Le Corbusier and Alberti through symbolic content – that of the search for a recovery of antiquity by Alberti and the search for a discovery of a dialect between a highly elevated conception of mechanism and a highly edited conception of antiquity.

This thesis identifies Alberti's method of translating architectonic information into written form represents a novel codification of architectural thinking and design, which much later evolved through algorithmic and automated modes of codification for two-dimensional and three-dimensional inscription suitable for design, prototyping and fabrication. Analysing Le Corbusier's villa

Figure 4.6. Andrea Palladio's *Villa Malcontenta*, 1550–60. Norbert Huse and Wolfgang Wolters, *The Art of Venice: Architecture, Sculpture, and Painting, 1460–1590* (Chicago: The University of Chicago Press, 1990), 123.

[150] Rudolf Wittkower, "Michelangelo's Biblioteca Laurenziana," 209–213.

[151] Colin Rowe, "Mannerism and Modern Architecture," *Architectural Review,* vol. 107 (May 1950): 299.

at *La Chaux-de-Fonds*, Rowe traces a decadence of elements derived from the architectural traditions of Renaissance humanism. Renaissance loggia and palace facades, with sequences of alternating windows and panels drawn from sixteenth century architectural topology, are interpreted into an essentialised, abstracted 'modern' language by Le Corbusier.

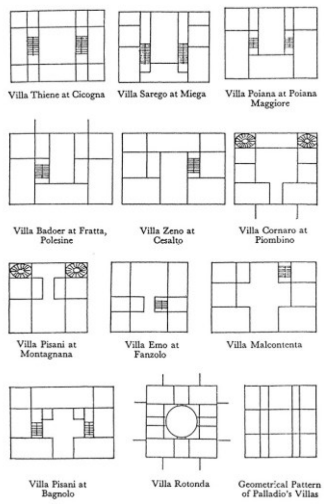

Figure 4.7.

There are parallels between classical and modernist modes of codification. The integration of geometry in architecture is explicit in Palladio's villas, characterised through diagrammatic structure, repetition and variations on a single theme. Wittkower defines Palladian villas according to their deep structure and geometrical ordering systems, discovered through measuring and drawing. He develops a set of diagrams as graphic expressions of a schematising machine that totalises the villa type (Figure 4.7). Wittkower's analysis of 12 Palladian villas reveals a variation on the same, identical spatial type. The diagrammatic type dominates all other constraints of a project – site, materials, technology, decoration, patrons, clients and program in favour of the geometric-mathematical systemisation of the ground plan. The historical continuity of classical elements in Palladio's villas is further extended, using new technologies, in the mathematical and spatial forms developed in Le Corbusier's villas.

Rowe extends Wittkower's geometrical analyses in *Mathematics of the Ideal Villa* (1947), arguing for a postmodern theoretical grounding of classical and twentieth-century mathematical and formal systems. Identifying Palladio's influence as a turning point in Le Corbusier's transition from premodern to modern, Rowe argues for architectural continuity across "cultural,

Figure 4.7. Palladian villas diagrammed by Rudolph Wittkower, 1949. Rudolf Wittkower, *Architectural Principles in the Age of Humanism* (New York: Norton & Company, 1971), 73.

historical, constructional and spatial particularities," upon which postmodern theoretical ground could be founded. Comparing Renaissance and modernist mathematical ordering systems in Palladio's *Villa Foscari (Malcontenta)* (1550–60) (Figure 4.8) and Le Corbusier's *Villa Stein* at Garches (1927) (Figure 4.9), Rowe notes a volumetric similarity.

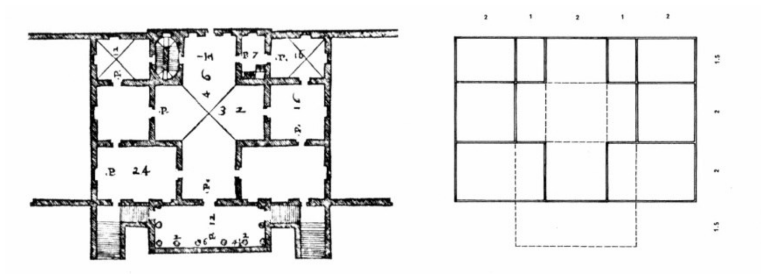

Figure 4.8. Andrea Palladio's *Villa Malcontenta*, 1550–60. Colin Rowe, *The Mathematics of the Ideal Villa and Other Essays* (Cambridge: MIT Press, 1976), 21.

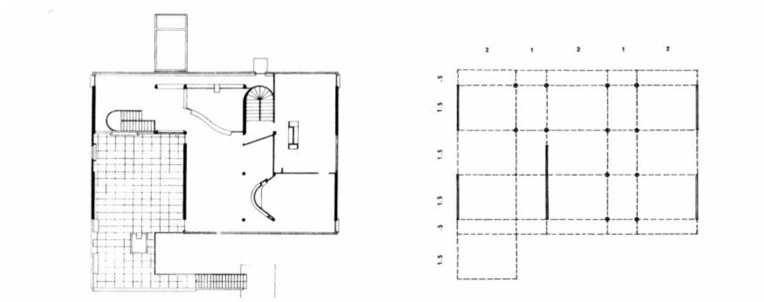

Figure 4.9. Le Corbusier's *Villa Stein*, 1927. Colin Rowe, *The Mathematics of the Ideal Villa and Other Essays* (Cambridge: MIT Press, 1976), 51.

While both villas share a similar proportioning system and a relationship to a higher mathematical order, Palladio's villa forms a pyramidal superstructure which amplifies the volume of the house, while Le Corbusier's villa is composed of horizontal layers with a free open plan, defined by the floor and the roof slabs. In the spatial subdivision, Palladio's solid wall structure is used for planning symmetry, while Le Corbusier's frame building makes the distinction between old and new systems, with columns and a free plan.

The facade of *Villa Malcontenta* is divided vertically into three principal fields: the portico, the flanking walls, and the horizontal sequence of the basement, piano noble and attic. In comparison, *Villa Stein* is a situation of at least two, or four fields of interest: the entrance elevation is a breakdown of four and one; and in the garden facade, the breakdown is four and two.[152] Le Corbusier integrates structure and column to create a free plan. Le Corbusier's *Dom-ino* system, evident in *Villa Garches'* structural column grid and reinforced concrete floor slabs, represented a modernist manifesto that reduced the language of architecture to five key components, or 'points': pilotis, free plan, free facade, long horizontal ribbon windows and roof garden. Le Corbusier saw this taxonomic codification of architecture into five component types as replacing the orders of classical architecture as design generators (Figures 4.10 and 4.11). The Second Digital Turn represented an additional stage in the evolution of design generators transformed through digital form finding based on design and material optimisation with the logic of engineering and fabrication.

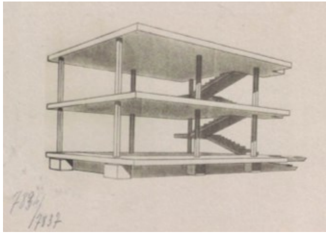

Figure 4.10.

Figure 4.11.

Figure 4.10. Ferroconcrete skeleton for a dwelling house *Maisons Dom-ino* (House Machine) by Le Corbusier, 1914. Olivier Cinqualbre, Frédéric Migayrou and Anne-Marie Zucchelli, *Une Adventure Moderne* (Paris: Centre Pompidou, 2018), 52.

Figure 4.11. *Savoye House* by Le Corbusier in Poissy-sur-Serine, 1930. Terence Riley, *The International Style: Exhibition 15 and the Museum of Modern Art*, ed. Stephen Perrella (New York: Rizzoli, 1992), 114.

[152] Colin Rowe, *The Mathematics of the Ideal Villa and Other Essays*, (Cambridge: MIT Press, 1976), 11.

4.3 The Means of Modern Architectonic Expression

Early twentieth-century modernist architects such as Reyner Banham and Le Corbusier sought the answers to the realisation of architecture in new technology in the form of machine aesthetics analogous to machines for travelling. In 1923, Le Corbusier in *Towards a New Architecture* aimed to resolve the problem of architectural design through engineering prototypes. Defining a house as a machine for living, Le Corbusier analysed the engineering prototypes of ocean liners, aeroplanes and automobiles as models for architectural production. In his analysis of craftsmanship, Le Corbusier refers to the aluminium framework of an aeroplane in the search for the economy of material, and lightness as a fundamental law of nature.[153] Outlining the engineer's aesthetic, industrial production and the need for mass housing in postwar France, Le Corbusier aimed to develop the architecture of its technological time.

In the form of analogue collaboration between different disciplines that would characterise the Second Digital Turn in architecture, Le Corbusier worked with the structural engineer Max Du Bois to develop the *Maisons Dom-ino Project, House machine* which integrated the structural frame prototype, based on the *Hannebique frame* in which the iron frame was covered with a thick layer of concrete for fireproofing. This concept informed Le Corbusier architectural ideology throughout the 1920s in addition to functioning as the structural basis of the majority of houses he designed until 1935.

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[153] Le Corbusier, *Aircraft* (Milano: Editrice Abitare Segesta, 1996), 24.

4.3.1 Standardisation of Architecture

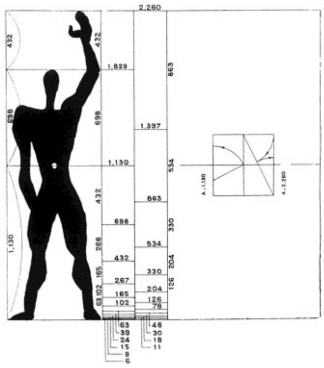

Figure 4.12.

Standardisation was an integral part of the modernist movement, and numerous solutions through new building technology and the freedom of a design process from historical forms were developed in the 1950s and 1960s. These include AFNOR (*Association Francaise de normalisation*), a non-profit organisation founded in 1926, as well as the association ASCORAL (*Assemblée des constructeurs pour une rénovation architecturale*), founded by Le Corbusier in 1940. Both were concerned with standardisation and industrial fabrication methods. Le Corbusier's investigation of standardisation led him to develop the *Modulor* in 1948, following well known classical and Renaissance models such as Polykleitos' Kanon and *symmetria* (450 BCE) and da Vinci's Vitruvian/Universal Man (1490 CE). In an attempt to find modules and serial measurements for building components, Le Corbusier applied the *Modulor* as a universally applicable measure for construction derived from both a six-foot human body and a mathematical theorem of the golden ratio (Figure 4.12).[154] Similarly, Palladian architecture should be designed in accordance with ideal proportions drawn from mathematics and musical concord, corresponding to perfect numbers and to the proportions of the human figure. An extreme instance of Le Corbusier's idea of the 'architectural machine' is Adolf Behne's 1925 call for radical functional practicality. For Behne, to achieve this, a building must become a tool; and having

Figure 4.12. *The Modulor*. Le Corbusier, *The Modulor and Modulor 2* (Basel: Birkhauser, 2000), 172.

[154] Le Corbusier, *The Modulor and Modulor 2* (Basel: Birkhauser, 2000), 41–43.

done so, it will liberate itself of formal and representational imperatives. The guiding principle for design is "adaptation to technical and economic functions, which with consistent work must lead to the dissolution of the concept of form. Thus, the building would unconditionally become a tool."[155]

While Renaissance and Baroque architecture created meaning through signs both inherent and attached to the surface of the buildings, modernist architecture became its sign immanent in the pure forms created through the new technology. As Walter Benjamin argued, in the age of mechanical reproducibility, an original entity loses something intrinsic in the process of being reproduced – whether by an image, a drawing or a simulation. What it loses is its authenticity, its identity with a particular spatiality, a particular temporality and a particular gesture of making; that is, it loses its *aura.* Furthermore, this opened progressive possibilities in technical reproduction, rendering the simulacrum independent of its source and indefinitely available anywhere and at any time. Benjamin's critical reading of mechanical reproduction is instructive when considering the parallel imperatives of standardisation and codification, which were so pivotal to the digital and parametricism.

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[155] Adolf Behne, *The Modern Functional Building* (Santa Monica: Getty Research Institute for the History of Art and the Humanities, 1996), 119–120.

4.3.2 New Construction Methods and Perception of Architecture

Figure 4.13. *Library of Sainte-Geneviève* by Henry Labrouste, 1843–50. Barry Bergdoll, Corrine Belier and Marc le Coeur eds., *Henri Labrouste: Structure Brought to Light* (New York: Museum of Modern Art, 2013).

In the nineteenth century, architectural history was inaugurated as an autonomous concept, discipline and practice, distinguished from earlier architectural treaties that focused predominantly on buildings. New spatial experiences, integrating ideas of infinite space realised through standardisation, modularity, reproducibility and prefabrication, are most strikingly evident in *Library of Sainte-Geneviève* by Henry Labrouste and *Crystal Palace* by Paxton, built for the Great Exhibition of 1851. The projects incorporated new materials such as cast iron, and a new construction system of modular units laid out on a regular grid, erected manually. The result was a strikingly innovative spatial environment, characterised by indefinite extension, openness, radical transparency and luminosity (Figure 4.13). The modular system was developed with innovative roof principles integrating longer sash bars supported by cast-iron trusses and standard glass panels,


Figure 4.14.

Figure 4.14. *AEG Turbine Factory* by Peter Behrens in Berlin, 1909. Adolf Behne, *The Modern Functional Building* (Santa Monica: Getty Research Institute for the History of Art and the Humanities, 1996), 158.

determining the roof design. Structural members in the form of lattice were achieved with columns mass-produced from hollow cast iron, riveted wrought iron and wood. The analogue technics demonstrated architecture and fabrication processes of the Industrial Revolution that with the advent of technology developed into automated prefabrication embedded with robotic technology.

In *Building in France, Building in Iron, Building in Ferro-Concrete* (1928), Sigfried Giedion mounted a critique of this significant architectural moment. For him, the evolution of architecture stalled in 1830. Thus, advances in modern technology and new materials did not contribute to the development of modern architecture; rather, they triggered 'industrial Neoclassicism' that was resolutely stylistic and aestheticised, rather than foundational and formative.[156] To conceptualise twentieth century contemporary architectural practice, Peter Behrens turned to the representational role of commercial architecture. His critique drew from Hegel's theory of representation in architectural history, characterised by the cultural ethos and Gottfried Semper's theory on the beginnings of architecture, based on the concept of the four anthropological elements of architecture: the fire, the base, the tectonic superstructure resting on the base with the woven enclosure, and the wooden roof. The facade is tripartite, consisting of a shallow concrete base, framed window panels 'woven' of steel and glass and a barrel roof (Figure 4.14). Through Semper's theory, Behrens brought the industrial factory into the realm of architecture,

[156] Sigfried Giedion, *Building in France, Building in Iron, Building in Ferro-Concrete* (Santa Monica: The Getty Center, 1995), 94.

comparing it to monumental history beginning with the Greek temple.

Following Behrens' concept for commercial architecture, Walter Gropius refined architectonics based on industrialised processes of construction, mass production of building components and newly evolving glass and steel technologies, manufacturing and materials. *Fagus Factory* (1925) by Gropius declares this new architectonic language (Figures 4.15 and 4.16). The factory might be considered to be the first constructed from iron, concrete and glass. In his approach, Gropius subjects American directness to a certain aesthetic filtering. Gropius's view coincides with John Cocteau's, for instance, on the resemblance of American machines and buildings to Greek art in the sense that utility confers on them a spareness and a grandeur stripped of the superfluous.[157] In contrast to Behrens' infill glass walls bounded by load-bearing masonry walls, Gropius' glass walls assume greater structural function and autonomy. There are parallels with Le Corbusier's (1922) *Ozenfant House* (Figures 4.19 and 4.20), but here Gropius goes further. In his architectural principles, structural glass is achieved with a variation of industrial glass and steel aesthetics in the form of a curtain wall, hanging free of the structure.[158] Nevertheless, Le Corbusier implements an industrial aesthetic with an emphasis on the universal type of plan in skyscrapers and apartment blocks (Figures 4.17 and 4.18).

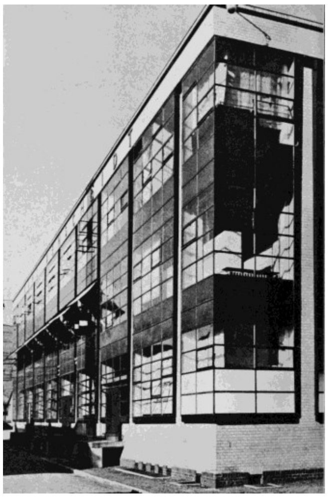

Figure 4.15.

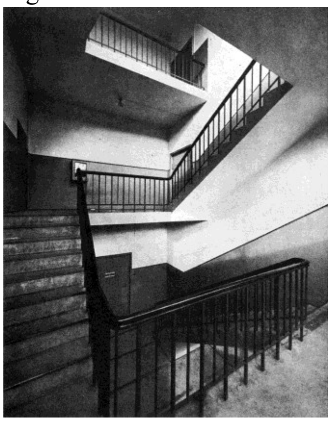

Figure 4.16.

Figure 4.15. *Fagus Factory* by Walter Gropius in Lower Saxony, 1925. Corner glass detail, acting as a curtain wall without the intervention of piers. Sigfried Giedion, *Space, Time & Architecture* (Cambridge: Harvard University Press, 2008), 483.

Figure 4.16. *Fagus Factory* staircase by Walter Gropius, 1925. Adolf Behne, *The Modern Functional Building* (Santa Monica: Getty Research Institute for the History of Art and the Humanities, 1996), 164.

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[157] Adolf Behne, *The Modern Functional Building* (Santa Monica: Getty Research Institute for the History of Art and the Humanities, 1996), 111.

[158] Walter Gropius, *The New Architecture and the Bauhaus* (Cambridge: MIT Press, 1965), 33.

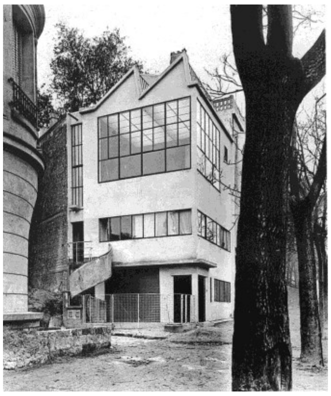


Figure 4.17.

Figure 4.18.

Figures 4.17. and 4.18. Exterior and interior views of the studio *Maison-Atelier Ozenfant* in Paris by Le Corbusier, 1922–24. Oliver Cinqualbre and Frédéric Migayrou, *Le Corbusier: The Measures of Man* (Zurich: Scheidegger & Spiess, 2015), 59.

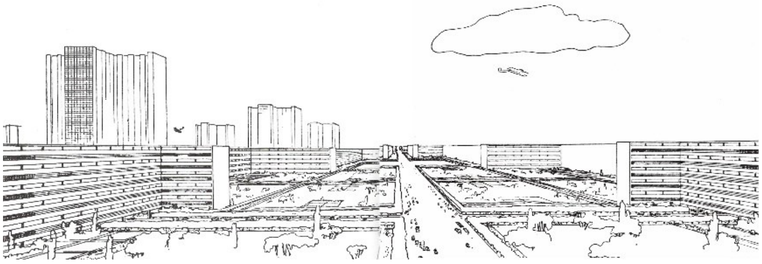


Figure 4.19. City skyscrapers and apartment blocks in a modern city by Le Corbusier, 1912–22. Adolf Behne, *The Modern Functional Building* (Santa Monica: Getty Research Institute for the History of Art and the Humanities, 1996), 218–219.

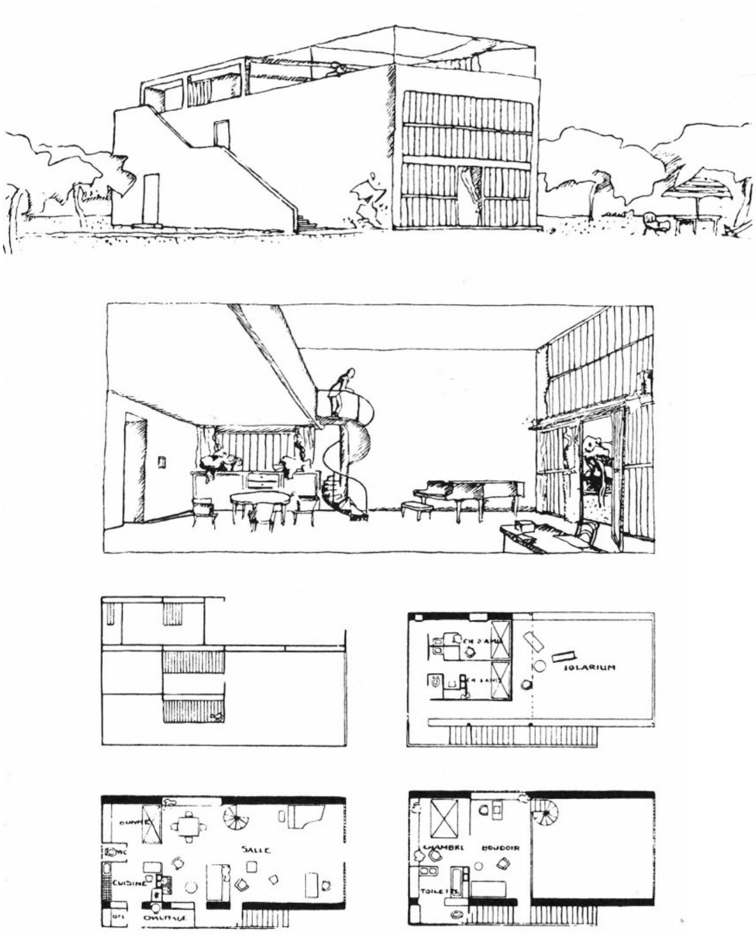


Figure 4.20. Prototype for mass-production house by Le Corbusier, 1922. Adolf Behne, *The Modern Functional Building* (Santa Monica: Getty Research Institute for the History of Art and the Humanities, 1996), 220.

The pinnacle of the modernist high-rise architecture is the *Seagram Building* (1954), a commercial office tower by Mies van der Rohe. The structural steel frame insulated with concrete had additional steel I-sections externally welded to the window panels as an architectural ornament for the vertical articulation of the building as well as for stiffening the skin for insulation and wind loading (Figure 4.21). The expressed steel element in the form of ornament, recalled Alberti's ornamental column as opposed to Peter Behrens and Le Corbusier's structural systems (Figure 4.22). The tower typology introduced the free floor plan (Figure 4.23) in comparison to overlapping planes that characterised the modernist approach of Le Corbusier. Homogenous treatment of the glass and steel by bronze created opacity as opposed to the modernist transparency explored by the Bauhaus.

Figure 4.21.

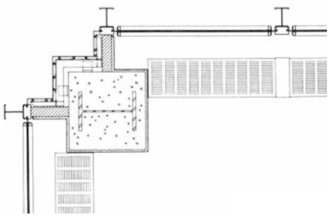


Figure 4.22.

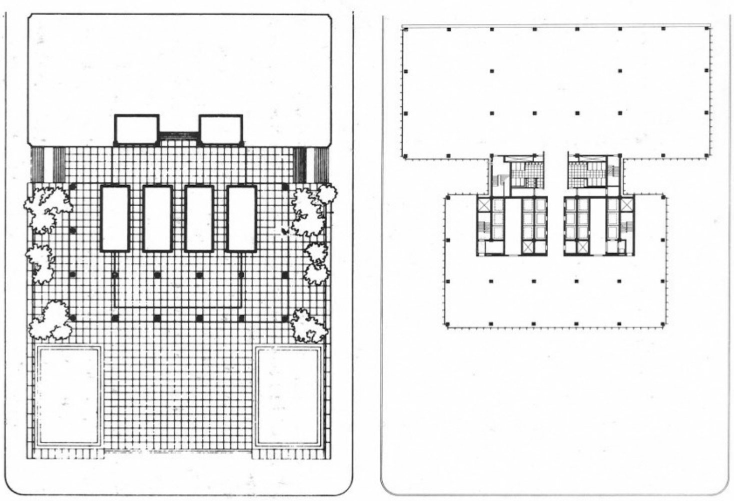
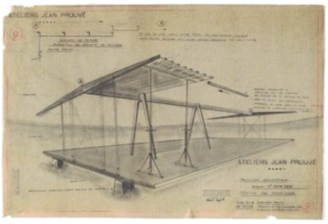


Figure 4.23. Seagram Building plan at street level and typical floor plan by Mies van der Rohe in New York, 1954. David Spaeth, *Mies van der Rohe* (New York: Rizzoli, 1978), 166.

Figure 4.21. *Seagram Building* by Mies van der Rohe in New York, 1954. Jean-Louis Cohen, *Mies van der Rohe* (Basel: Birkhäuser, 2018), 140.

Figure 4.22. Column detail of the *Seagram Building* by Mies van der Rohe. Claire Zimmerman, *Mies van der Rohe* (Cologne: Taschen, 2016), 75.

4.3.3 Impact of Industrialisation on Architecture



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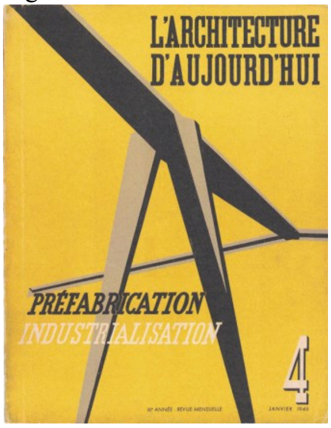

Figure 4.25.

The impact of industrialisation on the construction industry multiplied the variety of building components that were possible and potentially readily available and this consequently affected the building process from factory to site. In the late eighteenth and nineteenth centuries, new machinery, serial-produced elements and industrially fabricated materials complemented existing construction techniques and materials. The potential of cast-iron beams and columns, glass and factory-made bricks was explored on large industrial sites. New and evolving construction techniques required specially developed building machinery and cranes. In time, industrial fabrication and serial production of building components proved economically viable.

Nevertheless, it was not until the twentieth century that industrial manufacturing processes were adopted – for example, by Jean Prouvé in *Meudon House* (1950–1952). A leading proponent of the French *Union of Modern Artists* Jean Prouvé investigated aluminium material for *Meudon Houses* (1952) as a deployable serial system (Figure 4.24). Raised above the ground on a masonry basement for cooling purposes, the main structure featured a central aluminium *portique* – a tuning-fork-shaped central portal frame. At the beginning of the 1960s, mass-produced building elements of large-scale projects were prefabricated in steel and concrete in increasing numbers of factories or near the building sites (Figure 4.25). The thesis finds these methods persist in the construction industry showing the possibilities offered by digital technologies in architecture.

Figures 4.24 and 4.25. *Meudon House* drawing by Jean Prouvé and the Architecture of Today Journal cover from January 4, 1946. Olivier Cinqualbre, Frédéric Migayrou and Anne-Marie Zucchelli, *Une Adventure Moderne* (Paris: Centre Pompidou, 2018), 208–209.

4.3.4 Lightweight Structures in Architecture

In the 1950s, advances in new materials – plastic, aluminium and composites – and stronger machinery prompted new engineering and design opportunities afforded by the unique ratio of height strength to low bending stiffness in these materials.[159] Carbon fibre reinforced polymers were integrated to generate freeform geometries and industrially manufactured modular structures. The first architectural prototypes made from carbon fibre reinforced polymers were the *House of Future* by the Monsanto Chemical Company in 1954 and the *Futuro* by Suuronen in 1968. Both suggest high-tech technology in their appearance, yet manual lamination techniques were used to produce curved surfaces.[160] Architectural design using carbon fibre reinforced polymers reached its peak with Buckminister Fuller's *Fly Eye Domes* in 1975. Experimental tensile structure *Dome over Manhattan* (Figure 4.26) considers enclosing space in terms of material, time and energy. The dome is used to control the environment of the city, such as illuminating daylight without direct sunlight.

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[159] Jan Knippers et al., *Detail: Construction Manual for Polymers + Membranes* (Basel: Birkhauser, 2011), 24.

[160] Julian Leinhard, "Bending-Active Structures," (PhD diss., University of Stuttgart, 2014), 48, accessed June 1, 2016, https://elib.uni-stuttgart.de/handle/11682/124.

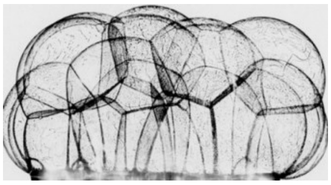

Figure 4.27.

Figure 4.26. *Dome Over Manhattan* by Buckminister Fuller. Robert Marks and Buckminister Fuller, *The Dymaxion World of Buckminster Fuller* (New York: Anchor Books, 1973), 234.

From a different perspective, Frei Otto conducted intensive research on cable net constructions and form finding design development focused on the principles of nature, aiming for the minimal surface with adaptable, lightweight architecture. The Frei Otto principle employed flexible, wire rope cable nets with covering membranes fixed and then suspended from masts and framed by cables around the edges which transferred the stresses to anchor-points. Autonomous formation processes – uniting natural form finding and adaptability – were created using models as well as specially developed measuring arrangements and test setups that allowed simulation of shaping and self-formation processes[161] (Figure 4.27). This autonomous formation process is a tool for optimising structural form and for generating novel construction when a cable is stretched between two points and placed under load. For

Figure 4.27. Pneumatic form finding with soap bubbles. Rainer Barthel, *The Work of Frei Otto and his Team 1955–1976*, ed. Ludwig Glaeser (Stuttgart: Karl Krämer, 1978), 22.

[161] Irene Meissner and Eberhard Moller eds., *Detail: Frei Otto* (Berlin: De Gruyter, 2015), 19.

tension structures, it is a measure used to reduce material to a minimum. For compression structures, autonomous formation processes reveal information about particular efficient shape possibilities. However, autonomous formation processes for Frei Otto cannot replace an architectural design. Although the experiment constitutes a very direct way of achieving the form, which, by its very nature, has already undergone an optimisation process, design work can only be seen in relation to the complexity of a building task and the integration of the building into its surroundings and society. Hence, it was never the objective of the Institute for Lightweight Structures to create a design theory.[162] This notion is directly related to the Third Digital Turn of Non-Standard Architecture proposed by this thesis where the optimisation process is one of the Statutes, for instance, optimisation of concrete through grading that is part of the protocol beginning with the codification of architectural design. For Otto, the first large-scale realisation of lightweight structures was the cable net roof of the *Munich Olympic Stadium* in 1972 (Figure 4.28).

Figure 4.28.

Figure 4.28. Lightweight cable net roof for *Munich Stadium* by Frei Otto, 1972. Irene Meissner and Eberhard Moller, *Frei Otto: A Life of Research Construction and Inspiration* (Munich: Detail, 2017), 60.

[162] Frei Otto and Wolfgang Weidlich, *Form, Force, Mass 5: Experiments* (Stuttgart: University of Stuttgart, 1990), 5.

4.4 The Last Modern Utopia

Metabolism, a utopian movement originating in Japan and inspired by a biomorphic model of growth and transformation, presented new design solutions for radically reconfiguring the modern city and its ideologies. Metabolists believed this manifesto would lead to a new order critical for society entering the post-industrial age.[163] Metabolism was founded in 1960 by Kenzo Tange and included Kiyonori Kikutake, Kisho Kurokawa and Fumiko Maki. The movement was concerned with the nature and expression of private and public spaces, with flexibility and changeable use. Prefabrication, advanced technology and industrialisation were used to create small capsules or living units for private spaces, connected to service towers and circulation areas. Metabolist projects represented a radical challenge to concepts of urbanism with an envisioned *tabula rasa* for the cities of the future built on the sea and land with new technology. The Metabolist manifesto emerged as a response to the high rate of urbanisation and the inadequacies of urban infrastructure to deal with it; but it was also a challenge to the persistence of Japan's archaic feudal urban structure, characterised by castle towns that impeded the realisation of a necessary and urgent modern urbanism. Ultimately, their goal was to:

> regard human society as a vital process - a continuous development from atom to nebula. The reason why we use such a biological word, metabolism, is that we believe design and technology should be a denotation of human society. We are not going to accept metabolism as

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[163] Zhongjie Lin, *Kenzo Tange and the Metabolist Movement* (London: Routledge, 2010), 1.

a natural historical process, but try to encourage active metabolic development of our society through our proposals.[164]

For Metabolists, the Industrial Revolution had brought an opportunity to liquidate the continued causation between man and continent. Kenzo Tange's *Plan for Tokyo* represented a synthesis of Metabolist urban concepts, expanding their utopian themes to an unprecedented scale (Figure 4.29). *Tokyo Plan, a* master plan for a city on water, attempted to increase land surface on a regional scale and restore it to its natural state. It was a vision for a new Tokyo expanding across the bay with a central spine carrying an elevated highway system with a series of interlocking loops spanning thirty kilometres over the sea. The loops water accommodated a new civic centre and a port. With a similar vision, the *Tower-shaped City* (Figure 4.30) project introduced urban dwelling in the form of a vertical ground, defined as "the combination of individual and society, architecture and city, as well as a new modern monument."[165] The concept was for a vertical megastructure or urban infrastructure, in the form of a concrete cylinder 300 metres high, with magnetically attached steel units as prefabricated modules, that would be renewed every fifty years. In 1972, prefabricated manufacture of an adaptable system of industrialised

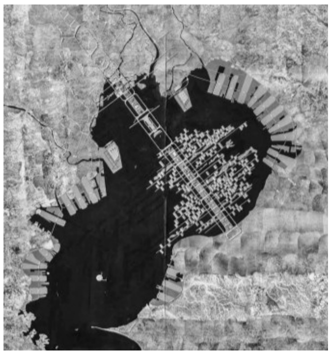

Figure 4.29.

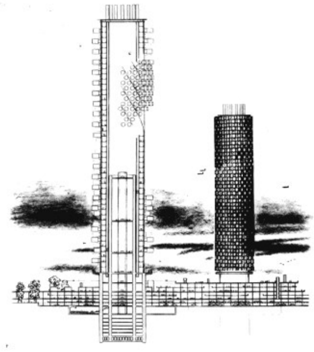

Figure 4.30.

Figure 4.29. Tokyo Bay Project by Kenzo Tange, 1960. Agnes Nyilas, *Beyond Utopia* (Milton: Routledge, 2018), 81.

Figure 4.30. *Tower Shaped Community*, Kiyonori Kikutake, 1958. Ken Oshima ed., *Kiyonori Kikutake Between Land and Sea* (Zurich: Lars Muller Publishers, 2016), 96.

[164] Kiyonori Kikutake, *Metabolism: The Proposal for New Urbanism* (Tokyo: Binjutsusha, 1960), 3.

[165] Kikutake, *Metabolism: The Proposal for New Urbanism*, 59.

building units that could be reorganised within a large, fixed infrastructure was developed by Kisho Kurokawa in Tokyo for his Tokyo *Nakagin Capsule Tower* (Figure 4.31).

Figure 4.31.

4.4.1 *Avant-garde* in Japan and Europe

Paralleling the Metabolist movement, Archigram*,* an *avant-garde* movement, emerged in Europe in the early 1960s, integrating futuristic design with a formal strategy based on the design of buildings that resembled machines or machine parts and structures that exhibited their services and structural elements. Initially formed by Peter Cook, Ronald Herron and Warren Chalk, Archigram was influenced by Cedric Price, especially his *Fun Place* (1961). It provided precedents for the high-tech style and promoted architectural ideas through futuristic graphics, exhibitions and the magazine Archigram. The group's vision of disposable, flexible, easily extended constructions was influential, although very few of its projects were realised. Archigram's drawings were intended to match their new vision of open-ended and evolving architecture based on information exchange. Archigram material included visual elements and graphic techniques from earlier architects like Chernikhov and the Futurists, from technical magazines like *Flight* and science fiction drawings.[166] The critical practice of the *Archigram* was a representation of architectural concepts by drawings that looked machine made. The manual techniques used

Figure 4.31. Construction photo of *Nakagin Capsule Tower* by Kisho Kurokawa in Tokyo, 1972. Barry Bergdoll and Peter Christensen, *Home Delivery: Fabricating the Modern Dwelling* (New York: MOMA, 2008), 145.

[166] Robert Bruegmann, "The Pencil and the Electronic Sketchboard: Architectural Representation and the Computer," *Architecture and Its Image*, eds. Eve Blau and Edward Kaufman (Cambridge: MIT Press, 1989), 143.

anticipate computer-generated architectural drawing. For example, the *Plug-In City* diagram by Peter Cook resembles an apparatus. By the early 1970s, the computer was increasingly integrated into medium-size architectural offices.

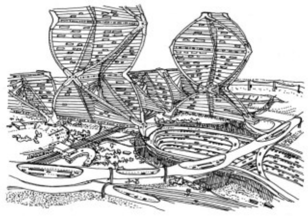

Figure 4.32.

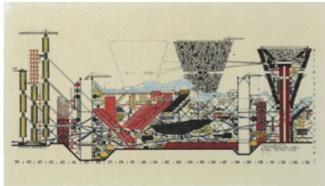

Figure 4.33.

While Archigram drew concepts from mechanistic metaphors strengthened by information and electronic media, the Metabolist approach embraced the Japanese traditional idea of organic expansion and replacement. By comparison, the Metabolists published one manifesto and continued to elaborate those concepts through urban and building projects (Figure 4.32), while Archigram published ideas in a series of Archigram magazines and continued concept development introducing new themes like *Plug-In City*, *Walking City* and *Living Pod* (Figure 4.33). In the 1960s, specialised robotic machinery and automated high-rise construction sites were introduced in Japan. Nevertheless, the technological progress that brought a universality to architecture was still held back by local restrictions where creativity was not fully developed on the basis of technology.

4.4.2 The Logic of Machine in Architecture

During the latter half of the twentieth century, a variety of scientific and cultural disciplines turned their attentions to a notion of the 'field' as opposed to a traditional conception of the 'object.' The emergence of field sensibilities can be related to the modern invention of infinitely expanding grids and an evenly divided, uninterrupted division of space that originated in the code of classic modernity. In the 1960s, Archizoom and Superstudio proposed infinite, uninterrupted fields of space

Figure 4.32. *Helix City* by Kisho Kurokawa, 1961. Zhongjie Lin, *Kenzo Tange and the Metabolists Movement: Urban Utopias of Modern Japan* (London: Routledge, 2010), 99.

Figure 4.33. *Plug-In City Project* by Archigram, 1964–1968. Terence Riley and Matilda McQuall, *Envisioning Architecture: Drawings* (New York, MOMA, 2002), 143.

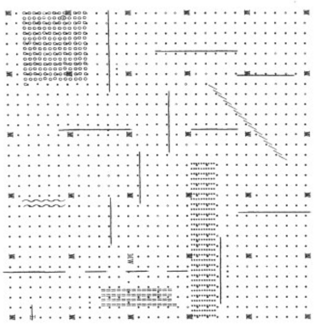

Figure 4.34.

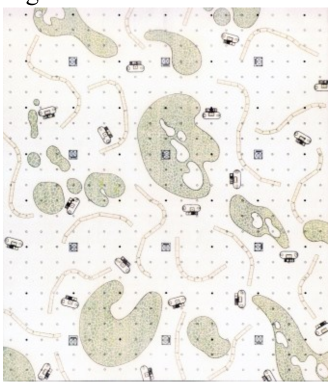

Figure 4.35.

Figures 4.34 and 4.35. *No-Stop City* by Archizoom, 1968–70. Andrea Branzi, *Weak and Diffuse Modernity* (Milan: Skira, 2006), 24, 73.

as a new kind of architectural project, and during the 1970s new largely horizontal diagrams emerged. The critical practice of Archizoom was a *tabula rasa* research by Andrea Branzi on *No-Stop City* from 1967 that rejected the design criteria of the contemporary city, linked to figurative codes, and characteristics of the fragmentation of pre-industrial architecture. Branzi's first drawings of the *No-Stop City* produced using typewriters and their orthogonal movement mechanisms aimed to rationalise space in urban grids that offered potential to function as environmental, organisational schemes, into which plug-ins for systems and services could be inserted (Figure 4.34). Archizoom's implementation of the twentieth-century building type of factory and commercial mall as models of spatial organisation for all civil functions in the city generated functional potential of architecture with infinite dimensions as an organism artificially ventilated and lit.[167] In turn, the city became free from architecture, conceived statically as many concrete objects. It was considered in terms of market flows and dynamic processes, in an unlimited zone where form, value and meaning could only impede design and economics (Figure 4.35). In comparison to Archigram's mechanical *avant-garde*, *No-Stop City* sought the logic of the industrial system in the quantitative utopia of consumer society. Today, Archizoom drawings can be seen as a literal codification of architecture evident in the digital revolution of the 1990s and automation. The thesis identifies the continuity of the orthogonal with the logic of machine in the industrial production that only began to explore

[167] Andrea Branzi, *Weak and Diffuse Modernity* (Milan: Skira, 2006), 70.

algorithmic parametrisation with the introduction of robotics.

Inspired by Guy Debord's Situationism, Superstudio critical practice was experimental production of architecture based on the notion of field as an endless framework structure of extravagant ideas of cities built in space with a radical program antipathetic to the capitalist system. Superstudio's manifesto rejected contemporary planning and even the need for architecture as a fabrication of bourgeois ownership. Superstudio's *Continuous Monument* series, a utopian vision of wrapping the planet in an uninterrupted framework, uses photomontage for a heightened sense of reality. The drawing from the series illustrates the Manhattan skyline as a stopover in the global superhighway (Figure 4.36). In a similar vein *Exodus* by Rem Koolhaas reads as a simultaneously factual and fictional scenario for the contemporary metropolis. The scenario with elements of manifesto takes a metropolitan strip flung across London, with its two parallel walls hermetically enclosing a dozen squares designed as a series of collective monuments. The branching strips cut through the slum areas of London, devoted to the private accommodation of prisoners. Their presence transforms slums into ghost towns and picturesque ruins (Figure 4.37).[168] This polemical project affirms that architecture is taking over from nature in the metropolis.

Figure 4.36.

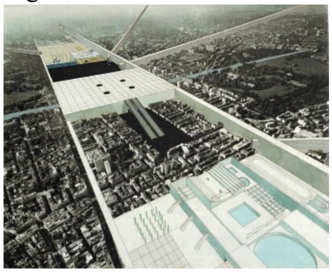

Figure 4.37.

Figure 4.36. *The Continuous Monument: New York* by Superstudio, 1969. Neil Bingham, *100 Years of Architectural Drawing* (London: Laurence King Publishing, 2013), 219.

Figure 4.37. *Exodus* by Rem Koolhaas and Elia Zenghelis with Madelon Vriesendorp and Zoe Zanghelis, 1972–74. David Frankel ed., *Envisioning Architecture* (New York: Museum of Modern Art, 2002), 168.

[168] Florian Herthweck and Sébastien Marot eds., *The City in the City Berlin: A Green Archipelago* (Baden: Lars Müller Publishers, 2013), 34.

4.5 Conclusion: The End of Modernist Ideology

This chapter traces the motif of standardisation as pivotal to the Enlightenment and its subsequent role during the Industrial Revolution. Standardisation was intrinsic to modernism, however it was a limit to realising the complex stereotomic formal program sought in the Renaissance. The limits of Modern utopia in architecture emerged from modernist architectural discourse and experimentations between architecture and industry that characterised an image of modern living equal to innovations in materials and techniques of production. Modernist interest in the machine aesthetic gained currency in the 1920s with Le Corbusier's proposal for slowing the housing crisis and with mass production of cars and techniques of Taylorised assembly evident in *Towards A New Architecture.*

With the advent of digital technology, the complexity of projective geometries has become rationalised by integrating algorithms to produce architectural drawings and automated fabrication. With the digital turn, it was possible to realise complex forms. However, this did not translate to the automated realisation on a construction site or to graded concrete parametric forms that are the main concern of this thesis. The question posed by modernist architects in terms of the resistance to building a culture to the revolution taking place in the factory finds its moment in what this thesis calls the Second Digital Turn of Non-Standard Architecture. There and then, mass customisation could be achieved through parametric digital architecture. However, while mass customisation did change design methods in the form of parametric data modelling, it did not eliminate the challenge of constructing parametric architecture on the building site. In the case of

Modernism, in 1968 it ceased to define a form of social organisation in terms of a position on a traditional–modernity axis. Jurgen Haberman argues the crisis affecting the idea of modernity has two possible responses: the first, that its decay is irreversible; and second, that modernity can and must be defended, or even extended.[169] Following the Second Digital Turn, the Third Digital Turn of Non-Standard Architecture identified by the thesis sought to extend automation to the site by reconsidering those constraining regulations that frame technology and by implementing topologically ecological approaches in the *Statutes of Non-Standard Architecture*.

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[169] Alain Touraine, *Critique of Modernity*, trans. David Macey (Oxford: Blackwell, 1995), 178.

CHAPTER 5

The Second Digital Turn

The second digital style, the style of data-affluent society and of nouveau data-rich technology, is the style of the late 2010s.[170]

5.1 Introduction: From Modernity to Postmodernity

The postmodernist break with the modernist idea of rational and efficient urban planning, characterised by austere functionalist surfaces, has cultivated a concept of the urban fabric as necessarily fragmented: a superimposition and collage of past forms and present uses. This section reviews the transition from Modernity to Postmodernity in architecture. The roots of postmodern architecture can be found in two technological shifts: first, contemporary communication and transport technologies which have collapsed modern space and time boundaries to produce a new internationalism and strong internal differentiations within cities and societies based on place, function and social interest; and second, new computer technologies that have enabled a shift in mass production from repetitive parts to customised products in a variety of styles.[171] Thus, postmodern architecture begins to enable a digitised platform for communication and design. The notion of modern power as single and centralised, either by the State or the ruling class, shifts to a regulatory system distributed around a norm. Michel Foucault argues that

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[170] Mario Carpo, *The Second Digital Turn* (Cambridge: MIT Press, 2017), 56–57.

[171] David Harvey, *The Condition of Postmodernity* (Oxford: Blackwell, 1990), 75.

social organisations exercise power through what he termed normalisation, that is, a system of finely gradated and measurable intervals, of distributions of individuals around the norm that controls as well as becomes the product of these controlled distributions. In turn, power distributed autonomously within institutions such as architecture normalises the law; that is, the measure of judgements about what is normal in a given population.

Section 5.2 reviews the postmodern turn when architects sought to develop an autonomous practice, raising and addressing questions about process and meaning through deconstructive means that challenged the geometric purity of modernist formalism. In the 1980s, realisations of deconstructivist architecture emerged, reflecting originality and individualism by dislocating architectural conventions on structure and envelope of the built form. Deconstructivist architecture adapted pivotal ideas from the philosophy of Jacques Derrida, particularly the notion of difference. In a diagram, difference stimulates ways of thought with collage and montage that deconstructs the text for both author and reader to produce significations and meanings. Section 5.3 reviews the computational turn during the past decade with interest in machinic design operations linked to new design systems and technologies, especially digital design and increasingly, manufacturing processes. Section 5.4 relates this generation of process-oriented design work to matter and algorithmic form finding experiments in automated design processes of Non-Standard Architecture. Section 5.5 argues for the Third Digital Turn emerging out of the Second Digital Turn of Non-Standard Architecture, identified as an architectural movement beginning in 2012. Section 5.6 identifies the limits of Non-Standard Architecture that persist in the Third Digital Turn of Non-Standard Architecture.

5.2 The Architecture of Postmodernity

Postmodernity refers to significant changes in the social, economic and political forms and systems associated with modernity that was introduced in the West from the eighteenth century onwards. In architecture, postmodernism refers to a specific style from the late 1970s to the early 1990s. As opposed to modern architecture shaped for social purposes, postmodern architecture was independent and autonomous shaped to achieve timeless and disinterested beauty as an objective.[172] The emergence of new computer modelling technologies became a method of experimentation of postmodernist architects that enabled mass production and evolved into Non-Standard seriality.

Charles Jencks was concerned about the inability of postmodern advocates and critics to give the movement a definite conceptual definition – a positive identity for the new architecture. In *The Language of Post-Modern Architecture* (1977), Jencks started to build a theory for a new spatial language, which drew on a comprehensive knowledge of western architectures past and present. Jencks' analysis of the examples of postmodern architecture focused on the expression of cultural assumptions, values and institutions. The architectural language of Robert Venturi integrates collage comprised of text and references. For instance, the word "or" is used to

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[172] David Harvey, *The Condition of Postmodernity* (Oxford: Blackwell, 1990), 66.

describe an ambiguous relationship between elements. To signal contradictions and paradoxes in architecture, Venturi uses the conjunctive "yet." The ambiguities and tensions sought by Venturi respond to what he sees as the complex and contradictory relationship between architectural elements, their meaning and interpretations in history and practice. In *Complexity and Contradiction* (1966), Venturi applied this strategy to re-examine architectural history following the *avant-garde* of the twentieth century. His manifesto referenced the buildings of Mannerism and late Baroque in England and Italy as the exemplary embodiment of an anti-classical architecture and the abstract idea of complex and contradictory aesthetic order, compared to modernist architecture. This applied in particular to Baroque mediation of the spatial needs of the inside and outside of a building. According to Venturi, this principle was lacking in modernist architecture with a functionalist expression of the exterior. Thus, in *Learning from Las Vegas* (1972), Venturi, in collaboration with Denise Scott Brown and Steven Izenour, developed the idea of a clear separation between the functional interior structure and the detached facade. The facade responded to its context and communicated with its onlookers as a symbol (Figure 5.1). In their analysis, Venturi and Brown equally distinguished between buildings whose form expressed function and buildings with generic form using signage to express function. Venturi's use of figuration by distorting an abstract type of architecture was a criticism of modern architecture. As opposed to Venturi's basis for architecture, Non-Standard architectonic extended the scope of design with novel computation to integrate new methods of form finding and fabrication.

Figure 5.1.

Figure 5.1. Car view of the strip in Las Vegas 1968–1972 by Studio Robert Venturi. Quentin Bajac ed., *Dreamlands: From Amusement Parks to Cities of Tomorrow* (Paris: Centre Pompidou, 2010), 21.

5.2.1 Emergent Topology in Architecture: The Concept of Soft Systems

The relationship of digital architecture to technology was analysed by Pierre Bourdieu, Jean Baudrillard and Paul Virilio. By integrating discourses on digital computation, architecture reconceptualised the idea of topology, which was described in terms of Waddington's epigenetic landscape: that is, a complex multiplicity of conditions in constant interaction that give rise to novel events and unpredictable outcomes. This notion of emergent topology developed during the 1960s and 1970s, through the concept of 'soft systems' – a term coined by Stanford Kwinter to explain the science of complex systems that became embedded into contemporary design practice. Soft systems implied the concept of an intelligent environment, where data is converted into information**.** They are maintained by a dense network of active information or feedback loops, and emerge from the need to understand nonlinearity, firstly in complex organic systems studied by biology and secondly in the military to model nonlinear dynamics of 'moving boundary' problems in ballistics and to design communication engineering in general intelligence operations.[173] A number of centres for research in computing and architecture emerged across the world, in London around Gordon Pask and in Cambridge, Turin, Boston (MIT) and Madrid. The potential of soft architecture was explored by Nicholas Negroponte in the digital installation *Seek*, by Gordon Pask through cybernetic

[173] Stanford Kwinter, "Soft Systems," *Culture Lab*, ed. Brian Boigon (New York: Princeton Architectural Press, 1996), 211.

models such as *Chemical Computer* and by Cedric Price in his *Fun Palace* project (1961–64).

While architects explored the possibilities of computerised data processing like Richard B. Fuller, Pierre Bezier's pioneering use of computers for drawing and modelling, and other early developments in computer-aided design (CAD), began an architectural collaboration with leading computer science laboratories. The inventor of parametric curves and surfaces was in fact Paul de Casteljau, who in 1958 developed an algorithm to evaluate calculations on a certain family of curves.[174] The curve was later formalised and popularised by engineer Bezier at Citroen to develop a system of three-dimensional surface modelling to guide numerically controlled machine tools. His research led to the creation of the *Unisurf* CAD program in 1966. In the early 1970s, a new generation of architects began experimenting with dynamic CAD tools that could be easily parametrised and modified by users as an open source interactive design platform. With the digital revolution in the 1990s, new programs emerged like Form Z and Catia for the development of digital forms by architects like Cedric Price, John Frazer, Peter Eisenman, Frank Gehry and Greg Lynn. From the 2000s, the introduction of algorithmic design programming into architecture shifted identical production to Non-Standard seriality that allowed the emergence of robotics in architecture.

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[174] Paul de Casteljau, *Shape Mathematics and CAD* (London: Kogan Page, 1985), 10.

5.2.2 Deconstructivist Architecture

The *Deconstructivist Architecture* exhibition at the Museum of Modern Art in 1988, curated by Philip Johnson and Mark Wigley, foregrounded a new architectural style exhibiting qualities of irregular geometry as a structural condition in contrast to the geometric purity of formal modernist composition. The exhibition featured works of leading protagonists Frank Gehry, Daniel Libeskind, Rem Koolhaas, Peter Eisenman, Zaha Hadid, COOP Himmelb(l)au and Bernard Tschumi. These projects exhibited complex dissimulations of the architectural object, achieved by taking the structure apart along inherent fault lines, variously based on intrinsic theoretical, political, programmatic, contextual, formal or architectonic conflicts and dilemmas. Derived from the Russian *avant-garde* of the early twentieth century, together with the stability of high Modernism, deconstructivist projects applied radical tactical geometric operations geared to formal decomposition. At the same time, these projects radically deviated from constructivist formalism in that they exploited the aberration in the history of the *avant-garde* in which contorted architectural designs were proposed. Consequently, they produced the "De" of "De-Constructivism."

In contrast to modernist mechanic-organic formal processes associated with universal forms, deconstructivist architects used an analytic process of collage elements to generate irregular geometry. Derrida's diagrammatic reading of difference was pivotal. Operating between form and word, the diagram has the strategic, analytical value of producing variation and difference, rather than of valorising the identity of hierarchical idea. Such a strategic operation is geared to deconstruct the classical philosophical opposition of double writing, that is, writing that is in and of itself multiple by overturning the writing opposition hierarchy at a given moment.[175] This is evident in the architectural diagram through form finding that overturns or reverses the diagram or model into neutral, equally representing all elements of the opposition within the architectural model.

Figure 5.2.

Figure 5.3.

5.2.3 Deconstructivist Diagramming Techniques

Transformational methods of early deconstructivists established a code of spatial relationships based on a set of rules – such as shift, rotation, compression and extension – that were applied to the aesthetic of high Modernism through an analytical process geared to materialising novel forms (Figures 5.2 and 5.3). By contrast, Non-Standard formal practices use diagrams of the digital process, integrating and simulating real data. The fragmented and conflicting elements of deconstructivist architecture give way in the Non-Standard to singular complex surfaces.

In *Notes Toward a Conceptual Architecture* (1971) Eisenman refers to influences on his conceptual procedures in architecture. His approach to breaking down the architectonic object drew from Sol LeWitt's philosophical codification method in conceptual art, Donald Judd and Marcel Duchamp's aesthetic intentions, Noam Chomsky's discourse on deep structure and later Jacques Derrida's

Figures 5.2. and 5.3. *Parc de la Villette* by Bernard Tschumi, 1987. Bernard Tschumi and Anthony Vidler, *Parc De La Villette* (London: Artifice, 2014), 36, 159.

[175] Jacques Derrida, *Positions*, trans. Alan Bass (London: Routledge, 1978), 41.

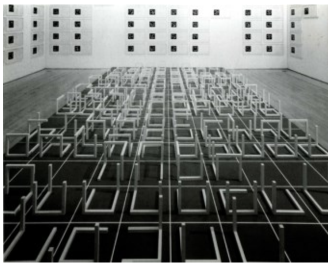

Figure 5.4.

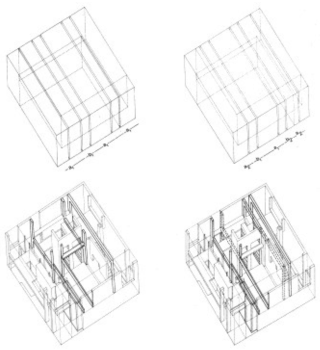

Figure 5.5.

mode of philosophical deconstruction (Figure 5.4). In his article, Eisenman distinguishes the fundamental difference of the idea of an object presence in architecture, within the intellectual realm and in the conceptual structure, that is different from the idea of art.[176]

Compared to the static diagrams of Rowe, Peter Eisenman's transformational diagramming technique took up Derrida's challenge. Initiated in the projects for *Parc de la Villette* (1987) (Figure 5.2) and *House* (post-1968) (Figure 5.5), it anticipated digital three-dimensional modelling platforms that would emerge around 2001. Eisenman's diagramming is based on linguistics and three semiological types: pragmatic relation of form to function or technology; semantic relation of form to meaning; and syntactic mediation of meaning and form through a structure of formal relationships. The form is defined as architecture's particular means of expressing intent and accommodating function with the ordered environment.[177]

The competition for the *Parc de la Villette* (1938) in Paris foregrounded the realisation of deconstructivist architecture, in particular, the entry from Jacques Derrida and Peter Eisenman and the winning entry by Bernard Tschumi. Derrida launched the collaboration on *Parc de la Villette* by suggesting a concept he was writing a paper on. The concept, named *khora,* was a term from Plato's dialogue *Timaeus.* The common translation of *khora* is place or space. Derrida's reading, however, highlights the

Figure 5.4. Models of cubes, 1974. Sol LeWitt, *Incomplete Open Cubes*, 1974.

Figure 5.5. *House I*, 1967–68. Peter Eisenman, *House of Cards* (New York: Oxford University Press, 1987), 54–55, 197.

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[176] Peter Eisenman, "Notes on Conceptual Architecture," *Eisenman Inside Out* (London: Yale University Press, 2004), 10–27.

[177] Peter Eisenman, "Toward an Understanding of Form in Architecture," *Eisenman Inside Out* (London: Yale University Press, 2004), 9.

formlessness of *khora,* its capacity to provide a space for becoming without itself having any discernible or stable form. Derrida and Eisenman's project established a Cartesian grid: an abstract, defined geometric system to limit the space and at the same time provide an open framework for the event. This architectural discourse advanced the notions of decomposition and fragmentation to contest the modernist geometric project.

The critical practice of Bernard Tschumi of discovering and working at the limits of architecture led to a strategy of disjunction: the deployment of transformative operations such as transference, superposition, distortion and de-centring. The programmatic potential of the strategy is evident in Tschumi's competition-winning project *Parc de la Villette* that aimed to displace the traditional hegemony of program in architectural expression by mobilising a series of operations to a reverse oppositions and displace the system reference[178] (Figure 5.6). The principle of superimposition overlaid three autonomous systems of point, line and surface references (Figure 5.7). The system of points contained the point-grid coordinate system of programmed activities; the system of lines related to an orthogonal system of high-density pedestrian movement through the park; and the system of surfaces marked all activities requiring large expanses of horizontal space for play, games, body exercise, mass entertainment, markets, etc.[179] The site was organised spatially through a grid of 35 points that located 35

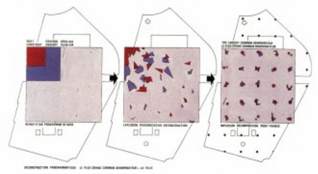

Figure 5.6.

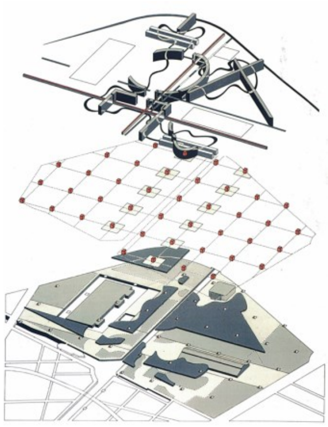

Figure 5.7.

Figure 5.6. Programmed deconstruction. *Parc de la Villette* diagram by Bernard Tschumi, 1983. Jacques Derrida and Anthony Vidler, *Tschumi Parc de La Villette* (London: Artifice Press, 2014), 39.

Figure 5.7. Superimposition of the three systems: points, lines and surfaces in the *Parc de la Villette* by Bernard Tschumi, 1983. Jacques Derrida and Anthony Vidler, *Tschumi Parc de La Villette* (London: Artifice Press, 2014), 43.

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[178] Bernard Tschumi, "Parc de la Villette, Paris," *Architectural Design*, vol. 58, no. 3/4 (1988): 32–39.

[179] Bernard Tschumi, *Event-Cities 2* (Cambridge: MIT Press, 2000), 57.

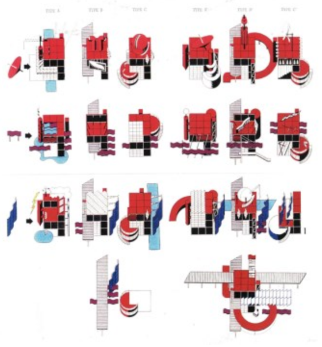

Figure 5.8.

Figure 5.9.

pavilions which Tschumi called *folies*. The *folies* gave a dimensional and organisational quality to the park serving as points of reference.

The programmatic potential of superimposition, permutation and substitution governing the design of *Parc de la Villette* is evident in a radical questioning of the concept of structure. The project was a reaction against the assumed privilege of coherence and structural consistency at play in the history of architecture, from Classicism to Modernism. By rejecting the symbolic repertory of architecture, Tschumi deliberately achieves critical destabilising relations of meaning by promoting programmatic instability through the unprogrammed, yet functional *folies.* The superimposition system and endless combination possibilities of the *folies* through discontinuity, distortion, fragmentation, repetition, transference, rupture, interruption and dislocation provided a multiplicity of impressions, rather than a singular, totalising *schema* (Figure 5.8). The superimposition of the simultaneous and independent existence of points, lines and surfaces, that is, different activities, constituted the park. This system allowed every user to project their interpretation, in an architectural parallel to Roland Barthes' 'death of the author'. Tschumi's project does not aim to communicate a pre-existing meaning by representing it in the built form (Figure 5.9). Rather, it attempts to erase the reprogrammed program by shifting the locus of the production of meaning away from the architect, towards the user. Tschumi's tectonic conceptualisation of points, lines and surfaces is Euclidean, and as such within a digital platform, is still proto-parametrical with an intrinsic limitation of computation and fabrication that the eventual Non-Standard Architecture would be able to achieve.

Figure 5.8. Permutations of the cube. *Parc de la Villette* folies created with the strategy for intersection, repetition, qualification, distortion and fragmentation by Bernard Tschumi, 1983. Jacques Derrida and Anthony Vidler, *Tschumi Parc de La Villette* (London: Artifice Press, 2014), 64.

Figure 5.9. *Parc de la Villette* diagram of lines, Bernard Tschumi 1983. Jacques Derrida and Anthony Vidler, *Tschumi Parc de La Villette* (London: Artifice Press, 2014), 138.

5.3 Topology of Architecture: The Computational Turn

The shift to digital design operations in the early 1990s, powered by new computer technology, was revolutionary for architecture. The method of software capability that introduced an algorithmic function of the real-time interactive rendering of non-uniform rational B-splines curves and surfaces grew out of the B-spline curves and surfaces in the early 1970s, which was the pioneering work of Pierre Bezier,[180] based on the Paul de Casteljau algorithm in 1958 for evaluating calculations on a certain family of curves.[181] The method introduced into digital design processes the physical properties of splines with mathematical precision, as opposed to earlier hand-drawn methods using flexible strips of wood, held in place to create a shape by elasticity that minimised the energy of bending. As a consequence, the digital revolution of the 1990s was characterised by a focus on smooth and continuous forms and surfaces, defined by the topological description of form – that is, of form as *topos* rather than *schema* or *morphe*. Gilles Deleuze's theory of the fold, referencing Leibniz's mathematics of continuity and differential calculus, was instrumental in architecture's takeup of these ideas. In *The Fold: Leibniz and the Baroque*, Deleuze applied his mediation on the fold in part on an interpretation of the space of Baroque architecture by introducing new terminology, the "objectile" to define the

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[180] Less Piegl and Wayne Tiller, *The NURBS Book* (New York: Springer, 1997), vii.

[181] Paul de Casteljau, *Shape Mathematics and CAD* (London: Kogan Page, 1985), 10.

object not as a singularity but as a function that virtually contains an infinite number of compossible objects.[182]

The thesis identifies the notion of topology with the autonomy of architecture. The conceptual apparatus of biopower and biopolitics was resituated within a broader notion of governmentality in 1978, and defined primarily as the ensemble formed by institutions, procedures, analyses, calculations and tactics.[183] This distribution of power gave autonomy to architecture to measure the judgments about what is normal in a given population which developed absolute autonomy in the realisations of digital architecture, emphasising its originality and individualism. The autonomous turn of the Second Digital Turn introduced novel possibilities with the parametric data modelling and a parametric architectural robot that, however, was limited by the regulatory environment and mainstream construction practices.

5.3.1 The Concept of Folding

The adaptation of computational methodologies and Deleuzean theory into architecture was promoted by a pivotal issue of the journal *Architectural Design, Folding in Architecture* (1993). Mario Carpo, Greg Lynn and Jeffrey Kipnis among others departed from the deconstructivist "fragmented, and conflicting formal systems" to develop "smooth transformation involving the

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[182] Gilles Deleuze, *The Fold: Leibniz and the Baroque* (London: Continuum, 1993), 20–21.

[183] Michel Foucault, *Security, Territory, Population: Lectures at the College de France*, trans. Graham Burchell (New York: Picador, 2007), 108.

intensive integration of differences with a continuous yet heterogeneous system."[184] The text attempted to provide theoretical and operative alternatives to deconstruction, particularly as formulated by Philip Johnson and Mark Wigley in the *Deconstructivist Architecture* exhibition and catalogue of the Museum of Modern Art in 1989. During this time, Columbia University and the Architectural Association introduced digital design into an open-source design studio dedicated to a systematic exploration of new design tools, systems and discourses for design innovation in architecture and urbanism.

The first experimental theme of the digital style was the concept of folding. This was characterised by non-uniform rational B-spline surfaces and operations like lofting that allowed for smooth transitions between sectional spatial profiles. The curvature produced by non-uniform rational B-splines provided a high degree of control with points, weights and knots. During this period, Zaha Hadid Architects explored formal possibilities of folding, together with investigations flowing from Deleuze and Guattari's writings in *A Thousand Plateaus,* dealing with the ways bodies and spaces are inscribed or demarcated by social, political, and cultural networks of power. Architecture's focus was recast away from formal concerns *per se* to the idea of network structures, which offered more freedom of expression and resistance. Characteristic themes in these explorations included the rhizome, multiplicities, assemblage, smooth space, line of

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[184] Greg Lynn, "Architectural Curvilinearity," *Architectural Design: Folding in Architecture*, vol. 63, no. 3/4 (2004): 24.

Figure 5.10.

flight, deterritorialisation, reterritorialisation and the abstract machine.

The new style that characterised folding was most clearly manifested in projects such as the *Yokohama Ferry Terminal* (1995–2002) by Foreign Office Architects, *MAXXI Museum* (1998–2010) by Zaha Hadid Architects and *Arnhem Central Transfer Station* (1996–2015) by UN Studio. Positioned as an antithesis to the formal concerns of Deconstructivism, folding attempted to formulate a new model of formal and spatial complexity anticipating or in some cases facilitated by the assistance of digital tools. As such, the logic and processes of folding generated new forms that would only later be facilitated digitally. The zeitgeist of the digital turn in architecture was captured by Frank Gehry in his 1997 *Guggenheim Museum* in Bilbao (Figure 5.10). The project realised the first freeform surface in digital architecture on a grand, industrial scale. Single-curved surfaces integrated by the virtual building design, manufacture and construction required custom tool design. Gehry's firm used *Dassault Sytemès CATIA* software, developed for aircraft construction to create *Digital Project,* a new interface between architectural design and production, piloted with the *Golden Fish* sculpture in Barcelona, where complex three-dimensional geometries were achieved through integrated and customised manufacturing.

5.3.2 Transformational Potential of Topology

Figure 5.10. *Guggenheim Museum* by Frank Gehry in Bilbao, 1997. Guggenheim Museum Bilbao, Wikipedia, last modified April 27, 2019, https://en.wikipedia.org/wiki/Guggenheim_Museum_Bilbao.

A topological approach to form emphasises not the shape of an object, but rather its transformational potential in terms of the multiplicity of forces at play in its creation. It focuses on evolutionary, time-based processes rather than final formal outcomes. Topological descriptions of form seek to capture the ways in which matter and information are fundamentally related. Stanford Kwinter's (1993) essay *Soft Systems* provides an overview of this different approach to architecture, which stresses the various ways in which projects have attempted to create conditions where design could be undertaken within a time-based approach to form. Lynn’s (1999) essay *Animate Form* is a statement on the important way in which time can become an integral parameter of design, through inherently dynamic digital design tools. Within the digital platform, the concept of the discrete prototype is subsumed by the model of “the numerically controlled multi-type that is flexible, mutable and differential.”[185] Lynn defines animated architecture on a virtual platform according to three fundamental properties of computational organisation: topology, time and parameters. The geometry defined by calculus is a topological entity composed of a continuous stream of relative values. Compared to Baroque discrete geometry of multiple points defined by multiple radii, the topological surface is defined by vectors that hang from weighted fixed points (Figure 5.11). The computational design reflects the method of multiplicity within which a change in any point distributes an inflexion across the region.

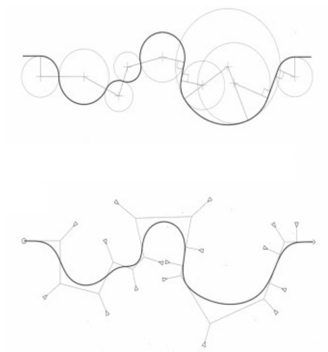

Figure 5.11.

Figure 5.11. *Above*, Composite curve generated by logic of regional definition and tangency. *Below,* Spline geometry generated by NURBS with control of points, weights and knots in *Rhinoceros* programming language.

The project *Embryological House* (Figure 5.12) explored a combination of splines that generate variations of the surface with a hierarchy of controlling points to shape more than 3,000 panels. The strategy involved specifying each panel’s position, with an increased number of control

[185] Greg Lynn, *Animate Form* (New York: Princeton Architectural Press, 1999), 13.

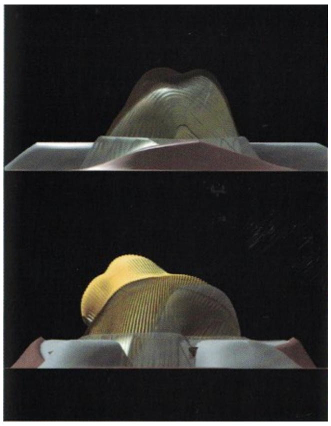

Figure 5.12.

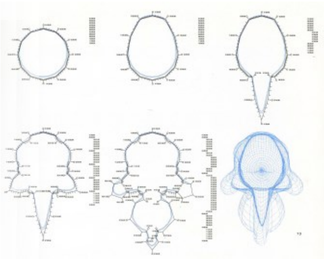

Figure 5.13.

points (Figure 5.13). The geometric coding of these forms allowed the creation of virtually infinite series using numerically controlled machines. Lynn describes the schema as a departure from Wittkower, Rowe and Eisenman, defining his counterposition of animate geometry and continuous differentiation. His approach attempted to project a new form of architecture aligned with theory and unfolded theoretically using the capacities of the new medium. In addition to geometry defined by mathematics, Lynn recognised formless writing in architecture leading with a different kind of alliance emerging from geometry and organism, "resulting in anexact, multiplicitous, temporal, supple, fluid, disproportionate and monstrous spatial bodies" that resist any reduction to ideal form.[186] The topological description of form was the focal point of digital architecture, that increased capacity with the continuous evolution of software algorithms making a shift into automation as proposed by this thesis – the Third Digital Turn of Non-Standard Architecture.

Figure 5.12. Digital model for the *Embryological House* by Greg Lynn, 1998. Frédéric Migayrou ed., *Architectures Non Standard* (Paris: Centre Pompidou, 2003), 101.

Figure 5.13. Drawings for the *Embryological House* by Greg Lynn, 1998. Greg Lynn, "Embryological Housing," *Any: Diagram Work*, ed. Cynthia Davidson, no. 23 (1998): 47–49.

5.3.3 Architectural Strategy of Field Condition

The architectural technique of 'field condition,' generated from the materiality of the city, was raised by Stan Allen in *Architectural Design: After Geometry* in 1995.[187] This concept of 'field conditions' is intended to oppose the traditional conception of architecture as an

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[186] Greg Lynn, "Multiplicitous and Inorganic Bodies," *Folds, Bodies and Blobs: Collected Essays* (Bruxelles: La Lettre Volée, 1998), 42.

[187] Stan Allen, "From Object to Field," *Architectural Design: After Geometry,* ed. Stanford Kwinter (1995), 24–31.

object. The emergence of field sensibilities can be related to the modern invention of the expanding grid as a division of space. Compared to the classical notion of architecture organised by a logical geometric system of proportions, field condition is a digital framework defined by connections between elements. The logistic of context recognises the limits of architecture's ability to create order within the project and to learn from complex self-regulating orders already present. For example, Jesse Reiser and Nanako Umemoto's (1997) *Water Garden* is concerned with information technology and virtual space through the concept of a solid-state architecture – that is, the conception of a diagram that folds media as a material substance and a virtual or informing potential. *Water Garden* is a concrete slab with 24 parallel grooves generated from a "laminar process" applied to the site[188] (Figure 5.14). The characteristics of this topological surface were derived from 'field data' by integrating flows from living and non-living systems. The full potential of the topological description of form was enabled with the digital parametric data model that allowed a method of design with a collaborative digital platform between architects and other disciplines to realise complex topological surfaces.

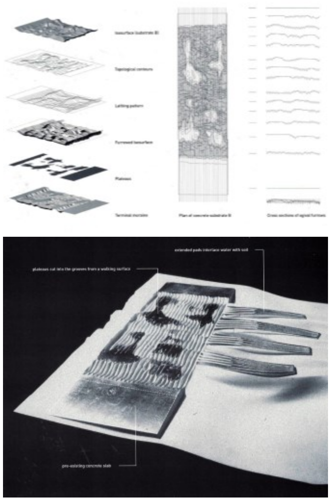

Figure 5.14.

5.3.4 The Realm of the Hyperreal and Simulation

The revolution in communications, cybernetics and systems theory during the 1980s led to the full realisation of simulation as a guiding method for architecture discourse and practice. Sign systems developed to produce simulated

Figure 5.14. Water level study and the model for the *Water Garden* project by Reiser + Umemoto, 1997. Andrew Benjamin ed., *Architectural Design: Reiser + Umemoto* (1998): 84–91.

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[188] Andre Benjamin ed., "Water Garden," *Architectural Design: Reiser + Umemoto* (1998): 86–91.


Figure 5.15.

realities on the basis of models or codes of the mass media and the political process. Digital technology proliferated at the time and was critically studied by Jean Baudrillard. For Baudrillard, simulation represented part of a global shift in the way culture communicates. It was generated by models of the real with no origin in anything real – what he termed the hyperreal. In this context, Baudrillard's theory illustrates the disappearance of the real and the associated decline of theory and politics in the contemporary moment, beginning with the events of 1968. To conceptualise the evolving social processes, Baudrillard moved to a position pivoting on his theme of the hyperreal: an aesthetic category and mode of reproduction or replication that strives to produce effects that are more real than the reality being simulated. The realm of the hyperreal included simulated realities, such as Disneyland, amusement parks, malls and consumer fantasylands, TV sports and other excursions into ideal worlds. In these hyperrealities, signs and codes controlled thought and behaviour (Figure 5.15).[189] Baudrillard observed that the extent of simulation in the hyperreal reversed the usual order of things with the simulation preceding the original. In fact, simulation threatened to erode the distinction between real and copy, true and false, concrete and imagined.[190]

Figure 5.15. *The Grandcourt Brothers stand between Caesar and the Thief of Bagdad*, 2003. Image by Allan de Souza. Quentin Bajac ed., *Dreamlands: From Amusement Parks to Cities of Tomorrow* (Paris: Centre Pompidou, 2010), 23.

Baudrillard defined the orders of simulation as corresponding to three stages of societal development. The first order of imitation, characterising the classical period, presupposes dualism where appearances disguise reality. In

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[189] Douglas Kellner, *Baudrillard: A Critical Reader* (Oxford: Blackwell, 1994), 8.

[190] Jean Baudrillard, *Simulacra and Simulation*, trans. Sheila Glaser (Ann Arbor: University of Michigan Press, 1994), 3.

the second order of production, typical of the modernity of the Industrial Revolution, appearances create the illusion of reality. In the third order of simulation, typical of postmodernity, appearances invent the reality.[191] Here, the images are generated from the model. For Baudrillard, this simulation lacks a reference point and therefore threatens the distinction between true and false. The difference between the first and second orders of simulation is comparable to the difference between human productive activity and automated robotic production activity.[192] In this context, Baudrillard describes two types of automation. The first is mechanical, guided by analogue techniques implemented by human actors and geared to the "effect of semblance". The second is dominated by technical principles where the machine supplants and becomes independent of human action. The second automation described by Baudrillard corresponds to the Second Digital Turn that introduced Non-Standard architectural automation with robotics controlled using algorithmic programming languages liberating it from independent human activity. This thesis formulates methodology that links automation from design to construction as part of the Third Digital Turn of Non-Standard Architecture.

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[191] Douglas Kellner ed., *Baudrillard: A Critical Reader* (Oxford: Blackwell, 1994), 121.

[192] Jean Baudrillard, *Simulations* (New York: Semiotext, 1984), 92.

5.4 Matter and Algorithm in Architecture: Non-Standard Architecture

Contrasting with the concerns of Modernism, Non-Standard Architecture emerged in 2001, powered by new computer technology, as a reaction to the constraints and limits of rational order embedded in mass production and the standardised fabrication of identical components. The Non-Standard countered the mechanical paradigm of architectural production by integrating algorithmic, continuous functions for the serial production of non-identical parts. It was a claim for a new logic of digital design thinking, with the focus on the associative and dependency relationship between objects and their parts. As discussed in Chapter 3, several exhibitions emerged promoting the Non-Standard protocol including *Latent Utopias, Architectures Non Standard* and *Remote Echo*. Phillippe Morel, the prominent protagonist of Non-Standard Architecture, defined the initial premise of its design process as the implementation of a programming protocol – or at least a mathematical and/or logical script – followed by the premise that the protocol remains architectural.[193] Grid computing by Morel was enabled by the protocol for linking discrete but geographically dispersed machines into a distributed parallel processing network. This collective process was analysed in optimisation data for *Computational Chair Design Using Genetic Algorithm* (Figure 5.16).

In architecture, the Non-Standard evolved through innovations in surface geometry including Bernard Cache

[193] Philippe Morel, *Five Essays on Computational Design, Mathematics and Production*, Haecceity Papers, vol. 3, no. 2 (Spring 2008): 5.

and Patrick Beaucé's group Objectile, which explored the relationship between computer-aided design and programmed industrial machinery. Objectile approached the real production of objects that at the time did not have standard software by using *TopSolid* polyhedral modelling software and numerically controlled machines, from file to the factory. They imported design parameters of the non-uniform rational B-splines surface into CAD/CAM post-processing software and interpreted the data through a numerical tool path to produce a corrugated pattern in a specific material. For fabrication, Objectile applied a modification of design parameters in the CNC milling machine tool path for the panels, which in turn produced differentiations with mass-customisation potential. While their process began three-axis fabrication for timber, they distanced from the process of automated fabrication of concrete objects by identifying it as a limit of software. Their automated fabrication was not concerned with assuring, for example, that the four corners of a flat board are coplanar.[194] With the development of software and algorithmic programming language automation extended into functionally graded concrete first, as a linear element in the Second Digital Turn and then as a parametric and algorithmic element investigated by this thesis in the Third Digital Turn.

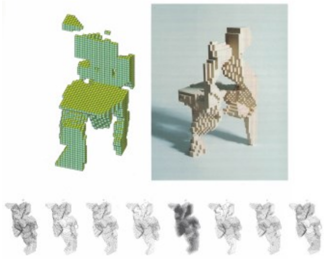

Figure 5.16.

Figure 5.16. *Computational Chair Design Using Genetic Algorithms* by EZCT Architecture & Design Research, 2004. Philippe Morel, "Computational Intelligence: The Grid as a Post-Human Network," *Architectural Design: Collective Intelligence in Design*, vol. 76, no. 5 (September/October 2006): 100–103.

[194] Bernard Cache, "Towards a Non-Standard Mode of Production," *Projectiles* (London: AA Publications, 2011), 61.

5.4.1 Parametric Architecture

The power of parametric modelling was expanded with the introduction of *GenerativeComponents:* a parametric CAD software that led to tool design development in architecture by Smart Geometry Group in 2003. The power of parametric modelling allowed for the proliferation and adaptive differentiation of complex components. The technique was initially developed to adapt, for example, facade panels that could be generalised across complex surfaces. In 2008, Patrik Schumacher coined the style of contemporary *avant-garde* architecture parametricism, from design research programs based on the constraints of parametric design. Parametricism was generated from new scientific paradigms that offered a new conceptual framework and formulated new aims, methods and values.[195] In contrast to Modernism, founded on the concept of Cartesian space, parametricism was based on differentiated fields – that is, fluid mediums, such as liquids in motion, structured by radiating waves, laminal flows, and spiralling eddies. The *Parametric Urbanism* in digital form was announced at the Architectural Association Design Research Lab's first Smart Geometry conference in 2007.

Initial investigations of parametricism in architecture are evident in Zaha Hadid Architects' master planning project *Kartal Master Plan* in Istanbul (2006). As opposed to modernist tectonics, parametric modelling aimed to emphasise conspicuous differentiation and visual

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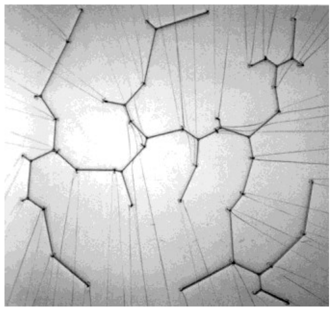
[195] Patrik Schumacher, *Parametricist Manifesto 2008*, accessed October 24, 2019, https://www.patrikschumacher.com/Texts/Parametricism%20as%20Style.htm.

differentiating logics. Aesthetically, it was "the elegance of ordered complexity and the sense of seamless fluidity, akin to natural systems."[196] The project developed geometry for the parametric urban plan by using the Maya software hair dynamic tool that had the properties of Frei Otto's analogue model for minimising a detour network. The minimal system by Frei Otto was a form of open branchings with the shortest connection – as the sum of all partial distances – between a number of points distributed freely in space.[197] A characteristic feature of all minimal way systems is a three-arm node with a constant node angle of 120 degrees that corresponds to the solution of 'Stainer's problem' in mathematics (Figure 5.17). Thus, the resultant diagramming for *Kartal-Pendik* was a hybrid of minimised or optimised detour network and deformed grid with the mutual correlation of multiple urban systems such as urban fabric modulation, towers, streets and open spaces (Figure 5.18). Used initially to address urban planning complexity, parametrics was eventually extended from the city scale to individual buildings in later projects by Zaha Hadid Architects.



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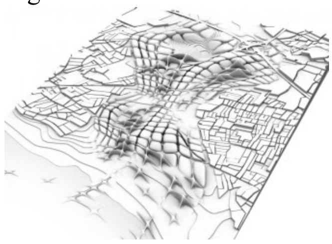

Figure 5.18.

Figure 5.17. Apparatus for computing minimal path systems by Frei Otto, 1988. Patrik Schumacher, "Parametricism", *Architectural Design: Digital Cities*, ed. Neil Leach, vol. 79, no. 4 (July/August 2009): 14–22.

Figure 5.18. *Kartal Master Plan* winning competition proposal by Zaha Hadid Architects, 2006. Zaha Hadid Architects, *Kartal Master Plan*, accessed August 8, 2019, https://www.zaha-hadid.com/masterplans/kartal-pendik-masterplan.

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[196] Patrik Schumacher, "Parametricism: A New Global Style for Architecture and Urban Design," *Architectural Design: Digital Cities*, ed. Neil Leach, vol. 79, no. 4 (July/August 2009): 14.

[197] Frei Otto and Wolfgang Weidlich, *Form, Force, Mass 5: Experiments* (Stuttgart: University of Stuttgart, 1990), 2.44.

5.4.2 Algorithmic Architecture

The emergence of programmatic modelling applications and other design and manufacturing processes post-2001 integrated algorithms for all digital and computational operations as a set of written computer instructions or codes to define and initiate specific design processes. The overall direction of Architectural Association research indicates that the appearance of Non-Standard based software such as *Catia*, *GenerativeComponents*, *Maya, Rhinoceros, Mathematica* and *Processing* moved architectural design into the realm of cellular automata material-based computation, and an agent-based architecture which bridged other disciplines including physics, biology and material science.[198] Architectural Association annual exhibitions in London, specifically of the Design Research Lab, traced the development of Non-Standard Architecture research (Figures 5.19 and 5.20). David Rutten initiated significant changes to the prominent computer graphics and computer-aided design application software *Robert McNeel & Associates Rhinoceros* by David Rutten integrating algorithms in the form of Grasshopper visual programming language in 2007. This algorithmic scripting platform advanced digital geometry to include Non-Standard Architecture logics and direct fabrication simulation for form finding processes as part of the digital design process.

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[198] Tom Verebes, Yusuke Obuchi and Patrik Schumacher, *DRL TEN: A Design Research Compendium* (London: Architectural Association Publications, 2008), 66–264.

Figure 5.19. Melika Aljukic as part of the Design Research Lab (2011–13) assembling end-of-year postgraduate exhibition at the Architectural Association in London, June 2012. Photograph by Valerie Bennett. Architectural Association, *AA Book 2013* (London: Architectural Association, 2013), 206–207.

Figure 5.20. Melika Aljukic, Architectural Association Design Research Lab Exhibition in London, 2013.

Figure 5.21.

Figure 5.21. *ARACHN[OL]OIDS* shell surface model manufactured in polymethyl methacrylate with a rapid prototyping technique. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

Digital protocols based on algorithms in *Rhinoceros* created a major change in the production of parametric architecture. The computer-controlled algorithm tools embedded constructional logic which enabled access to parametric kinematic simulations for automated fabrication beginning as research in academia. In contrast to control over information associated with Modernism, which was repetitive and standardised, encoded algorithmic design allowed an architect to control Non-Standard fabrication interactions between singular material elements and facilitate the direct generation of machining data. Such programming of the design process implied an understanding of architectural geometry and material properties spanning from a digital drawing of geometric elements to the logic of their fabrication and eventual assembly. The exhibition *AA_DRL* with the design research agenda Proto-Design in 2013 showcased the first parametric robot prototype *ARACHN[OL]OIDS,* designed by the research team at the Architectural Association in 2012 (Figure 5.21) that characterised the Second Digital Turn of Non-Standard Architecture.[199]

[199] Melika Aljukic, "Design as Research," *Architecture Bulletin: Life Lessons*, vol. 77, no. 1 (May 2020): 28–29.

5.4.3 Robotic Automation in Architecture

In 2005, research on industrial robots for manufacture in architecture increased in academia. Generic six-axis industrial robots were diversified with the design for customised end-effectors attached at the end of a universal arm to allow a material machining process. The manufacturing process was defined by a digital protocol that controlled simulation of a robot and the properties of its end effector. In 2008, the parametric design process was significantly advanced by integrating algorithmic simulations resulting in more complex iterations of sequential walls. For example, the wall installation for the 11th Architecture Biennale in Venice by ETH took advantage of the automation devised by the algorithm for the geometric and structural relationship of individual elements (Figure 5.22). The project incorporated the parametric design process as the assembly logic based on coding.

Similarly, the fabrication process of the *Sequential Wall* by ETH in 2008 modified the individual wooden battens during the automation process using a high component information level that allowed high-resolution, soft movements and transitions, and the integration of technical aspects such as load transfer, thermal insulation and weatherproofing (Figure 5.23). The information embedded in the design algorithm had the ability to assemble high-performance building elements. Despite the technical performance limitations of being folded into the design engine as a constraint, there were sufficient degrees of freedom to solve complex problems of architectural organisation and articulation.

Figure 5.22.

Figure 5.23.

Figures 5.22. and 5.23. Brick wall installation at Architecture Biennale Venice 2008 and the *Sequential Wall*, ETH Zurich. Tobias Bonwetsch, Fabio Gramazio and Matthias Kohler, "Digital Craft," *GAM: Nonstandard Structures* (Vienna: Springer, 2010), 172–176.

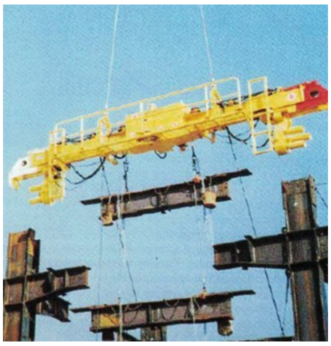

Figure 5.24.

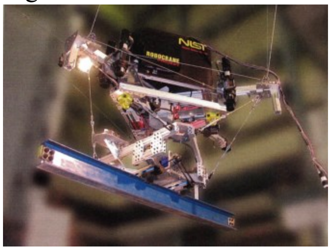

Figure 5.25.

Computational sophistication and tools evolved by integrating engineering logics and physics simulation for form finding and optimisation processes as part of the design process. The development of end-effectors – the tool that defines the material machining process attached to the end of the arm, or that delivers material at the point of construction or assembly – progressed in parallel, starting with drill and brick grips to metal folding and robotic hotwire cutting end-effectors in 2009. This enabled the cutting of foam block material to be used for interlocking between individual elements and as formwork for casting curved concrete shapes. This end-effector development initiated research in automated stereotomy explored by robotic cutting into the styrofoam. For instance, Odico Formwork Robotics began research on the robotic hotwire cutting technique in 2009 and commercialised it in 2012. It is only during the Second Digital Turn of Non-Standard Architecture that robotic fabrication protocol and design were progressively integrated into architectural research and made commercially available to the industry.

Prototypes began as robotic crane end-effectors for site construction in Japan (Figure 5.24). The robotic crane end-effector became more autonomous in its freedom of movement with new prototypes without lifting mechanisms. There was also research on a variety of control mechanisms for automated operation, for example, in the work of developers like the United States National Institute of Standards and Technology (Figure 5.25). The *Flight Assembled Architecture* (2011) by ETH investigated the possibility of a drone to lift small building parts such as bricks into a digitally determined position (Figure 5.26). This quadrocopter prototype had a polystyrene module in the form of a brick, controlled with sensors and algorithm.

Figure 5.24. Mighty Jack by Shimzu Corporation. Thomas Bock and Thomas Linner, *Construction Robots* (New York: Cambridge University Press, 2016), 140.

Figure 5.25. Robot crane by National Institute of Standards and Technology, 2006. Thomas Bock and Thomas Linner, *Construction Robots* (New York: Cambridge University Press, 2016), 142.

Aerial robotic construction aimed for information over oversight across the design and building process and to liberate the need for a bottom-up approach, scaffolding and cranes. There are self-evident limitations, and the current research suggests that flying robots are relatively imprecise when placing a building element for realising full-scale aerial construction.[200]

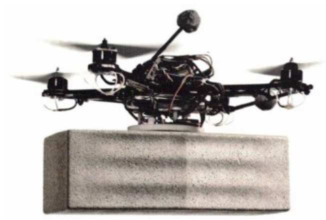

Figure 5.26.

Figure 5.26. Quadrocopter by ETH Zurich, 2011. A quadrocopter placing a polystyrene module. Thomas Bock and Thomas Linner, *Construction Robots* (New York: Cambridge University Press, 2016), 125.

[200] Jan Willmann et al., "Aerial Robotic Construction Towards a New Field of Architectural Research," *International Journal of Architectural Computing*, vol. 10, no. 3 (September 2012): 439–459.

5.5 The Second Digital Turn of Non-Standard Architecture

This thesis contends that a shift occurred around 2012 in Non-Standard architectural design thinking and production, prompted by research in the academy and industry and following the development of parametrics. This led to an investigation of innovative tectonic possibilities no longer based on form finding but on formative processes integrated across architectural design, fabrication and construction. The shift constitutes a 'second turn' of Non-Standard Architecture, whose objectives were to realise parametric tectonic and constructional possibilities using data models and robotics. At the beginning of the Second Turn of Non-Standard Architecture, computation meant the use of the computer to process information with the digital model generated by an algorithm. Computation enabled the development of protocols for complex projects with a variety of parameters that are instrumental in building formation.

A useful precedent is the parametric data model developed for the *Morpheus Hotel* project by Zaha Hadid Architects completed in 2019, which explores Non-Standard parametric forms in the parametric data model. The overall development of the Second Turn of Non-Standard Architecture seems to indicate that algorithmic architecture increased the potential of computation in architectural practice. A protocol that began with an architect using software developed by others as a practical tool became a protocol where an architect assumes the role of software designer as well as designer of the hardware custom tools necessary for the fabrication and construction of architectural projects.

5.5.1 Computation in Architectural Practice

The thesis argues that the nature and structure of architectural practice has to change in response to developments in computational design. The emergence of computer-aided fabrication significantly recasts the entire design and construction process. Apart from the introduction of new tools, in the Second Digital Turn it required breakup of traditional role models as a potential for innovation. The implementation of digital design in practice involved the development of specific tools for geometric investigation development and for data exchange between different disciplines. Specific solutions had to be adapted to meet each project's requirements. In the Second Digital Turn, Brady Peters categorised the role of computational designers in professional practice in four ways: the internal specialist group, the external specialist consultancy, the computationally aware within an integrated practice, and the lone software developer/designer.[201] Architectural computation was increasingly used to simulate building performance, including performance analysis and information about material, tectonics and parameters of production machinery. The further integration of engineering and fabrication logics with novel software development like *Kangaroo, Karamba, Millipede* and *Rhino-vault* represented an additional stage in the evolution of the Second Digital Turn.

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[201] Brady Peters, "Computation Works: The Building of Algorithmic Thought," *Architectural Design: Computation Works The Building of Algorithmic Thought*, eds. Brady Peters and Xavier de Kestalier, vol. 83, no. 2 (March/April 2013): 8–15.

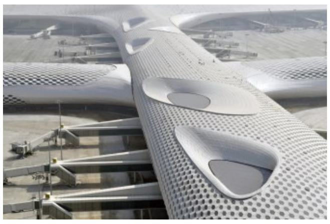

Figure 5.27.

Figure 5.28.

Figure 5.27. *Bao'an International Airport* in Shenzen, 2012. Fuksas Architects, "Shenzen Bao'an International Airport," *Studio Fuksas*, accessed October 5, 2019, http://fuksas.com.

Figure 5.28. *Bao'an International Airport* in Shenzen, 2012. Fuksas Architects, "Shenzen International Airport Under Construction," *Designboom,* accessed October 5, 2019, https://www.designboom.com/architecture/massimiliano-doriana-fuksas-shenzhen-international-airport-under-construction/.

A parametric data model is a new form of communication and collaboration between architects and engineers. For structural engineer Jan Knippers, the introduction of computational design processes, and particularly computer-aided fabrication methods, recast roles across the design and structural engineering teams and provided the potential to "break through the barriers of the conventional model (thinking in discrete typologies) and to embrace process design and new forms of interaction."[202] Knippers highlights the impact of computational design strategies on the development of load-bearing structures in three areas: advanced computational mechanics that enable simulation of controlled buckling and large elastic deformations in contrast to any traditional engineering design goals; meshing tools and the precise transfer and control of data; and generation of the parametric data model as a new form of communication and collaboration between architects and engineers. Knippers considers that the *Bao'an International Airport* (2013) redefined the role of structural engineers. The complex cladding geometry required a parametric data model organised in layers: two for the neutral axis of the double-layered grid structure, and one each for the inner and outer surface (Figure 5.27). The parametric model was generated in Rhinoceros and Microsoft Excel software (Figure 5.28). The design process allowed for continuous adjustment of form and tessellation. The final linear sequence of panels was selected from the generation of fifty different models. The project's

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[202] Jan Knippers, "From Model Thinking to Process Design," *Architectural Design: Computation Works The Building of Algorithmic Thought*, eds. Brady Peters and Xavier de Kestalier, vol. 83, no. 2 (March/April 2013): 81.

pioneering parametric data model represented a new method of communication and collaboration between architects and engineers.

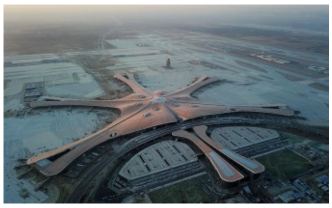
Figure 5.29.

5.5.2 Architectural Precedents of the Second Digital Turn

This thesis identifies the complexity of a novel freeform high-rise exoskeleton for the *Morpheus Hotel* by Zaha Hadid Architects (2012), which generated an innovative tower typology, as instrumental in triggering the Second Digital Turn of Non-Standard Architecture. The specific method for design and documentation of the project implemented was a parametric data model, a new form of a collaborative digital platform between architects and engineers, that included the design and development of new tools necessary to realise such typological innovation.

The concept for the recently completed *Beijing Airport* (2019) integrates the same parametric data model for the form of a phoenix to minimise distances between check-ins and gates (Figure 5.29). The roof of the terminal building was built as a large-span, complex hyperboloid steel grid structure covering over 350,000 m^2. The structural columns were covered by a convex 100-metre diameter skylight to funnel natural light into different areas of the terminal.[203] The project implies the stylistic heightening of fabrication based on form finding and an optimisation process. Arup engineers developed custom

Figure 5.29. *Beijing International Airport* by Zaha Hadid Architects, 2019. Alex Klimoski, "Beijing Daxing International Airport," *Architectural Record* (June 2019), accessed October 5, 2019, https://www.architecturalrecord.com/articles/14154-beijing-daxing-international-airport-by-zaha-hadid-architects.

[203] Alex Klimoski, "Beijing Daxing International Airport," *Architectural Record* (June 2019), accessed October 5, 2019, https://www.architecturalrecord.com/articles/14154-beijing-daxing-international-airport-by-zaha-hadid-architects.

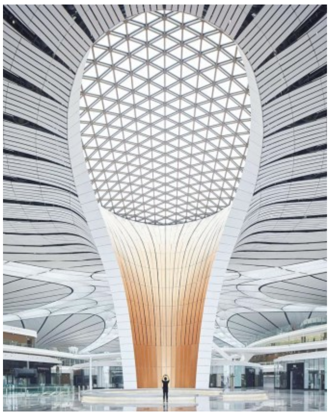

Figure 5.30.

Figure 5.30 *Beijing International Airport* by Zaha Hadid Architects, 2019. "Beijing Daxing International Airport," Zaha Hadid Architects, accessed October 5, 2019, https://www.zaha-hadid.com/architecture/beijing-new-airport-terminal-building/.

software to analyse the structural configuration, loading and vertical support system reactions as well as structural deflection and displacement. The proposed structural strategies for the different zones of the terminal improved the roof truss patterns and reduced unnecessary structural depth and member sizing (Figures 5.30). The optimisation strategy by Arup also reduced steel tonnage, saving significant costs and reducing carbon emissions.

Promoting these advances in computational analytics and optimised techniques at Zaha Hadid Architects, Patrik Schumacher 're-launched' parametricism as parametricism 2.0 in 2016. The new style aimed to promote firstly, "the emphasis on research-based best-practice expertise that can deliver large, important buildings"; and secondly, a "new focus on social functionality."[204] Parametricism 2.0 integrated recent advances in structural and environmental engineering based on computational analytics and optimised techniques. It aimed to address the challenges posed to architecture by the new social dynamics of the information age through recent advances in structural and environmental engineering based on computational analytics and optimisation techniques.

[204] Patrik Schumacher, "Parametricism 2.0," *Architectural Design: Parametricism 2.0*, vol. 86, no. 2 (March/April 2016): 9.

5.5.3 Automation of the Second Digital Turn of Non-Standard Architecture

In academia, research extended into the architectural custom robotic design to achieve parametric geometry with algorithmic architecture. The thesis identifies the Second Digital Turn of Non-Standard Architecture beginning in 2012, characterised by the first Non-Standard architectural automated robot and parametric data model. Robotic fabrication emerged based on six-axis industrial robots such as Odico Formwork Robotics, RoboFold, Machineous, ROB Technologies, Greyshed and XtreeE. Beginning in 2012 Odico Formwork Robotics specialised in formwork production and research development technology. Their initial target was to manufacture polystyrene moulds by hot wire cutting which opened an opportunity for concrete formwork and stereotomy. Adaptation of stereotomy for automation with the six-axis industrial robot was engineered and built as a custom diamond wire saw in 2003 by Jelle Feringa and Frank van Brunschot with the support of the industry partner Husqvarna. Robotic stonecutting research at the marble quarry of Carrara identified that while stonecutting was a mechanical and time-intensive process, the effectiveness of abrasive diamond wire cutting was easily proportionate to the speed-up achieved by robot hot-wire cutting (Figure 5.31).[205] With the advent of customised end-effectors, robotic research in architecture also developed


Figure 5.31.

Figure 5.31. Diamond wire saw set-up, Italy, 2014. Jelle Feringa and Asbjorn Sondergaaed, "Fabricating Architectural Volume: Stereotomic Investigations," eds. Fabio Gramazio, Matthias Kohler and Silke Langenberg, *Fabricate* (Zurich: Gta Verlag, 2014), 76.

[205] Jelle Feringa and Asbjorn Sondergaaed, "Fabricating Architectural Volume: Stereotomic Investigations," eds. Fabio Gramazio, Matthias Kohler and Silke Langenberg, *Fabricate: Negotiating Design and Making* (Zurich: Gta Verlag, 2014), 76.

into 3D printing in thermoplastic polymers (2013), ceramic (2013) and concrete (2015).

Figure 5.32.

Figure 5.33.

The Non-Standard architectural automated robot *ARACHN[OL]OIDS* was designed as part of a postgraduate research project in 2013 at the Architectural Association. The prototype introduced a new seven-axis robot based on a 7R-Bricard Linkage robotic apparatus with revolute joints that define the shell as a three-dimensional ruled surface of third order (Figure 5.32). The prototype integrates kinematics embedded in the kaleidocycle geometry and proposes other variations of shell surface geometry with computational and fabrication methods integrating different degrees of freedom. The overall direction of robotic fabrication at the Architectural Association in London contributed to the design and development of custom end-effectors which enabled novel possibilities and conception of architecture. The symbolic language for robotic apparatuses was defined by Bricard Linkage of kaleidocycle geometry of *ARACHN[OL]OIDS*. Spatial analysis of the kaleidocycle geometry was used as a strategy for parameterisation of the form (Figure 5.33). *ARACHN[OL]OIDS* addressed the gap between computational technology and the existing techniques of production for automated shell geometry.

Figures 5.32 and 5.33. First Non-Standard architectural robot *ARACHN[OL]OIDS*. Melika Aljukic, et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

Another automated robotic prototype distinguished by this thesis as part of the Second Digital Turn is a method of manufacturing graded concrete components developed in 2015 by researchers at the Institute for Lightweight Structures and Conceptual Design in Stuttgart building on earlier work by Frei Otto (1963) and Werner Sobek (2006) at the Institute for Lightweight Structures and Conceptual Design. Grading concrete involves the alignment of the internal composition of structural components with a specific structural and thermal performance by continuously altering the characteristics of the material, including its porosity, strength or rigidity, in three spatial dimensions.[206] This process of material optimisation is achieved using a robotic spraying technique. An automated application system allows precise management and change of different variables in the spraying process (Figure 5.34). The spraying nozzle guidance is managed through an SLE (Steel-Linear-Unit) heavy-duty multi-axis portal made by the linear technology specialists Winkel. This allows the nozzle to move three-dimensionally in the XYZ direction. The concrete spraying process can be managed in fine detail to obtain optimal structural results by varying porosity, strength or rigidity, in three spatial dimensions. The process has enormous potential as a sustainable method by reducing material and cost. The thesis contributes towards functionally graded concrete and ultra-high performance concrete by extending the method from linear to nonlinear, Non-Standard graded concrete components.

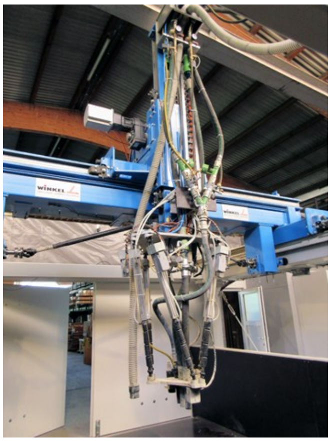

Figure 5.34.

Figure 5.34. Concrete spraying robot at the University of Stuttgart, 2016. Photography by Melika Aljukic.

[206] Michael Herrmann and Werner Sobek, "Functionally Graded Concrete – Numerical Design Methods and Experimental Tests of Mass-Optimised Structural Components," *Structural Concrete* (Berlin: Ernst & Sohn, 2016), 54.

5.6 Conclusion: The Limits of the Second Digital Turn

Although the protocol for the design and documentation of Second Digital Turn projects including *Morpheus* and *Beijing Airport* consisted of digitally advanced and integrated parametric data models, the fabrication of components required a high level of skilled manual work. This thesis argues that fabrication in practice remains constrained by a range of theoretical and technical limits that can be traced back to the persistence of Euclidean spatial theory and the influence of that theory on current, standard means of manufacture, assembly and construction. The thesis identifies this challenge as a limit of the Second Digital Turn, which has so far constrained its capacity to fully implement robotic automation for construction. The thesis suggests that this limit can be overcome by addressing the *Statutes of Non-Standard Architecture* that constrains the implementation of Non-Standard.

The Third Digital Turn coined by this thesis integrates specific means to codify architecture and for construction like functionally graded concrete and Non-Standard architectural automation that have the potential to eclipse the limit of the Second Digital Turn. They can achieve automated construction by recalibrating architecture at the limit of the technical system in the parametric digital model combined with simulation protocols for functional gradation of concrete and custom robot prototypes that integrate automation in construction. The development of architecture follows an evolutionary process based on historical advances in technological systems, regulations and their aesthetic consequences.

CHAPTER 6

Architectural Automation and Case Studies

We must find the machines to make our components and devise some means to put these elements together only limited to the size and weight of our mechanical age to erect them. The architect therefore has researched into the maximum capabilities of factory production and having found the scope of minimum and maximum capacity of the machine, he works within this discipline.[207]

6.1 Introduction: Emergence of Architecture as an Evolutionary Process

A pivotal means of eclipsing the limits that have obstructed the full realisation of Non-Standard Architecture is in the automation capacity of the built environment profession and industry. This suggestion is investigated through a series of case studies. Section 6.1 reviews transformations in fabrication tracing the idea and motif of the tool through the disciplines of archaeology and anthropology to identify the emergence of architecture as an evolutionary process determined by technology. Section 6.2 then argues for the implementation of automation into architectural practice tools. Section 6.3 provides a case study on the recently completed architectural project *Morpheus Hotel* by Zaha Hadid Architects to demonstrate the limit of the tool in architectural practice. Section 6.4 provides a case study on automated architecture of the first

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[207] Jørn Utzon, *Sydney Opera House, Descriptive Narrative*, unpublished manuscript compiled by M. L. Challenger, Sydney Opera House Trust Records at State Archives (January 1965).

Non-Standard architectural robot prototype *ARACHN[OL]OIDS,* which I developed at the Architectural Association in London as a team project. Section 6.5 provides a case study on Non-Standard automated construction using functionally graded concrete.

This thesis relates the evolution of architectural topology to the evolution of the human body and the use of tools. Biological anthropologists Tim Ingold and Kathleen Gibson investigate interrelated phenomena in the evolution of tool making and language. Gibson reconstructs the evolution of language and social behaviour based on the ability of humans to infer higher-order cognitive capacities, evidenced by hominoid tool-use and other artefactual remains.[208] Tool use and manufacture entail both technique and technology. Techniques consist of a set of specific inherent sensorimotor skills and action sequences. Technology is the codified body of accumulated knowledge integrating mathematical and scientific principles as well as information about geographical, biotic, physical and social environments in which tools are made and used. Current research in the anthropology of human evolution argues that social behaviour directly influences technique.[209] This form of development of tool techniques in humans is mostly accomplished by social imitation. Recent anthropology argues that cultural knowledge is constituted rather than imported into the settings of practical activity, and developed through specific dispositions and sensibilities

[208] Kathleen Gibson, "Tools, Language and Intelligence: Evolutionary Implications," *Man*, vol. 26, no. 2 (Jun 1991): 255.

[209] Kathleen Gibson and Tim Ingold eds., *Tools, Language and Cognition in Human Evolution* (Cambridge: Cambridge University Press, 1993), 3.

that lead people to orientate themselves in relation to their environment.[210] Consequently, tool making has enabled major changes in human knowledge and thought, for example, by providing means to keep permanent records. In the Second Digital Turn in architecture, parametric digital capacity increased the body of knowledge within which professionals operate. The approach redefined architectural codification with a Non-Standard optimised ecological approach, enabling new architectural typologies.

In 1964, French paleoanthropologist André Leroi-Gourhan extended the definition of the human by considering diverse externalisations of mind and body in different forms of technical behaviour, such as species-related, socio-ethnic and individual.[211] He found there was a continuous reinvention of the human emerging as a result of advances in technics, that in turn overcame the absence of anatomical specialisation. The development of technical apparatuses represents a differentiated variety of liberations for the human species and is evidenced throughout the history of evolution, for example, in the freeing of the hand from the requirements of locomotion for the use of tools or that of the brain from the facial mask.

Leroi-Gourhan's book *Gesture and Speech* (1965) provided a scientific foundation for Jacques Derrida's *Of Grammatology* (1967). In Derrida's analysis, human evolution of the hand distinguished the human from the ape,

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[210] Tim Ingold, *The Perception of the Environment* (London: Routledge, 2000), 153.

[211] André Leroi-Gourhan, *Gesture and Speech*, trans. Anna Berger (Cambridge: MIT Press, 1993), 227.

by formulating an enormous articulation.[212] Derrida related the concept of *différance* to the evolutionary trace, that is, humans were open for evolution when the subsequent interpretations retroactively transformed understanding of its earlier instances. In *Technics and Time 1* (1994), Bernard Stiegler differentiated Derridean *différance* into two regimes of evolutionary development concerning natural and artificial selection. Natural selection is a finite human memory, which requires the backing of artificial memory such as the alphabet, and analogue and digital recording. This concept was initially theorised by Plato – with the notion that artificial memory is a *pharmakon*, characterising the differing function and value of memory across history. The method of natural selection stimulates the mutation of organs, like the brain or the hand. For Leroi-Gourhan, this mutation was a matter of 'liberation,' and for Stiegler, a matter of 'reinvention' through technics.

The reinvention of the human enabled by the tool included a transformation in the experiential sphere, affording new possibilities of the subject through new processes of creating its objects. Hence, the *différance* of artificial selection can be defined as a continuous reinterpretation of the subject and the tool. Stiegler further relates the effects of the tool on prosthetics – specifically in relation to the human brain that is "perpetually undergoing functional redefinition."[213] The thesis relates the notion to Poincaré's theory in *Science and Hypothesis* (1902) that geometrical transformations are possible because of the

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[212] Jacques Derrida, "Geschlecht II," *Deconstruction and Philosophy*, ed. John Sallis (Chicago: University of Chicago Press, 1987), 169.

[213] Bernard Stiegler, *Symbolic Misery, Volume 2: The Catastrophe of the Sensible,* trans. Barnaby Norman (Cambridge: Polity, 2015), 141.

ability of the solid body to assess the relative position and enact the “correlative movement.”[214] On that basis, this thesis adopts Stiegler’s notion that the evolution of technics, currently enabling automated Non-Standard Architecture design and production, will consequentially affect and transform the complex economic and political contexts of architecture and society of the architect and the citizen.

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[214] Henri Poincaré, *Science and Hypothesis* (New York: Dover Publications, 1952), 61–62.

6.2 Transformations of Technics in Architecture

Figure 6.1.

Adapting Leroi-Gourhan and Stiegler's arguments to the domain of architecture, the thesis contends that the emergence of human beings within an evolutionary process is determined by technology – specifically the technologies of computation, the digital, automated fabrication and robotics. Accordingly, the development of architecture can be seen to follow an evolutionary process based on historical advances in technological systems, regulations and their aesthetic consequences. In the Second Digital Turn of Non-Standard Architecture, formal programs are calibrated to novel geometries and automated design operations that owe much to technological advances, such as parametric data models and the potential of computational and robotic fabrication. On the other hand, robotic fabrication remains constrained by technical limits that can be traced back to Euclidean, standard bases of spatial conception and subsequent manufacture.

This thesis identifies a further limit in the Second Digital Turn, brought by a persistent challenge from the regulatory environment and conventional construction practices in the industry, which prevents the implementation of robotic automation for construction. In turn, there is a gap in automated production techniques and materials for the design and manufacture of Non-Standard architectural elements. The thesis identifies a gap between the figurative, architectural design driven by digital technologies and formal possibilities offered by the current capacities of the building industry that still require a highly skilled manual work to realise them. These epochal changes represent paradigm shifts related to critical aspects of modern science and its discourses, including the guiding

Figure 6.1. Hand axe 20.5 cm long in flint from 500,000 BCE in France. Nathalie Prata-Couadau ed., "From Technology to Symbols," *Louvre Abu Dhabi: Masterpieces of the Collection* (Abu Dhabi: Skira, 2017), 14.

importance of techniques, that emerged in architecture in the form of projective geometry and stereotomy associated with the late Renaissance, rationalisation and standardisation in modernity and, more recently, as mass customisation with the development of the digital model.

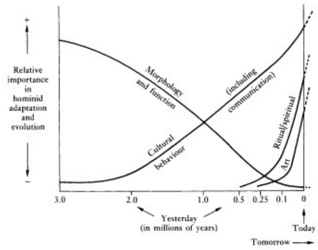

Figure 6.2.

6.2.1 Technology and Anthropology

The tool making that began around 1.7 million years ago to butcher animal carcasses (Figure 6.1) evolved with human cognition into automation based on algorithmic embodied knowledge, a characteristic of the skilled practitioner in architecture. Tim Ingold argues that object development considered the worlds of living beings and inert materials as being in mutually informative relationships, and in terms of evolving processes rather than as outcomes of predetermined design intentions. Similarly, for Michel Serres, the emergence of objects characterises the human species and objects are assignable to human relationships and the materiality of everyday life.[215] Analysis of artefacts of ancient hominoid populations by paleoanthropologists suggests that while morphological and functional factors were predominant determinants of survival 3 million years ago, cultural mechanisms of adaptation became progressively more significant from 2.5 to 2.0 million years ago (Figure 6.2). This behaviour is biologically grounded, with sophisticated cultural conduct predicated upon structural and functional patterns of the central nervous system, and depends on peripheral

Figure 6.2. Relative importance at various times during the evolutionary adaptation of the hominids. Tim Ingold ed., *Companion Encyclopedia of Anthropology* (London: Routledge, 1994), 68.

[215] Michel Serres, *Genesis*, eds. Genevieve James and James Nielson (Ann Arbor: The University of Michigan Press, 1995), 87.

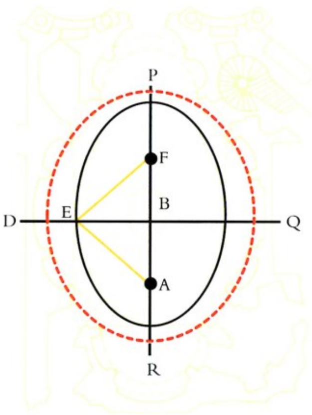

Figure 6.3.

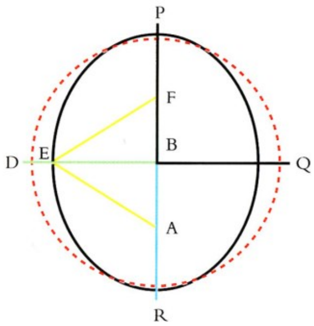

Figure 6.4.

Figures 6.3. and 6.4. *Above.* Borromini's San Carlino oval as an ellipse in black. *Below.* Kepler's diagram of planetary orbit in black. George Hersey, *Architecture and Geometry in the Age of the Baroque* (Chicago: University of Chicago Press, 2000), 141.

instruments of the hands and the vocal tract.[216] These patterns and instruments were transmitted genetically and through social life. This indicates that behavioural traits, including material culture and articulate speech, became important for adaptation and survival, while anatomical and physiological adjustments played an ever-diminishing role.

Ingold identifies a locus of growth within a field of relations traced out in a flow of materials rather than the organism, human or a discrete, bounded entity, set against an environment.[217] Thus, the process demonstrates that digital architecture has the potential for an evolutionary scheme. As a result, Ingold points to making as a topological process of growth defined by connections between elements, as opposed to the hylomorphic model of making as a project that is a discrete and pre-formed entity. Nonetheless, Ingold regards longitudinal making as a confluence of forces and materials as form generating or a morphogenetic process.[218] Evident development of architecture as an evolutionary process of human thought was considered as a translation of Johannes Kepler's diagram of a planet's elliptical orbit (Figure 6.3) into Francesco Borromini's *San Carlino* Baroque architecture's oval geometry (Figure 6.4)[219] in which certain social relations and activities developed and became normative.

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[216] Tim Ingold ed., *Companion Encyclopedia of Anthropology* (London: Routledge, 1994), 67.

[217] Tim Ingold, "Prospect," *Biosocial Becomings: Integrating Social and Biological Anthropology*, eds. Tim Ingold and Gisli Palsson (Cambridge: Cambridge University Press, 2013), 10.

[218] Tim Ingold, *Making: Anthropology, Archaeology, Art and Architecture* (New York: Routledge, 2013), 22.

[219] George Hersey, *Architecture and Geometry in the Age of the Baroque* (Chicago: University of Chicago Press, 2000), 141.

6.2.2 The Role of Technics in Human Intelligence

André Leroi-Gourhan observes the organic link between technology, language and the human body, arguing that the prehistory of human intelligence and consciousness is intricately connected to the conquest of tools, language and aesthetics. His original contribution to the field of aesthetics is an analysis of the role of ethnicity and ethnic identity through rhythms, forms and values, rather than limiting it to artistic production. Leroi-Gourhan claims the aesthetics originated in biological properties common to all living organisms with the highest sense of achievement in the extension of biology into technical objects that condition body rhythms and establish norms for the distribution of bodies within a society.[220] This hypothesis rests on the morphological changes in the human body following a transition to bipedalism, which freed the hands for grasping, and the face for gesturing and speaking.

In 1917, D'Arcy Thompson was one of the first to look coherently at such similarities in a form. A diagram with the Cartesian coordinates of an ape transformed into curvilinear and non-equidistant coordinates in a man indicate similar deformation with increased intensity or degree of deformation (Figure 6.5). Thompson notes these transformations of anthropoid skulls by continuous transformation are admirable examples of 'topological similitude.' Gerhard Heilmann argues this series of such successive and continuous gradations is not obtained in a transitional series between the human skull and some pre-

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[220] André Leroi-Gourhan, *Gesture and Speech*, trans. Anna Berger (Cambridge: MIT Press, 1993), 281–311.

human, anthropoid type. It merely indicates that no one straight line of descent, or of consecutive transformation, exists. On the contrary, human and anthropoid types, recent and existing, are part of a complex problem of divergent, rather than continuous, variation.[221]

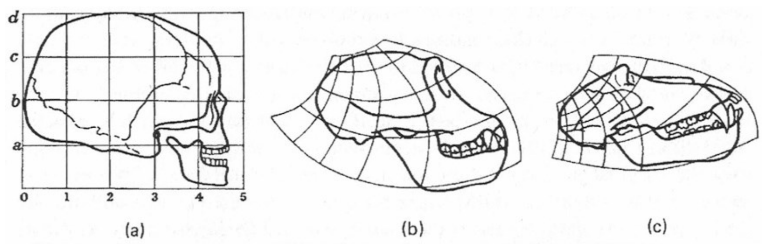

Figure 6.5. Diagram by D'Arcy Thompson showing the transformation of (a) a human skull to that of (b) a chimpanzee and (c) a baboon by a simple projection involving the continuous transformation of Cartesian coordinates. D'Arcy W. Thompson, *On Growth and Form* (Cambridge: Cambridge University Press, 1961), 320–21.

With the new information on human ancestry, Hutchinson points out and illustrates that it is now possible to trace a sequence of early man by coordinate transformation (Figure 6.6).

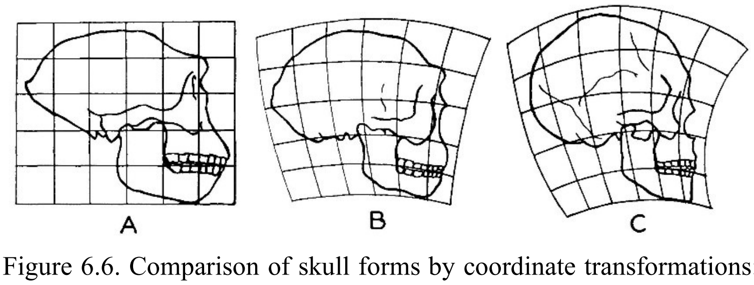

Figure 6.6. Comparison of skull forms by coordinate transformations: (A) *Pithecanthropus robustus;* (B) *P. pekinensis*; (C) *Homo sapiens*. Evelyn G. Hutchinson, "Marginalia," *American Scientist*, vol. 36, no. 4 (October 1948): 600.

[221] D'Arcy Thompson, *On Growth and Form* (Cambridge: Cambridge University Press, 1961), 320–21.

In every case of these fossil forms, the structure has been harmoniously changed as a whole, but no dynamic explanation of the process can yet be given. Nevertheless, it is clear that the method of coordinate transformation, along with the whole Cartesian system, has its origin in the proportionate diagrams of the artists of the Renaissance, which in turn have a respectable lineage in the work of Greek architects.

Leroi-Gourhan claims the technical progress in early humans is driven by natural phenomena, biological extension or externalisation of the human body movement, whereas the creative capacities of *Homo sapiens* are evidence of increased autonomy of the mind in relation to the material. Correspondingly, characteristics associated with the human include the development of upright posture due to the need to free the hands for technical activity, correlated with a flattening of the face, recession of the teeth, expansion of the cerebral cortex and a decoupling of the hand from its locomotive function. The thesis suggests that one of the limits of the Non-Standard lies in the adoption, in current computation, automation and robotics, of an antiquated figure of human technical being, of the hand in particular, which was carried into digital tools by default. This is evident in the six-axis industrial robot arm. Thus, rethinking the geometry of automation expands the capacity of Non-Standard architectural automation.

The relay between the human brain and technosphere mediated through the hand resulted from the coupling of the cortex and the hand because of the close interaction between hand and face in coordinated tasks such as tool making. The application of the hand for tool making determined the complexity of the neurological and anatomical apparatus that laid the foundations of the mental

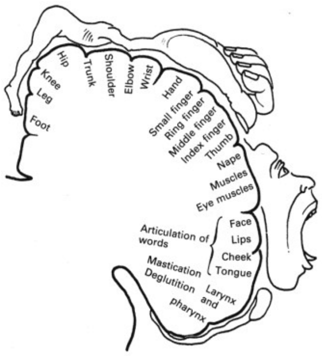

Figure 6.7.

Figure 6.7. Reduction of the foot and the tremendous importance of the hand and the organs of speech in the human. André Leroi-Gourhan, *Gesture and Speech*, trans. Anna Berger (Cambridge: MIT Press, 1993), 82.

architecture on which human language was built.[222] Leroi-Gourhan's analysis emphasised that the control of body parts in modern humans is not distributed equally across the pre-motor cortex but is attributed approximately 80% to the head and the upper part of the body, with at least 50% of motor coordination devoted to the hands and the organs of speech articulation.[223] This differential distribution of neurological control within the topography of the brain is illustrated with a diagram in which the human body is drawn to scale relative to the amount of neural activity dedicated to each part (Figure 6.7). Leroi-Gourhan's analysis shows the human mind as an open system resulting from the co-determination of the biological and technological where the language is a product of the zoological evolution of forms.

The externalisation of hand function through control systems of the advanced computing for Leroi-Gourhan has already destroyed the link between language and the aesthetic image of reality and ultimately threatens to affect the future revolution of the human body and its nervous system. Earlier, Heidegger considered the emergence and privileging of writing as responsible for a parallel devaluation of the spoken word. Similarly, Derrida writes of Heidegger's indictment of typewriters as machines that degrade the word, responsible for the increasing alienation of the hand.[224] In turn, automation is criticised as a

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[222] Christopher Johnson, "Derrida and Technology," *Derrida's Legacies*, eds. Simon Glendinning and Robert Eaglestone (London: Routledge, 2008), 58.

[223] André Leroi-Gourhan, *Gesture and Speech*, trans. Anna Berger (Cambridge: MIT Press, 1993), 84.

[224] Jacques Derrida, "Geschlecht II," *Deconstruction and Philosophy*, ed. John Sallis (Chicago: University of Chicago Press, 1987), 171, 179.

regression of the human, bringing humans closer to the animal by virtue of a consequent impoverishment in the world. Heidegger defined this distinction for the material objects as wordless, the animal as poor in the world and man as world-forming.[225] Within this framework of thinking, Derrida articulates an idea of the 'monstrosity' of the hand – its de-monstrating capacity – which constitutes the difference between human and animal (Figure 6.8). Derrida relates this determining role of technology in the emergence of the prehistory of human intelligence to the cybernetic component by referencing Norbert Wiener. In *Of Grammatology*, Derrida attributes the possibility of deconstruction, that is, logocentrism, to a certain state of the scientific-technological apparatus.[226]

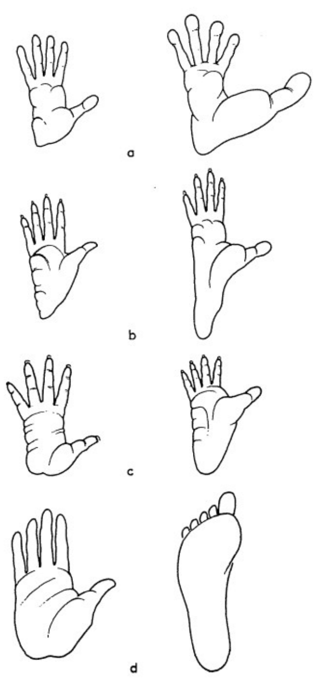

Figure 6.8.

In *Technics and Time 1*, Stiegler adopts Derrida's deconstructive method to analyse the impact of technics on the existence of human beings.[227] In his analysis, Stiegler re-articulates Derridean *différance* from the double meaning of deferral and differentiation. Stiegler employs these concepts within a reading of the Heideggerian temporality in the historical invention of the human and technical as opposed to transcendental phenomenology, which conditions Derrida's notion of *différance*. Stiegler argues that the emergence of human beings as an evolutionary process is determined by technology, starting

Figure 6.8. Hands and feet of primates: (a) lemur, (b) guenon monkey, (c) chimpanzee, (d) human. André Leroi-Gourhan, *Gesture and Speech*, trans. Anna Berger (Cambridge: MIT Press, 1993), 62.

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[225] Martin Heidegger, *The Fundamental Concepts of Metaphysics*, trans. William McNeill and Nicholas Walker (Bloomington: Indiana University Press, 1995), 177.

[226] Christopher Johnson, "Derrida and Technology," *Derrida's Legacies*, eds. Simon Glendinning and Robert Eaglestone (London: Routledge, 2008), 55.

[227] Bernard Stiegler, *Technics and Time 1: The Fault of Epimetheus*, trans. Stephen Barker (Stanford: Stanford University Press, 1994), 134.

with the first stonecutting tool users, *Zinjanthropus*. Therefore, becoming technical is a diversion in evolutionary development that is also an invention and an innovation. These include novel methods of form finding, material selection and construction methods identified by this thesis that extended the limits of the Non-Standard based on technological development, specifically, Non-Standard architectural digital modelling and automation, in the Second Digital Turn. The Third Digital Turn of Non-Standard Architecture proposed by the thesis is a fully automated digital process as the *Statutes of Non-Standard Architecture*.

6.2.3 The Limit of a Technical System

The limit of a technical system is identified in disruption by humanity that opens a space for the difference between invention and innovation through positing of directions and adjustment; notably, as a result of resistance encountered in the adjustment between technological evolution and social tradition. Stiegler's interrogation of technics led him to identify the structural limits within technical systems "either in the problem of increasing quantities, or in the impossibility of reducing production costs, or in yet another impossibility, that of diversifying production."[228] Stiegler defined the limits of technical systems in terms of a process of human disorientation within cultural development: that is, within the technical system itself, as well as in its mode of operation. As

[228] Bernard Stiegler, *Technics and Time 1: The Fault of Epimetheus*, trans. Stephen Barker (Stanford: Stanford University Press, 1994), 32.

disorientation is constitutive of a certain limit in the technological, it creates similar limits in Non-Standard Architecture to the extent that it is also situated within the technological and deploys technical means. Primarily, the thesis identifies that disorientation has affected the speed of technological development since the Industrial Revolution, which has widened the distance in its acceleration between technical systems and social organisations and made negotiation between them impossible, thus resulting in their final separation.

6.2.4 Industrialisation of Memory

In terms of the key question of this thesis, overcoming the limit of Non-Standard architectural design with codification, Stiegler's analyses are instructive, for example in terms of industrialisation of memory brought by technological development by external records accessible through different forms of objective memory such as the cinematogram, photogram, phonogram, writing, digital models and monuments.[229] In *Technics and Time 3,* Stiegler furthered his investigation of technological systems by investigating the relationship between consciousness and new industrial temporal objects such as digital technologies. On this basis, the human being constitutes cultural knowledge, and the industrialisation of memory is rendered possible. Similarly, Derrida identifies consciousness through the industrialisation of collective memory in the form of orthographic writing of history.

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[229] Bernard Stiegler, *Technics and Time 3: The Fault of Epimetheus*, trans. Stephen Barker (Stanford: Stanford University Press, 2001), 28.

With the advent of printing, successive generations have transformed architectural tools geared to the orientation of knowledge. The book, the photograph, voice recording and video are tools responding to a manual machine. Admittedly, the Second Digital Turn opened an opportunity for the digitised collective design distribution system of an architectural project which changed an architectural practice. While the digital platform enabled collaborative real-time access to the data, authorship became anonymous and vested under the nominated architect of the company.

However, the fabrication of Non-Standard architectural projects has yet to adapt to the parametric digital platform and modelling of the Second Digital Turn. Such projects continue to be largely hand-built using conventional methods of construction. Where automation and robotics are incorporated, fabrication is still constrained by the orthogonal, Cartesian axiality of the three-dimensional movement which conditions robotic apparatuses currently being developed according to the number of axes controlling movement such as a six-axis industrial robot. The gap identified by this thesis with the orthogonal codification of architectural automation capacities of the building industry was addressed with the Third Digital Turn of Non-Standard Architecture.

6.3 Architectural Practice Tools

In the late twentieth century, new spatial and formal capacities in architecture emerged, generated by digitally-based technologies and techniques such as form finding that contributed to new tectonics of curvilinearity and dynamism. This digital tectonic marked a paradigm shift within architectural culture, facilitated by a renewed interest in the structural logic of building and in part by the technological possibilities offered by the digital realm. Throughout the history of architecture, structural engineering and architectural design contributed to the evolution of tectonics characteristic of different historical epochs. Kenneth Frampton identified tectonics attributes of buildings resulting from developments in the structural logic of architectural form.[230] Instead of mere visual fabrication, Frampton established tectonic deriving from properties of materials, structural conditions and the craft of making. Similarly, Patrik Schumacher differentiates between architecture and engineering through their autopoietic systems of communication and distinct domains of competency emerging over the last 200 years. The two disciplines are defined by unique responsibilities, concepts, methods, values and criteria of success. While computational analytics and optimised techniques introduced recent advances in architecture, this thesis suggests that a limit persists in the conceptualisation, the standard bases and the systems of manufacture that prevent a full realisation of Non-Standard tectonics.

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[230] Kenneth Frampton, *Studies in Tectonic Culture* (Cambridge: MIT Press, 1995), 2.

6.3.1 Early Computation of Non-Standard Architecture

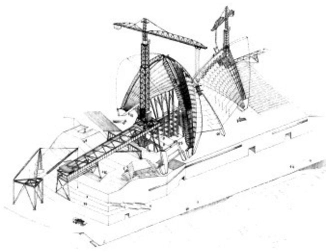

Figure 6.9.

Figure 6.10.

The first computational power to realise a Non-Standard building of significant scale was used for the *Sydney Opera House* (Sydney, 1959). It was a codification of architectural design by Jørn Utzon for a spherical form with distributed loads and forces. The shell geometry for the *Sydney Opera House* was formulated as an equation by analyst and mathematician Roland Jenkins and computer programmers. Structural engineers Ove Arup and Jack Zunz claimed that the shells could not have been built without using computers due to the amount of information and analytical work required to construct the complex building (Figure 6.9).[231] The first British digital computer, Pegasus, was used by Arup engineers to generate data for the computer model from drawings, and its sequence for the computer program on datasheets (Figure 6.10). This process took 12 to 14 hours to complete compared to a modern personal computer which takes less than a minute for the same task.

Figure 6.9. Sequence of the erection of the *Sydney Opera House* shells by Arup. Anne Watson ed., *Building a Masterpiece: The Sydney Opera House* (Sydney: Powerhouse Publishing, 2013), 113.

Figure 6.10. *Ferranti Pegasus Mark 1* computer, 1957. Anne Watson ed., *Building a Masterpiece: The Sydney Opera House* (Sydney: Powerhouse Publishing, 2013), 87.

[231] David Taffs, "Computers and the Opera House: Pioneering a New Technology," *Building a Masterpiece: The Sydney Opera House*, ed. Anne Watson (Sydney: Powerhouse Publishing, 2013), 85.

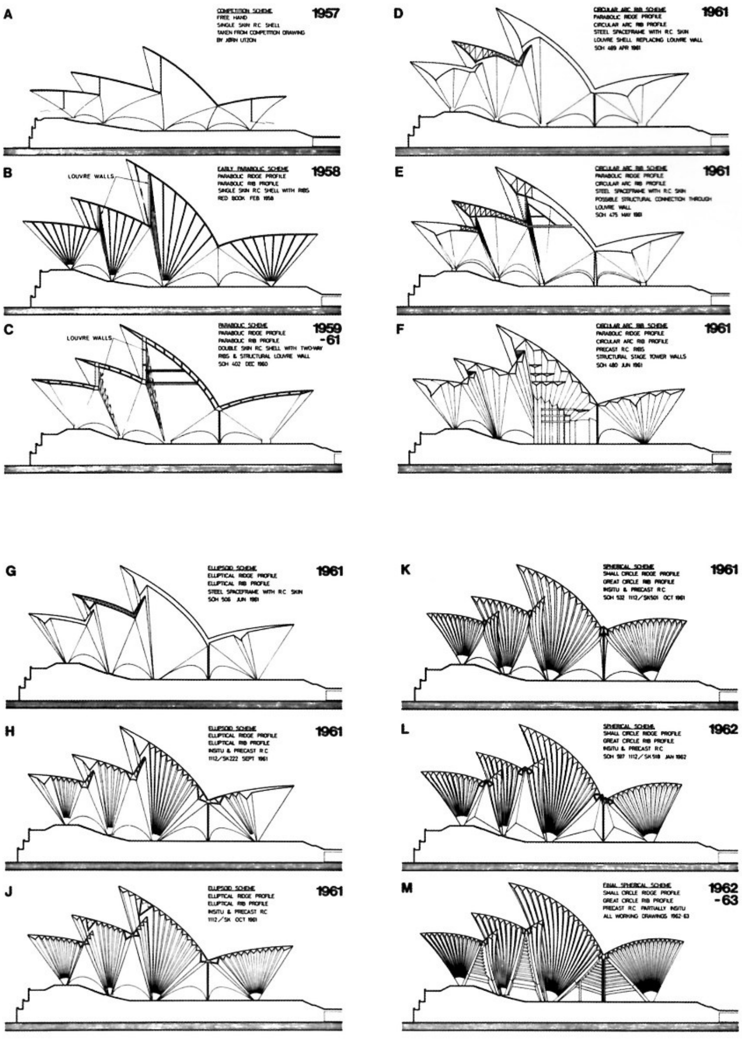

Figure 6.11. Evolution of the *Sydney Opera House* roof form from the freeform shape of the original competition design, to the parabolic and ellipsoid schemes of 1959–61, to the final spherical geometry of 1962–63. Anne Watson ed., *Building a Masterpiece: The Sydney Opera House* (Sydney: Powerhouse Publishing, 2013), 109.

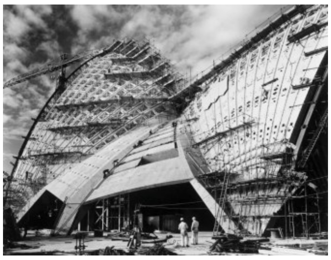

Figure 6.12.

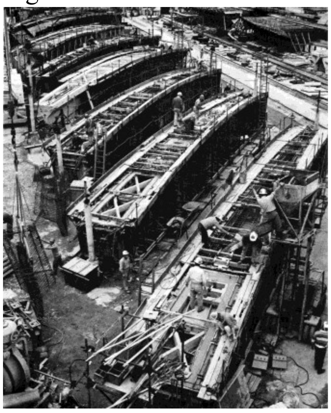

Figure 6.13.

Figure 6.12. *Sydney Opera House* construction, 1965. Photograph by Max Dupain. State Library of NSW.

Figure 6.13. *Sydney Opera House* moulds made of 25 mm plywood and steel frames for casting concrete rib segments. The Hornibrook Group, *The Sydney Opera House* (North Sydney: The Hornibrook Group, 1973), 11.

Repetitive factory production of elements from the same moulds influenced Utzon to change the ellipsoidal geometry of the shells to spherical geometry (Figure 6.11) to meet this requirement.[232] Hence, the final *Sydney Opera House* structure was not a shell, but an inter-connected rib structure with joined segments cast on site (Figure 6.12). The spherical geometry adopted in 1962 for the roof enabled mass production prefabricated by bending plywood with steel frames on the ground for each mould of the formwork system. The construction method is Non-Standard based on the spline geometry that derives from the shipbuilding method. The roof prefabrication involved the pre-casting of many copies of a small number of plywood ribs for use as standard segments in different areas of different shells (Figure 6.13). Nevertheless, the complexity of the Sydney Opera House superstructure was limited by the capability of computers at the time for the full realisation of mathematical rigour. Stress distribution of the shell superstructure was tested on a perspex model at the Structural Laboratory of Southampton University. During construction of the complex roof, engineers wrote a shell geometry program that allowed surveyed shell segment placement. The construction process was a continuous casting of rib segments on site which were then erected with a custom curved arch, designed to work on multiple angles at heights, to lift segments into place and follow the growing shell in a continuous workflow. Despite geometry changes and computer limitations, construction of the *Sydney Opera House* implemented many technological

[232] John Nutt, "Constructing a Legacy: Technological Innovations and Achievement," *Building a Masterpiece: The Sydney Opera House*, ed. Anne Watson (Sydney: Powerhouse Publishing, 2013), 111.

innovations which pointed the way to the introduction of computer design and analysis, as well as mathematics associated with computation. It was the first example of site pre-fabrication and erection of large precast concrete units for complex geometry with the pre-calculation of all dimensions.

Figure 6.14.

One of the first structures digitally developed from design through to construction was Bernhard Franken's *Bubble BMW Exhibition Pavilion* (1999) (Figure 6.14). The volumetric concept of a double-curved geometry required digital simulation and parametric design modelling. Novel appropriation and adaptation of technology with 3D film animation software was used. The design process required transdisciplinary and hybridised collaboration between architects, engineers, computational scientists and software manufacturers. However, film animation software limited the full realisation of the geometry with inexact data preventing digital coordination between different disciplines. Thus, engineers analysed load-bearing behaviour using finite element programs, and the manufacturers used parametric design software from the aviation industry for controlled surface segmenting.[233] Digital collaboration between different disciplines was only realised with software capability like Rhinoceros in the Second Digital Turn. The production process for *Bubble BMW Exhibition Pavilion* was guided by digital data files for CNC-milling to produce the polyurethane moulds, as well as to trim and cut acrylic panels to size using water jet cutting technology. The glass cladding elements were heat

Figure 6.14. *The Bubble – BMW Exhibition Pavilion* for the International Motor Show 1999 in Frankfurt. Fabrication process shows glued, self-supporting shell structure out of acrylic glass. Herald Kloft, "Logic or Form," *GAM: Nonstandard Structures* (Vienna: Springer, 2010), 113.

[233] Herald Kloft, "Logic or Form," *GAM: Nonstandard Structures* (Vienna: Springer, 2010), 112.

Figure 6.15.

Figure 6.16.

formed on the individually CNC-milled foam blocks into double-curved panels. Although the project reflects the novelty of digital processes based on film animation software to provide accuracy for statistical calculations, these were not able to be used as a data base for CNC production. The architect's data model was geometrically inexact and therefore analysed for discontinuities by an institute specialising in aerodynamics. The discontinuities were visualised and rectified with specialised software.

6.3.2 Digital Materiality

Research by design emerged with digital technologies in 2004, supporting the formation of new theory privileging process over form. A notable example is Mario Carpo's discourse on procedural design and scripting, representing a move away from compositional and representational theorising.[234] During this period, novel research units emerged within architectural practices to conduct multidisciplinary investigations exploiting computational geometry such as the Advanced Geometry Unit of Arup and Foster's Specialist Modelling Group. Among designs from this period, Balmond Studio and Toyo Ito's *Serpentine Pavilion* (2002) was produced using an algorithm for fractal geometry by incremental scaling and rotation of the square. The technique of recursion was used to generate a pattern of beams that were structurally sound and preserved the desired design of the building (Figure 6.15). The steel members were welded together and

Figure 6.15. Generative diagram of the roof panels for the *Serpentine Pavilion* by Toyo Ito and Arup. Daniel Bosia, "Digital to Post-Digital," *Architectural Design: Design Engineering Refocuses,* eds. Hanif Kara and Daniel Bosia (London: Wiley, 2016), 34–51.

Figure 6.16. *Federation Square* by LAB Architecture Studio and Bates Smart. Federation Square, *National Gallery of Victoria*, accessed July 27, 2020, https://www.ngv.vic.gov.au/media_release/draw-the-line-the-architecture-of-lab/.

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[234] Mario Carpo, "Ten Years of Folding," *Architectural Design: Folding in Architecture*, ed. Greg Lynn, vol. 63., no.3/4 (2004): 14–19.

assembled in zones with the algorithm identifying triangular areas for panelling.

Other notable surfaces based on mathematical algorithms included the facade design for *Federation Square* (2002) by LAB Architecture Studio and Bates Smart. The organisational system for the building facade was based on the different scales of the right-angle triangle achieved with Radin and Conway's pinwheel grid algorithm. The network of three-dimensional generalisation of the facade's pinwheel grid was used for the geometry of the Atrium steel network (Figure 6.16). Within the three-dimensional framing, redundant structural members were eliminated. This method of optimisation limited the full realisation of the initial design with framing evolving into another kind of system working with a three-dimensional load from one side of the structural frame to the other.[235]

Figure 6.17.

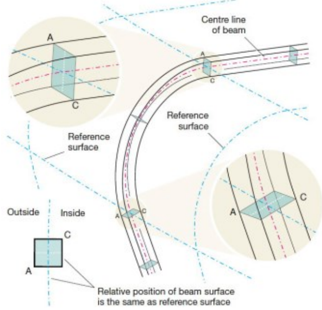

Figure 6.18.

The *National Stadium* (2008) by Herzog & de Meuron and Arup is an example of a form as an expression of efficiency in steel material. The concept, based on the rotation of three-dimensional portalised space trusses around the architectural form of the bowl and concourse structure, was innovative for its geometric complexity and equally complex exchange of digital information (Figure 6.17). As opposed to earlier methods where material developments gave rise to formal changes in architecture, the Non-Standard digital tools used for the *National Stadium* offered possibilities to define the form as a search for materiality. The design process required scripting to create the initial geometry, while the final geometry

Figure 6.17. A welding process in situ of the spatial bent steel tube profiles for the *National Stadium* by Herzog de Meuron in Beijing, 2008. Herald Kloft, "Logic or Form," *GAM: Nonstandard Structures* (Vienna: Springer, 2010), 109.

Figure 6.18. Detail of curved stadium element at eaves, Herzog de Meuron and Arup, 2008. Arup, "The Beijing National Stadium Special Issue," *The Arup Journal*, vol. 44, no. 1 (January 2009): 18.

[235] Branko Kolarevic ed., *Manufacturing Material Effects: Rethinking Design and Making in Architecture* (New York: Routledge, 2008), 169.

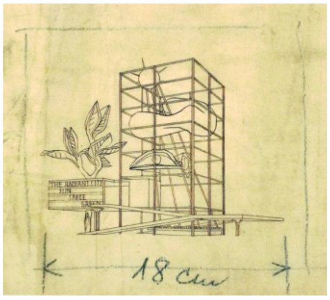

Figure 6.19.

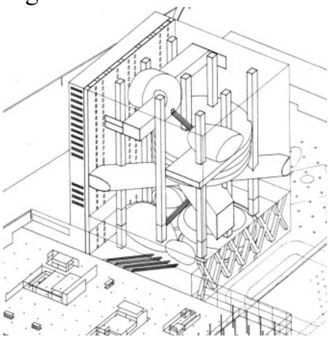

Figure 6.20.

Figure 6.19. Pavilion in the *Ideal Home* exhibition London by Le Corbusier, 1939. Oliver Cinqualbre and Frédéric Migayrou, *Le Corbusier: The Measures of Man* (Zurich: Scheidegger & Spiess, 2015), 21.

Figure 6.20. *National Library of France* by OMA, 1989. Richard Levene and Fernando Cecilia eds., *El Croquis: OMA/Rem Koolhaas*, vol. 53 + 57 (1998): 71.

required manual intervention to move elements and tweak the angles. The CAD software platform CATIA by Dassault Systèmes enabled a process of 'virtual prototyping'. This referred to the approach where all elements can be assigned and tested in a virtual environment before committing to construction.

For Arup, the advantages of this parametric component-based modelling included the ability to generate form within adjustable parameters such as geometric constraints, environmental factors and the limitations of construction materials. Fixed values like length, angle and depth could be provisionally assigned and adjusted later. Nevertheless, compared to the innovative form finding digital process, material and manufacturing remained very traditional. One of the most challenging fabrications described by Arup was the requirement to use a continuous box-profile over the whole facade (Figure 6.18). The box section was defined using a developable surface geometry that was part of the structure envelope. The outer flange of the box parallel to the control surface generated a twisting, curving box section that changed as the element progressed along the surface of the structure. This definition of the surface allowed forming of the box sections from flat steel plate. The project included the collaboration of the various teams, including Arup offices and Herzog & de Meuron.

6.3.3 Parametric Design: Conceptual Formalism

The parametric design emerged with a new type of digital design thinking and logic. The formal heuristics of parametricism evolved primarily through the work of Peter Eisenman, and the functional heuristics of parametricism through the work of Office for Metropolitan Architecture.

The Office for Metropolitan Architecture concept for the *National Library of France* competition of 1989 is a critical example of parametric architectural design thinking. For Rem Koolhaas, the concept marks the beginning of OMA's 'big' period and the shift of focus from urbanism to conceptual formalism.[236] The concept for the library excavated voids from a solid cube containing the archives. The project extends modernist notions of space evident in the *Pavilion in the Ideal Home* by Le Corbusier in 1939 (Figure 6.19), such as the measurements of the body moving through space. Le Corbusier's concept revealed the simulation of body movement within a building generating rhythmical space which pre-empted parametric architectural form generated by digital processes. The concept for the *National Library of France* (Figure 6.20) reinterprets existing programmatic and functional potential by integrating digitalisation that liberated architecture from the constraints of a predetermined form through geometrical solids as programmatic elements and an information system of technological scenarios developed with inventors, systems analysts, writers and electronic companies (Figure 6.21).

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[236] Rem Koolhaas and Clément Blanchet, *Very Big Library* (Montreal: Canadian Centre for Architecture, 2012). Exhibition catalogue.

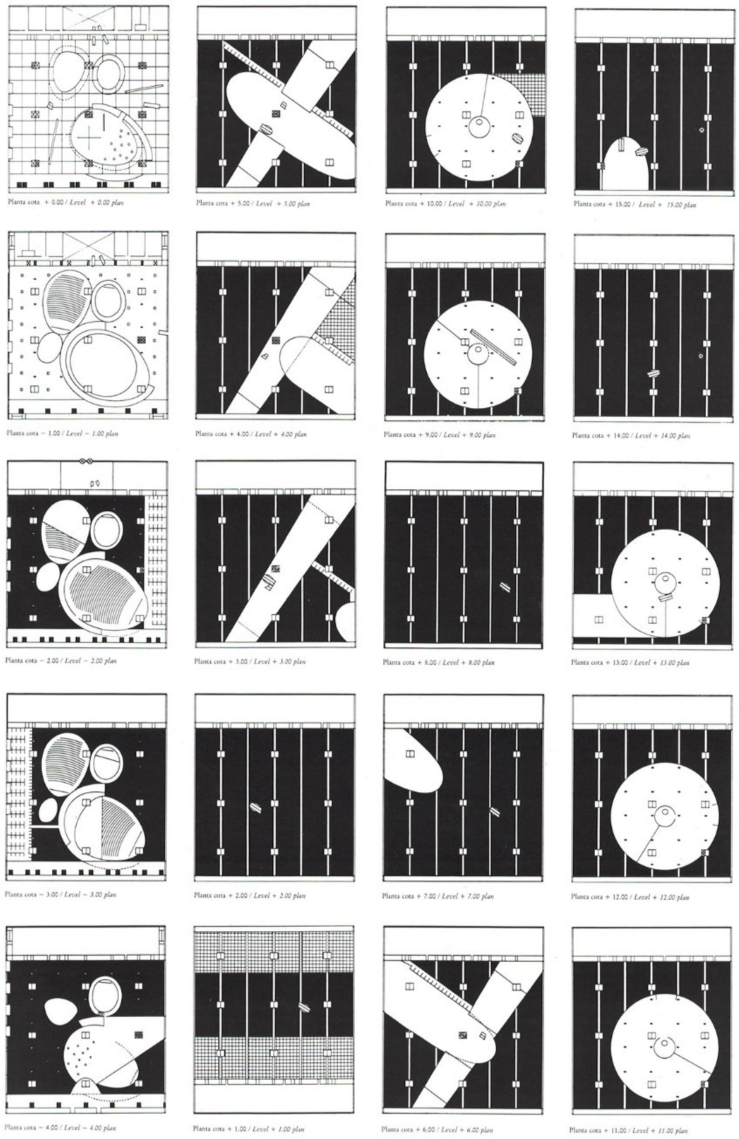

Figure 6.21. *National Library of France* competition diagrams by OMA, 1989. Richard Levene and Fernando Cecilia eds., *El Croquis: OMA/Rem Koolhaas*, vol. 53 + 57 (1998): 70.

The notion of the field became a device for design based on site conditions to explore a project program that heralded a new decade of surface projects evident in Office of Metropolitan Architecture's *Yokohoma Master Plan* (1992) (Figure 6.22), *Seattle Central Library* (2004) (Figure 6.23) and MVRDV's *Datascapes Metacity/Datatown* (1999). The critical research hypothesis integrated by MVRDV was based on the observation, extrapolation, analysis and critique of behaviour that aimed to introduce self-criticism in architecture, urbanism and a redefinition of practice.[237] The argument begins to address an emerging agenda of urbanism and architecture through data such as the increase of urban density and thus the reduction of available space. The design premised on a typological consolidation incorporated the concept of programmatic stacking to assign geometric volumes for architecture. The programmatic potential of the field, based on the concept of programmatic stacking, was integrated into a digital platform with the development of parametric digital modelling. Distribution of data and communication in the parametric data model is a characteristic of the Second Digital Turn.

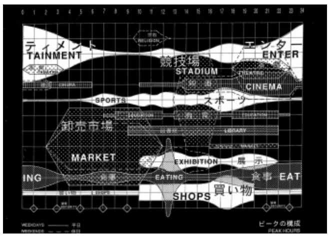

Figure 6.22.

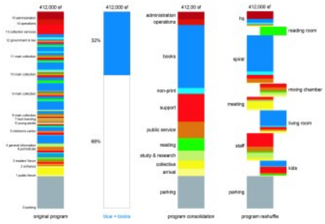

Figure 6.23.

Figure 6.22. *Yokohama Project* programs by OMA, 1992. Rem Koolhaas and Bruce Mau, *S, M, L, XL: Office for Metropolitan Architecture*, ed. Jennifer Sigler (New York: The Monacelli Press, 1995), 1219.

Figure 6.23. Diagram consolidating stable and unstable programs for *Seattle Central Library* by OMA, 1999–2004. Seattle Central Library, *ArchDaily*, accessed October 29, 2019, https://www.archdaily.com/11651/seattle-central-library-oma-lmn.

6.3.4 Formal and Material Optimisation in Architecture

Following the digital revolution, computation technology was increasingly reflected in the formal typological complexity of architecture. Complex programmatic connectivity and structure in the concept for *Central China Television (CCTV)* (2012) by OMA was reflected with two towers joined by a cantilevering bridge, generating a 75 m overhang (Figure 6.24). The structural challenge of the tower loop form is reflected in the facade, with the diagrid exoskeleton that functions as a twisting structural tube and a grid of columns (Figure 6.25). The two-storey bracing module was optimised by Arup's in-house finite element software Oasys GSA by adding or

237 Winy Mass, "Datascapes, the final extravaganza," *Daidalos*, vol. 69/70 (December 1998/January 1999): 49.

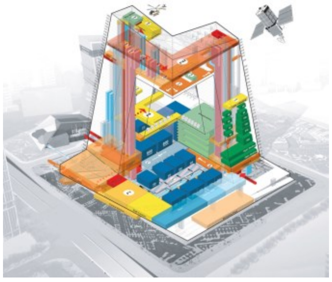

Figure 6.24.

Figure 6.25.

removing diagonals and changing brace plate thickness to match the strength requirements of the design.[238] The process of formal and material optimisation for the *CCTV* building reduced steel use by 20% compared to conventional high-rises. Systematic optimisation methods were applied to introduce modular elements into a rationalisation of design and fabrication. The distinctive loop was developed through analysis of structural implications in conjunction with aesthetic considerations, and digital simulation of the facade's bracing structure as a composite unfolded skin. An example of the requisite continuous surface is *Heydar Aliyev Cultural Centre* (2012) by Zaha Hadid Architects. Werner Sobek described the complex geometry of the building and the remoteness of the building site as two specific challenges for facade engineering (Figure 6.26).

Figure 6.24. Program diagram for *CCTV* by OMA, Beijing, 2002–12. CCTV Headquarters, *ArchDaily*, accessed October 29, 2019, https://www.archdaily.com/236175/cctv-headquarters-oma.

Figure 6.25. Construction during cladding installation of *CCTV* by OMA, 2002–12. Chris Carroll, "CCTV," *Detail: Building Design at Arup,* ed. Christian Brensing (Berlin: De Gruyter, 2013), 17.

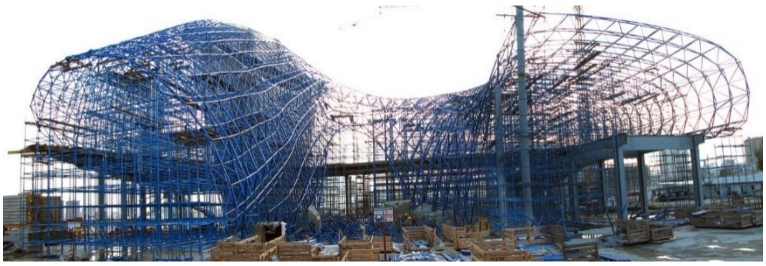

Figure 6.26. *Heydar Aliyev Cultural Centre* under construction by Zaha Hadid Architects, 2007–12. Patrik Schumacher, "Architectural Practice Now: Zaha Hadid Architects," *Harvard Design Magazine,* vol. 32 (Spring/Summer 2010): 64–65.

[238] Chris Carroll, "CCTV," *Detail: Building Design at Arup,* ed. Christian Brensing (Berlin: De Gruyter, 2013), 16–21.

The irregular diagrid was further developed in Zaha Hadid Architects' *Morpheus Hotel* (2019) into a novel free form exoskeleton by integrating a distributed design system in the form of parametric data modelling and new software tools. The *Morpheus Hotel* exemplified the new style integrating a parametric data model and reinvented the typology of the tower and structural facade. Architecture became computationally empowered by engineering logics that were available to architects at early design stages as structural form finding tools used for explorations in digital or robotic fabrication. These methodologies aim to meet current socio-economic transformation – the shift from an economy based on mechanical mass production to an economy of scope based on robotic fabrication and web-based services that can afford incomparably higher rates of innovations, which then also transform other aspects of societal life through the digitalisation of products, services and professional disciplines.

6.4 Case Study: *Morpheus Hotel*

Figure 6.27. *Morpheus Hotel,* Zaha Hadid Architects, 2019. Photograph by Ivan Dupont.

6.4.1 New Tower Typology

The *Morpheus Hotel* project[239] (Figure 6.27) developed a new tower typology featuring the first external load-bearing steel structure with a free form high-rise exoskeleton and a glass lattice shell as opposed to the internal wall and column load-bearing structure.[240] The exoskeleton geometry 'morphs' from an external flat facade into the central building section to define a 40-storey building with three voids integrated between two vertical circulation cores connected at podium and roof levels. The design methodology was enabled by the parametric data model and algorithmic computational design processes in

[239] Zaha Hadid Architects, *Morpheus Hotel at City of Dreams, Macau*, accessed January 15, 2020, https://www.zaha-hadid.com/architecture/city-of-dreams-hotel-tower-cotai-macau/.

[240] Zaha Hadid Architects, "City of Dreams Hotel Tower," *GA Document: International 2014,* vol. 27 (May 2014): 128–133.

novel software such as Rhinoceros that is characteristic of the Second Digital Turn of Non-Standard Architecture.

The specific building information modelling, a managerial approach integrated with the *avant-garde* experiments by the team, benefited from cross-disciplinary collaboration between architect and engineer including analysis of parametric object behaviour, with precise, fast and highly automated parametric digital strategy and coordination of the project through automated recalibration. The design of the first freeform exoskeleton and structural analysis used the new three-dimensional digital technics of parametric data modelling with custom scripting in Rhinoceros and Grasshopper of mathematical geometry for curved surfaces (Figure 6.28) and finite element analysis for large scale freeform irregular steelwork connections. Design and development of these new tools as part of the digital process was pivotal for achieving the desired, novel architectural typology.

Figure 6.28. Rationalisation of the *Morpheus* building components: exoskeleton, floor slabs, curtain wall and cores. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

Zaha Hadid Architects defined the digital in architecture as computational design processes and their architectural outcome, rendered or built. As a response to the continuous progress in digital design tools and methods, Zaha Hadid Architects' objective was a moving target. Situating itself within tectonism, the latest stage of parametricism, the firm integrated recent advances in structural and environmental engineering capacities based on computational analytics and optimisation techniques.[241] These included computational engineering logic that is now available to architects at the early design stage, and structural form finding tools like RhinoVAULT, physics engines like Kangaroo that can approximate shell or tensile structures, analytic tools like Principle Stress Lines analysis in Karamba that can be generative, and optimisation tools like the structural topology optimisation possible in Millipede.

6.4.2 Architecture Parametric Data Model

The project for *Morpheus Hotel* implements a parametric data model to enable the world's first freeform high-rise exoskeleton comprising a pattern of structural members at tower levels designed to progress upwards to a less dense grid of lighter members on the top of the building. This optimal arrangement of freeform geometry and irregular diagrid exoskeleton is combined with structural integrity and form into a design without traditional architectural typologies (Figure 6.29). The process of optimisation avoided warped structural members in the double-curved central area, which allowed constructability.

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[241] Patrik Schumacher, "The Digital in Architecture and Design," *AA Files*, no. 76 (June 2019): 47–52.

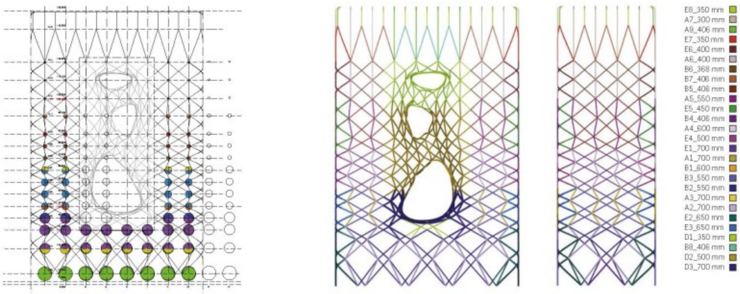

Figure 6.29. *Morpheus* colour coded diagram of exoskeleton nodes and member sizing. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

Structural analysis was performed and connected the form development in Rhinoceros 3D and Grasshopper to a Robot analysis model. The comprehensive parametric model enabled the integration of all of the aesthetic, formal, structural and fabrication requirements with the potential to radically change how the built environment is planned and constructed through the collective form of communication and collaboration.[242]

The collaboration between Zaha Hadid Architects and Buro Happold Engineering was an exchange of Rhinoceros files, Robot models for structural analysis, and Revit, AutoCAD, Solidworks and Tekla files to produce information. The freeform exoskeleton cladding fabrication – a process described as building information generation – was produced by facade specialist Front. The process involved modelling over 1.6 million geometrically complex components, including 1.2 million unique parts, and ranged from system design to information and data generation used directly by the factories for fabrication and accurate assembly (Figure 6.30).

[242] Zaha Hadid Architects, "The Morpheus Hotel: From Design to Production," *Robert McNeel & Associates Rhinoceros Webinar*, accessed February 8, 2017, https://vimeo.com/203509846.

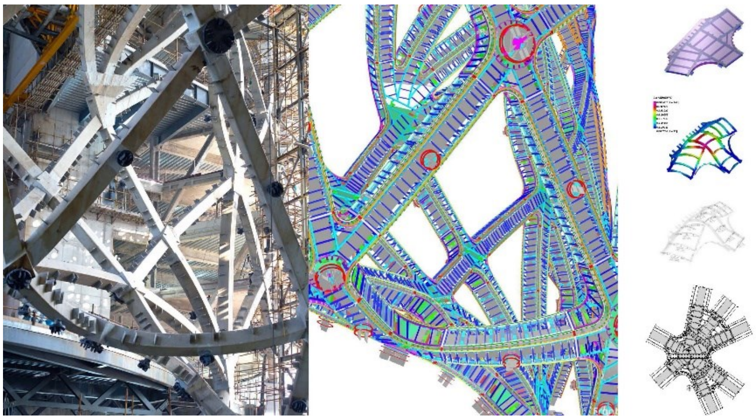

Figure 6.30. *Morpheus* site photo and a digital image of steel exoskeleton structure. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

The specialist Elefront software, integrated by Front, provided a detailed search for specific components, expedited technical development and helped to avoid overdesign and the application of the worst-case scenario. This data was added to the Rhinoceros model, enabling the BIM model to be created using the Rhinoceros platform. Compared to a traditional three-dimensional model, the BIM methodology increased the capacity to retain the initial set of parameters and subsequently absorb and adapt to the articulation of the subsystems. The design history was processed as a complete output set indicating a positive and negative effect of the system's components.

Custom codification was created for the facade geometry in Rhinoceros and Grasshopper software by the Zaha Hadid Architects design team. The design methodology involved parametric modelling and an algorithmic computational design process for an iterative exploration of multiple options. The digital model generated diverse types of required output, ranging from renders using surface modelling to structural wireframes and models for fabricators. A distinct advantage of integrating parametric tools was the continuous process development from concept design to construction that allowed backtracking and previously explored options and geometry to be revised.

6.4.3 Freeform High-Rise Exoskeleton

Working on the facade design development of the *Morpheus Hotel* as part of the Zaha Hadid Architects team in 2013, my role was to achieve the architectural typology of the world's first freeform high-rise exoskeleton. Form finding was defined with the process in which parameters were directly controlled to find an 'optimal' geometry of the structure. Optimisation for the exoskeleton emerged from a rationalisation of the facade geometry during the design development stage. The freeform exoskeleton was developed as a network of structural forces along the *Morpheus* facade transferred between the cores and composite beams and slabs (Figure 6.31). Between the two reinforced concrete cores, an additional series of trusses 36 metres wide was introduced to support restaurant floors, the sky pool and the exoskeleton (Figure 6.32). The structural trusses are reflected in the floor plan as bridges connecting the large atrium (Figure 6.33) and separate cores (Figure 6.34). Specific fire safety requirements for the *Morpheus* atrium were designed and specified by Arup fire engineers.

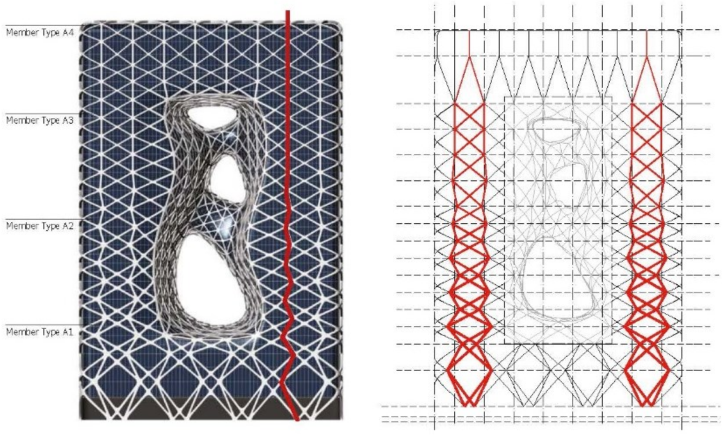

Figure 6.31. Preliminary exoskeleton pattern and vertical load path diagram. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

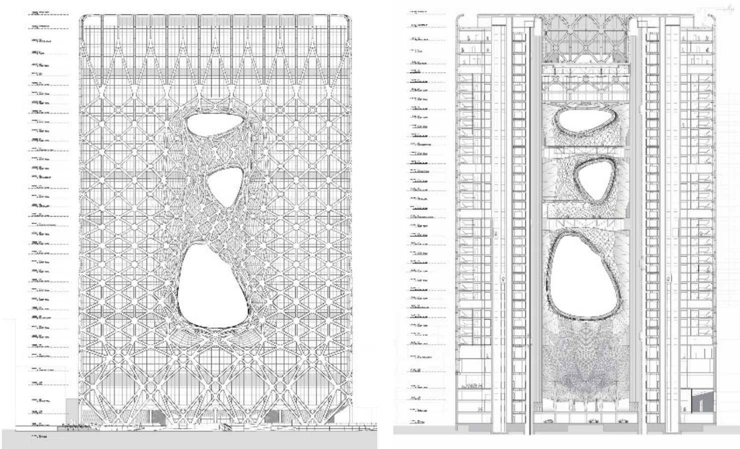

Figure 6.32. *Morpheus* north elevation and section through the two tower cores with exoskeleton in the central area supporting large micro-panels and bridges. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

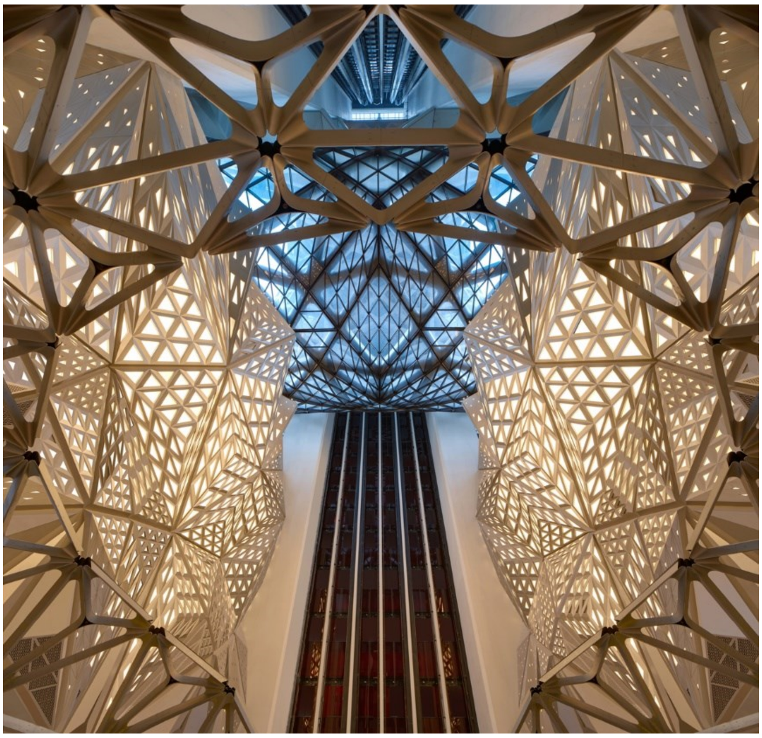

Figure 6.33. Atrium skylight of *Morpheus Hotel*. Photograph by Virgile Simon Bertrand. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

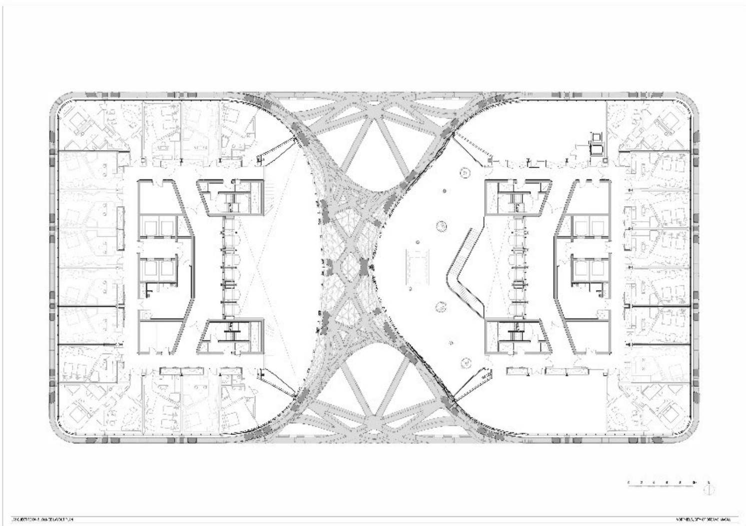

Figure 6.34. Floor plan of *Morpheus Hotel* with the two tower cores separated. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

Design for parametric connections of the exoskeleton optimised nodes installed on 2,500 steelwork connections significantly reduced the amount of steelwork. This algorithmic method enabled the fabrication of steel nodes for complex geometries to be created with a three-dimensional model, combining geometrical, structural and fabrication limitations. The geometry rationalisation input involved a reference surface in Rhinoceros and Grasshopper programming language to approximate the external face of the glass envelope using a T-spline polygonal surface tool custom-scripted by Zaha Hadid Architects. Within the central building area, a geometric solution was applied as a single curved structural member in the double-curved central area. This solution simplified the fabrication and erection of the steelwork as well as the detailing of the steel nodes. The secondary input involved using an algorithm to generate a topological mesh to define the exoskeleton pattern (Figure 6.35).

The primary data output by Zaha Hadid Architects was the wireframe used to set out the node points, member axes and planes of the exoskeleton frame issued to the structural engineer Buro Happold. The secondary output model defined the three-dimensional limits of the structural framing zone as the secondary support for the exoskeleton cladding located outside this zone (Figure 6.36). The exoskeleton cladding geometry was rationalised with panel axes on planes. The cladding was an offset of the reference surface, the polygonal T-spline geometry which the external face of the glass envelope approximates.[243]

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[243] Melika Aljukic, "Design of Towers with Parametric Data Models," *Architecture Bulletin: Constructions*, vol. 77, no. 2 (December 2020): 32–35.

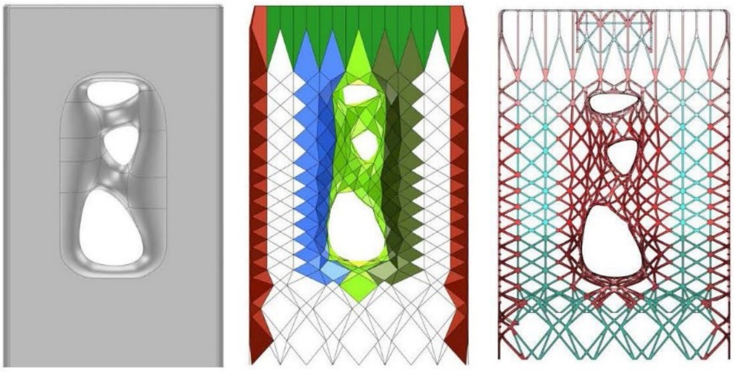

Figure 6.35. Reference surface, topological mesh and exoskeleton structural envelope model. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

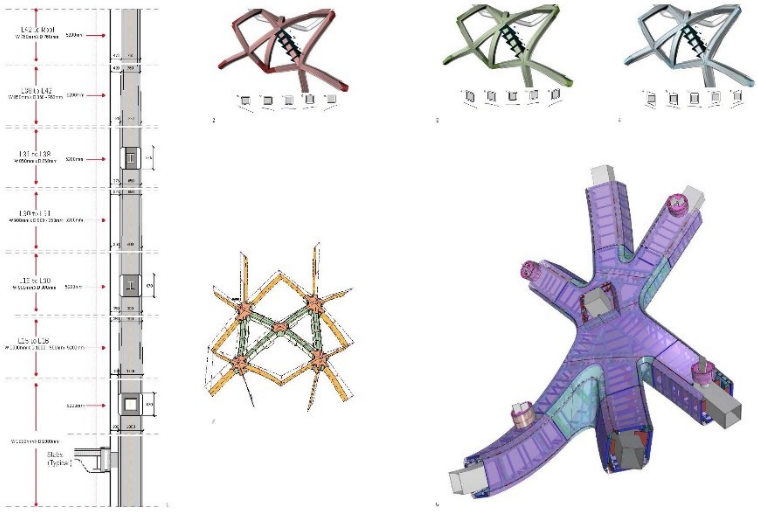

Figure 6.36. *Morpheus* exoskeleton cladding. *Left*, Schematic section of exoskeleton types; *Above,* Squared structure and skewed cladding; *Middle*, 3D model assembly of node's cladding sub-structure; *Right below*, Exoskeleton cladding geometric set-out. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

6.4.4 The Limit of the Tool in *Morpheus*

Figure 6.37.

This thesis argues that in practice, fabrication remains constrained by significant technical limits with the parametric design currently ahead of the capacity of conventional fabrication and construction processes, leading to a gap that remains to be overcome. A significant constraint identified by this thesis was a requirement for the translation of architectural information by the contractor because of the capacity of the building industry to realise information. During the structural optimisation of the project, Buro Happold used engineering software in unprecedented ways to create a novel method of separate local finite element models of the connections and load transfer rather than analysing all connections of the global project model.[244] Every aspect of the model generation was automated using bespoke Visual Basic scripts to link applications including MIDAS, RSA and Excel with Grasshopper via their application program interfaces. The Robot analysis by Buro Happold provided initial and final structural optimisation. The structural limitation included detailed analysis using MIDAS structural software on the complex exoskeleton structure (Figure 6.37). While the three-dimensional digital model was prepared for fabrication, it was limited by the fabricator's equipment which used Revit and Tekla software, neither of which was compatible with the Rhinoceros files generated by Zaha Hadid Architects.

Figure 6.37. Internal and external view of facade system triangulated area. 1. Aluminium clad exoskeleton structure, 2. Macro-window steel frames, 3. Stub connections supporting macro-windows, 4. Flat glass panels. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

Thus, the contractor Dragages Macau had to develop translation methodologies compatible with

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[244] BuroHappold Engineering, "Morpheus Hotel in Macau," *Detail: Structure*, vol. 4.18 (December 2018): 20–27.

geometric tolerances and check the final fabrication models against the original Rhinoceros design models. Diverse types of digital output had to be provided to fabricators, including photorealistic renders using surface modelling, structural wireframes and solid models. During the project design and documentation, the team was in continuous dialogue with the software companies' technical support, which in turn customised and developed the tools further. This process-based design approach from which the outcome emerged and evolved is germane to parametric architecture and is a characteristic of the Second Digital Turn of Non-Standard Architecture, in contrast to an object-based approach where the outcome is formalised in advance.

Despite the parametric capability of the digital platform, fabrication of the glazing facade panels was achieved by a conventional triangular glazing facade system (Figure 6.38). The size of the triangular glass panels of the macro-windows was rationalised and standardised for fabrication (Figures 6.39 and 6.40). This method of flattening the glazed areas reverted to a Euclidean framework, limited by available construction capacities. In response to these limits of the Second Digital Turn, the Third Digital Turn implements the *Statutes of Non-Standard Architecture* to enable the formulation of protocols that can automate architecture from design to construction phases, while avoiding the data translation required for the *Morpheus Hotel* project.

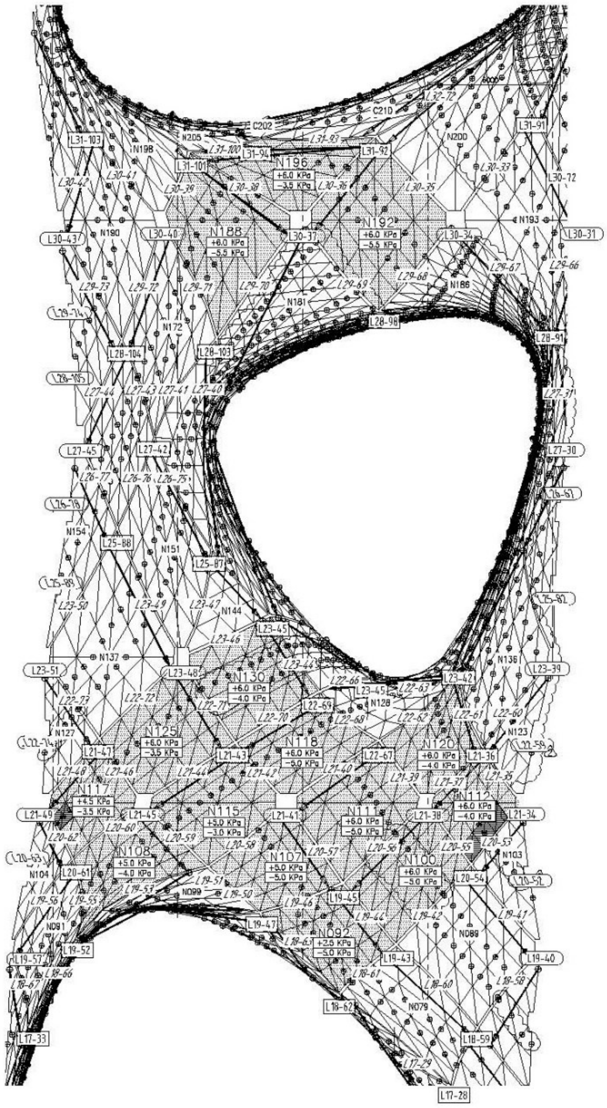

Figure 6.38. *Morpheus* shop drawing of macro-windows in freeform area. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

Figure 6.39. *Morpheus* micro-window site installation sequence. *Morpheus Hotel*, Zaha Hadid Architects, 2019. Photograph by Ivan Dupont.

Figure 6.40. *Morpheus* site construction of the freeform area. *Morpheus Hotel*, Zaha Hadid Architects, 2019. Photograph by Ivan Dupont.

Figure 6.41. *Morpheus* exoskeleton. *Morpheus Hotel*, Zaha Hadid Architects, 2019. Photograph by Ivan Dupont.

The thesis identifies the limit of the Second Digital Turn in the construction method for *Morpheus Hotel* was that it began to automate conventional construction approaches by defining analytical links between bars and shell elements using Robot Structural Analysis software and analytical supports. Nodes of the finite element mesh were imported into Grasshopper software, which applied a script that used geometric search algorithms to find appropriate nodes to which the bar elements should connect (Figures 6.41).

Although the protocol for design and documentation of the *Morpheus* project was largely driven by digital and integrated parametric data models, the actual fabrication of components required a high level of skilled manual work. This included pre-bending and welding of aluminium cladding panels by site workers (Figure 6.42). The panels had machine bent stiffeners welded to their reverse faces before being trimmed by a machine programmed to splay off the edges at a specified angle. Following the demoulding of the panels, they were manually tested for assembly in the factory before being powder coated and shipped to the site.

From this perspective, this thesis sees the Third Digital Turn of Non-Standard Architecture can adapt site construction technologies to the logic of architectural parametric data models, and update systems in terms of pragmatic processes necessary to achieve file to factory methods of design and construction. The parametric data model (Figure 6.44) developed for *Morpheus Hotel* was used to test the temporary and permanent works and to ensure the temporary works allowed interim movement of the exoskeleton. Likewise, the data model ensured the staged propping and de-propping of temporary work was consistent with the design of the exoskeleton.

Figure 6.42.

Figure 6.43.

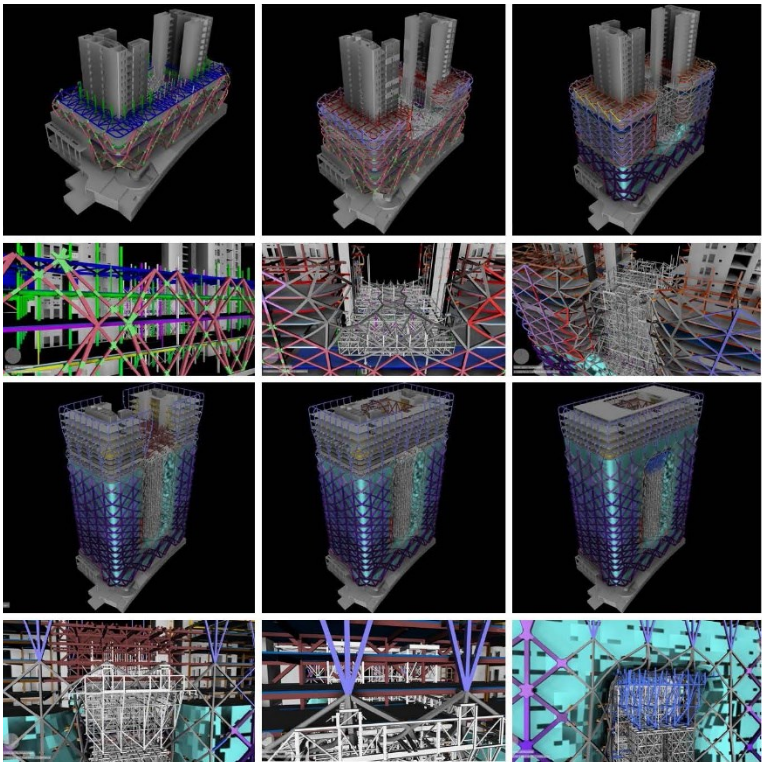

Figure 6.44. *Morpheus* parametric data model. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

Figure 6.42. Fabrication of *Morpheus* facade steel nodes in Guangzhou. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

Figure 6.43. Fabrication with FANUC industrial robots at Audi. FANUC Industrial Robots at Audi, accessed November 21, 2019, https://www.youtube.com/watch?v=rbki4HR41-4.

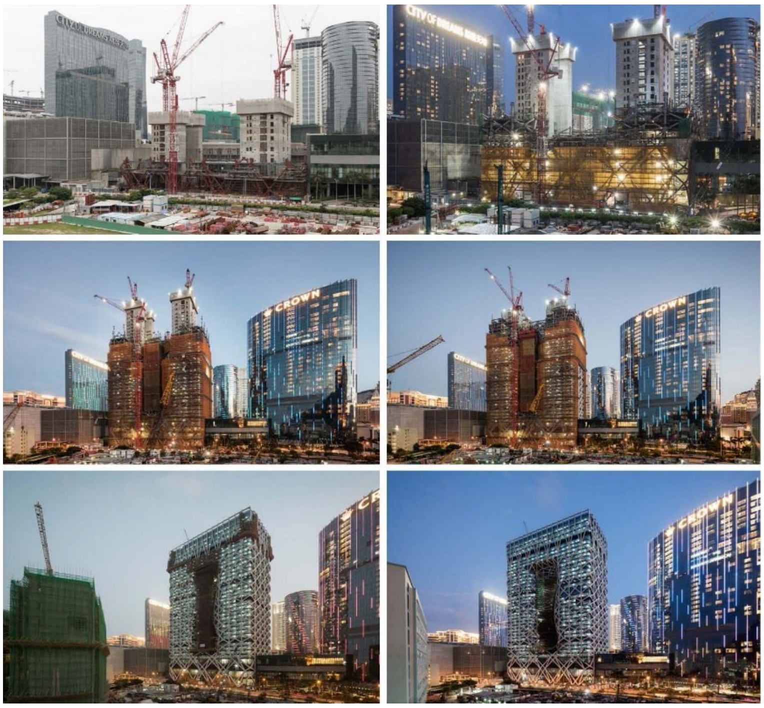

Figure and Video 6.45. *Morpheus* time-lapse construction sequence photos and video. *Morpheus Hotel*, Zaha Hadid Architects, 2019.

The identified limit of construction in the Second Digital Turn of Non-Standard Architecture was the digital automation on the construction site (Figure 6.45) that persists in the Third Digital Turn. The automation driven by the integration of digital parametric models has the capacity to eclipse these limits. The increased involvement of co-laboratories of architects, engineers and other consultants across all stages of a project, from design to construction, also has the capacity to increase the level of integration and eventual quality of architectural outcomes. Practically, the guidelines for the automated Non-Standard Architecture will reduce construction time, removing the need for iterative documentation in the design phase and manual operations in the prototyping, manufacturing and assembly phases. Examples of such robotic fabrication exist in the automotive industry (Figure 6.43), however, they have not yet been fully adapted into the built environment construction industry.

6.5 Automated Architecture

Technology is one of the determining factors of evolution in architecture. The integration of robotics in architecture has opened the prospect of entirely new ecological fabrication. Following the developments of automated manufacturing processes from Japan in the 1960s, research into realising Non-Standard forms in architecture with robotic fabrication has been undertaken across various universities since 2008. These investigations have led to the development of the architectural robot and end-effectors for the grading of material, where the composition of the material can be calibrated to specific structural and thermal performance criteria. The thesis identifies these developments with the potential to eclipse the limits of Non-Standard Architecture, with automated architecture and construction.

Robotic automation is the most recent step in an ongoing process of innovation in architectural construction, beginning with the use of the human body as a tool. Historian and philosopher Lewis Mumford divided tools and machines primarily on the degree of automation, where the machine emphasises specialisation of function and the tool indicates flexibility. This process of a gradual displacement of technical operations from human to artificial machine is defined by André Leroi-Gourhan as an 'externalisation' of the human, that is, automation of human body functions. His analysis finds that the externalisation of technical objects did not fundamentally change their nature, as the machine mimics the living body. Instead, he considered that automated machines constituted "the human machine and its improved artificial copy."[245] The antiquated figure of human technical being, of the hand in particular, carried into digital tools is one of the limits of the Non-Standard since it constrains it to the orthogonal, Cartesian axial three-dimensional movement currently being developed for a six-axis industrial robot.

Earlier comparison between humans and machines by Karl Marx proposed a fundamentally different theory. For Marx, the worker crucially guided the movement of the tool, supervised and made continual adjustments in response to environmental perturbations and monitored the developing form. The aggregate of such productive means and forces determined the condition of a particular society. The outcome has seen machines evolve through history where humans increasingly became the author of their dehumanisation. Within the discipline of architecture, technology facilitated the progressive evolution of architecture lineage. The Second Digital Turn of Non-Standard Architecture realised a parametric architecture with complex architectural geometry. Yet, while the protocol of the architectural model is digital, the fabrication of components still demands a high level of skilled manual work. The thesis argues the evolutionary step for automation through Non-Standard architectural geometry.

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[245] André Leroi-Gourhan, *Gesture and Speech*, trans. Anna Berger (Cambridge: MIT Press, 1993), 269.

6.5.1 Robotic Automation in Japan

The Industrial Revolution that changed the building process through industrial manufacturing eventually led, during the 1960s in Japan, to specialised robotic machinery and automated high-rise construction processes. These were characterised by a shift from in-situ processes on construction sites to remote automated factory environments which were the direct precursor of current robotics in architecture. Automation in prefabrication and construction was promoted in Asia in the 1960s, as a result of growth in population, cities and unskilled labour. The first robotic arm Unimate was invented in 1954 in America by George C. Devol. It was sold to Japan and adapted for the construction industry during the 1960s to replace human labour in laborious manufacturing tasks such as welding, lifting and stacking. While European prefabrication during this time initially focused on fast production of a large number of identical elements, Japan focused on customisation, personalisation and users' demands (Figure 6.46). The structured assembly line work using human labour in factory environments enabled customisation and personalisation without disturbing the production chain.

Figure 6.46.

This first generation of single-task construction robots attempted to replace specific repetitive construction tasks normally undertaken by human workers. The robots were used on site for tasks such as demolition, surveying, excavation, paving, welding of structural steel members and installation of facade panels. Research in automated construction in Japan intensified and led to the development of automated construction sites. The concept of automated construction was partly an automated environment organised as vertically moving on-site factories for the

Figure 6.46. *Misawa Homes* assembly line quality control in Tokyo, 1982. Thomas Bock and Silke Langenberg, "Changing Building Sites: Industrialisation and Automation of the Building Process," *Architectural Design: Made by Robots,* ed. Fabio Gramazio and Matthias Kohler, no. 229 (May/June 2014): 95.

Figure 6.47.

Figure 6.48.

assembly and disassembly process of prefabricated detailed building components.[246] Robot technology included automated overhead cranes, vision systems and other real-time control equipment. For example, Fujita's mobile welding robot was used to weld beam segments to individual columns (Figure 6.47). The robot allowed automatic overseeing of the welding process and manual guidance of the end-effector. The integration of automated technologies for facade concrete panel installation in Kajima construction company (Figure 6.48) enabled a single worker to install facade panels by manual remote control of the system. In 1982, Waseda Construction Robot Group developed an integrated automated construction site to increase productivity, stabilise quality, and reduce construction time and total construction cost. While the automated site had three-dimensional digital models and complex workflow management systems, the market share, takeup and application remained limited due to the relatively high installation cost. Hence, the method was only used in particular conditions of high labour cost, and on sites with waste and noise restrictions. Today robotic automation is limited to the academic context, the prefabrication industry and occasional off-site manufacturing and on-site assembly.

Figure 6.47. Steel beam welding robot by Fujita Corporation. Thomas Bock and Thomas Linner, *Construction Robots* (New York: Cambridge University Press, 2016), 153.

Figure 6.48. Facade concrete panel installation robot by Kajima Corporation. Thomas Bock and Thomas Linner, *Construction Robots* (New York: Cambridge University Press, 2016), 101.

Today Japan has focused on the prefabrication industry that embeds robotic technology with an increasing degree of quality producing about 150,000 prefabricated

[246] Thomas Bock and Silke Langenberg, "Changing Building Sites: Industrialisation and Automation of the Building Process," *Architecture Design: Made by Robots*, eds. Fabio Gramazio and Matthias Kohler, vol. 84, no. 3 (May/June 2014): 98.

housing units a year (Figure 6.49).[247] The cost of building from prefabricated elements is not significantly more expensive than conventionally built buildings and includes proactive building maintenance services integrated to guarantee consistent built quality and subsystems functionality. Furthermore, the prefabrication process pays the highest average salaries to workers in the Japanese construction industry. From the analysis of various prefabrication strategies in the Japanese prefabrication industry, the steel systems – in particular, three-dimensional space frames – enabled the highest possible degree of manufacturing systematisation and optimisation.[248] The Sekisui House factory, for example, operates under guidelines for robots to assemble, adjust and weld raw steel frames. This prefabrication assembly is optimised by implementing the automation ratio and human flexibility at the final production line where high flexibility is required.

Figure 6.49.

The method implemented for *Sekisui House* begins to automate prefabrication in architecture similar to the automatic car body assembly line of Volkswagen (VW) Phaeton. The VW production strategy marks Phaeton as a handmade car, since the configuration of each vehicle on the conveyor belt varies more than any other VW model, and it exploits the flexibility possible through the involvement of human workers (Figure 6.50), rather than relying only on robotic automation. Human workers are highly skilled and augment technology by guiding

Figure 6.49. Robot steel frame manufacturing at *Sekisui House*, 2015. Thomas Bock and Thomas Linner, *Robotic Industrialization: Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication* (Cambridge: Cambridge University Press, 2015), 120.

247 Thomas Bock and Thomas Linner, *Robotic Industrialization* (Cambridge: Cambridge University Press, 2015), 93.

248 Bock and Linner, *Robotic Industrialization,* 118.


Figure 6.50.
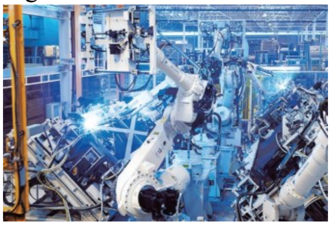
Figure 6.51.

specialised tools, mechanical equipment and robotic equipment through work flows. While the automation allows for high quality standards, it generates more individualised products for the purchaser (Figure 6.51). Hence, optimisation of the automation ratio and human flexibility in production provides an opportunity for balanced automation. Such manufacturing automation has the capacity to eclipse the limit of the Second Digital Turn of Non-Standard Architecture.

6.5.2 Robotic Automation in Architecture

Automation in architecture is now capable of being computational with the use of new programming languages, production technologies and open-ended generic fabrication, such as six-axis robots, which are commonly used in automotive and aeronautic engineering. Nevertheless, such automated robotic fabrication systems have specific constraints which define the limit of the tool. For an industrial robot, these limits are threefold: the capability and capacity of the end-effector which delivers material to a fabrication site; the simulation code which instructs; and the robot prototype simulation axis which performs a function. The capacity of current manufacturing processes is limited to off-site manufacturing and on-site assembly. These processes exclude robotic automation on site, which has the capacity to eclipse the limits of the Second Digital Turn. Although the protocol for design and documentation of projects has been digitised and integrates parametric data models, this thesis argues that fabrication of components still retains a high level of skilled manual work within largely non-prefabrication environments.

Figure 6.50. Automation of *Volkswagen Phaeton*, Dresden, 2002. Special jigs and fixtures orientate the car bodies to simplify assembly operations by human workers. Thomas Bock and Thomas Linner, *Robotic Industrialization* (Cambridge: Cambridge University Press, 2015), 140.

Figure 6.51. Automated steel panel production in *Daiwa House Industry*. Robots weld the profiles together which are placed on a jig template. Thomas Bock and Thomas Linner, *Robotic Industrialization* (Cambridge: Cambridge University Press, 2015), 160.

In the architectural and engineering academies, research contributed to the evolution of robotic end-effectors, where fabrication became customised for specific materials. Research into realising robotic fabrication in architecture emerged in academia with industrial robotic laboratories at ETH Zurich (2005), Harvard Graduate School of Design (2008), University of Michigan (2009), University of Stuttgart (2010) and the Architectural Association in London (2011). Their parallel research led to the advent of the tools, customisation, case studies and prototypes based on the six-axis industrial robot implemented for prototyping. Research by ETH Zurich focused on human–machine interactive end-effectors for a six-axis industrial robot for the mobility of industrial robots on site to perform prefabrication tasks (Figure 6.52). Algorithmic software was developed for robot operation with instructions and sensors such as feedback mechanisms, and two-dimensional and three-dimensional scanning guidance.

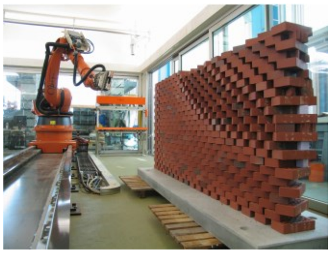

Figure 6.52.

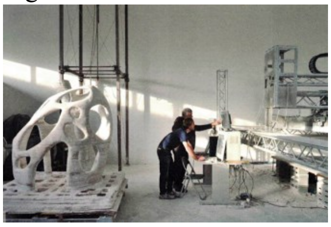

Figure 6.53.

Research on additive manufacturing focused on innovation with end-effectors, such as powder bed and inkjet head three-dimensional printing and fused deposition modelling to glue sand layers with a Portland cement paste.[249] The earliest three-dimensional concrete printing technique was unveiled by Contour Crafting's building printing research project in 1996. It was based on the extrusion of two layers of cement paste mix in 10 cm layers, delivered from a digitally controlled nozzle mounted on a large gantry crane. Nevertheless, the system was limited to

Figure 6.52. Integration of programmed wall simulation into an industrial robot. Thomas Bock and Thomas Linner, *Robotic Industrialization* (Cambridge: Cambridge University Press, 2015), 24.

Figure 6.53. *D-Shape* large-scale 3D concrete printing. Nick Dunn, *Digital Fabrication in Architecture* (London: Laurence King Publishing, 2012), 107.

[249] Branko Kolarevic ed., *Architecture in the Digital Age: Design and Manufacture* (New York: Taylor & Francis, 2009), 36.

Figure 6.54.

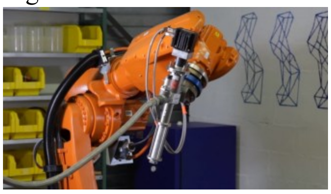

Figure 6.55.

vertical extrusion of a planar shape and required complex trowelling processes. An alternative method, *D-Shape* (Figure 6.53) for a three-dimensional printing powder deposition process in 2005 provided unrestricted virtual three-dimensional form, however with minimum detail restricted to approximately 20 mm in size and low material strength as a result of the durability of the layering process.

Research by Loughborough University on *Freeform Construction* in 2008 introduced a three-dimensional printing method based on high performance concrete created through a jetting system, depositing material with a robotic arm mounted on an overhead crane in layers ranging from 5 to 24 mm (Figure 6.54). Higher mechanical performance and geometrical control were achieved with better material properties of the concrete and small diameter of the extrudate reduced to 4–6 mm. Despite the material geometry control, there were significant technical issues in delivering material through a system of three-axis deposition to realise the concept. In 2015, *XtreeE* large-scale additive manufacturing in concrete achieved geometric complexity based on the fused deposition modelling technique, with layer by layer deposition of material through a custom-designed printhead mounted on the robot (Figure 6.55). The concrete material was developed with LafargeHolcim building materials manufacturer, to reach an efficiency of fabrication speed and mechanical resistance in large-scale concrete additive manufacturing. The method involved conveying the mix with a peristaltic pump towards a mixing screw located in the printhead. Additives were dispersed in the mix just after extrusion with a 20 mm wide designed extrudate. Compared to earlier methods, *XtreeE's* novel approach, enabled by new robotic apparatus and parametric data

Figure 6.54. 3D printing concrete equipment at Loughborough University laboratory. Thomas Bock and Thomas Linner, *Robotic Industrialization* (Cambridge: Cambridge University Press, 2015): 42.

Figure 6.55. *XtreeE* 3D printing concrete customised end-effector for six-axis industrial robot. "XtreeE the Large Scale 3D", accessed June 7, 2019, http://www.xtreee.eu/.

modelling, re-examined existing construction methods and consequently evolved robotic fabrication in architecture using concrete 3D printing technology.

The first contemporary architectural proposal as a redefinition of an industrial six-axis robot arm for parametric geometry was the *ARACHN[OL]OIDS* prototype (2013) developed as part of my group academic research project at the Architectural Association in London. This thesis identifies the *ARACHN[OL]OIDS* prototype as the first Non-Standard architectural robot. The only earlier speculative approach developed by R&Sie(n) was an extension of the industrial six-axis robot for concept *Olzweg* (Figure 6.56) in 2006. While *Olzweg* implemented a kinematic simulation of the six-axis industrial robot, *ARACHN[OL]OIDS* robot proposed novel kinematic simulation based on kaleidocycle geometry (Figure 6.57). The *ARACHN[OL]OIDS* 7R-Bricard Linkage robotic apparatus generated a shell as a three-dimensional ruled surface. The geometric simulation of surface automation was envisaged with the brainwave interface tool proposed as a new method of architectural codification in real-time. The *ARACHN[OL]OIDS* concept was developed as a parametric data model.

Figure 6.56.

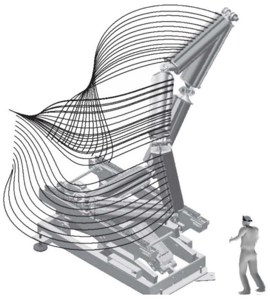

Figure 6.57.

6.5.4 Automation of Graded Material

In 2015, the Institute for Lightweight Structures and Conceptual Design in Stuttgart began developing automated production processes for functionally graded concrete as an ecological method of lightweight structures for linear design elements. The method integrated an optimisation process for the fabrication of linear functionally graded concrete geometry. Grading of concrete

Figure 6.56. *Olzweg* by R&Sie(n). Olzweg, New–Territories, accessed August 7, 2020, https://new-territories.com/welostit.htm.

Figure 6.57. Robot prototype and machine simulation for the generation of surface geometry. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).


Figure 6.58.


Figure 6.59.

Figures 6.58 and 6.59. The application system for the production of functionally graded concrete components with automated spraying nozzle at the University of Stuttgart. Photograph by University of Stuttgart.

components is a technological development that integrates two concrete reference mixes with contrary characteristics, deposited with the automation process in a continuous variability of the structure's properties along at least one direction in space. The method involves the arrangement of high performance concrete in stressed zones and highly porous concrete in regions with low stress, to achieve fully stressed components with minimum weight, in three spatial dimensions.[250] The spray robot is used to integrate different strengths of concrete into the spray method optimisation process for geometry fabrication (Figures 6.58 and 6.59). The method can be termed ecological in that distribution of concrete aims for efficiency, maximum structural performance and reduction in material bulk, energy, water and waste.

The methodology for fabricating functionally graded concrete components requires an automated manufacturing process that includes design, computation of optimum density distribution, transfer of the CAD model, mixing the concrete according to specifications and material application.[251] The concrete spraying automation parameters have a decisive influence on the manufacturing process of functionally graded concrete. The process parameters are divided into four areas: type of machine, type of energy input, conveying pipeline (diameter and

[250] Michael Herrmann and Werner Sobek, "Functionally Graded Concrete – Numerical Design Methods and Experimental Tests of Mass-Optimised Structural Components," *Structural Concrete* (Berlin: Ernst & Sohn, 2016), 54.

[251] Mark Woerner et al., "Automated Spraying of Functionally Graded Concrete Components – Analysis of the Process Parameters," *Proceedings of the International Association of Shell and Spatial Structures* (August 2015): 3.

length), and type and location of water supply. The current spray robot at the Materials Testing Institute of the University of Stuttgart integrates a digital system that allows adjustment of variables and analysis of the application system process parameters. The robot gantry has three-axis movement with an additional six-axis parallel robot mounted on the gantry to generate a three-dimensional orientation with the nozzles for the varied movements required. The working area is limited to a platform of 3 m length x 3 m width x 1.5 m height, which excludes large scale prototyping.

The concrete spraying technique consists of a mixing system with different concrete mixtures, designed as a fine grain concrete with high strength and low porosity, in contrast to the lower strength mix (Figure 6.60). Each mix travels through a conveyor belt with an evaluating device to a rotary dry spraying machine, which conducts the dry concrete with defined air pressure and flow rate to the nozzle. The process for wetting the concrete uses a water pump and a liquid dosing device prior to and inside the nozzle.[252] The automated end-effector consists of two superimposed spray jets that are in accordance with the specifications for the functionally graded concrete component (Figure 6.61). Thus, the digitised data protocol makes the production of gradient concrete possible only with automation.[253]

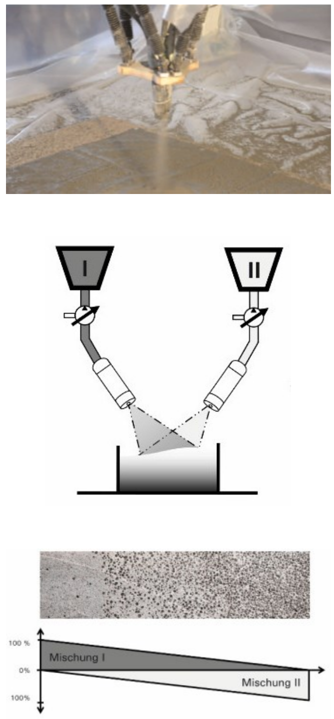

Figure 6.60.

Figure 6.60. *Above*, Spraying concrete application. *Below,* Graded spraying method components. Michael Herrmann, "Gradientenbeton" (PhD diss., University of Stuttgart Institute for Lightweight Structures and Conceptual Design, 2015), 25.

[252] Mark Woerner et al., "Automated Spraying of Functionally Graded Concrete Components – Analysis of the Process Parameters." *Proceedings of the International Association of Shell and Spatial Structures* (August 2015): 1–13.

[253] Werner Sobek, "Building with Concrete: New Impulses," *Best of Detail: Concrete*, ed. Christian Schittich (Berlin: De Gruyter, 2016), 29.

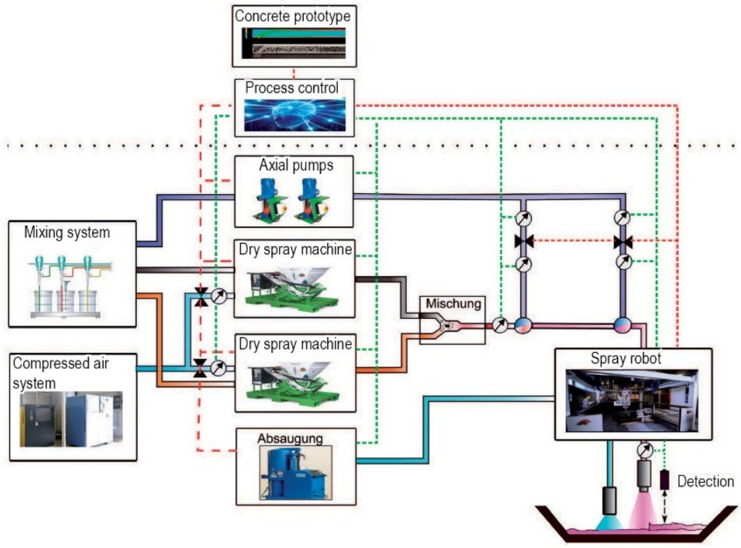

Figure 6.61. Schematic layout of graded concrete spraying optimisation process. Silke Scheerer and Manfred Curbach, *Leicht Bauen Mit Beton* (Dresden: Institut fur Massivbau, 2014), 174.

6.5.5 The Limits of Automated Architecture

Compared to traditional tools, automation brings consistency, a controlled environment and an easier setup, which significantly improves productivity. With software advances, programs and processes for managing the system have increased operator productivity. A significant benefit of automation is environmental sustainability, where Non-Standard construction component weight can be minimised with structural performance, topological variation and shape optimisation. With the reduced cost of robot technology, the return on investment for embedding automation has increased.

In addition, robot prototypes for complex geometries have been developed, integrating various axes for the development of curved surfaces. However, while robotic fabrication has advanced with increased range of movement of the robotic arm and with custom robot prototypes, construction capability still requires a high level of skilled manual work due to the limits of conventional construction practices. The thesis identifies this challenge as a limit in the Second Digital Turn of Non-Standard Architecture which has so far constrained its capacity to fully implement robotic automation for construction.

6.6 Case Study: The First Non-Standard Architectural Robot *ARACHN[OL]OIDS*

This case study identifies the first Non-Standard architectural robot prototype developed as part of my academic research at the Architectural Association in London. The *ARACHN[OL]OIDS* prototype (2011–13) introduced a novel seven-axis automated robot developed from the kinematics of kaleidocycle geometry for creating shell structure.[254] It aimed to fill a gap between computational technology and existing techniques of production that were not capable of generating complex shell geometries in built form. The robotic apparatus concept was oriented towards integrative computational and fabrication methods that combine technology, architecture and mathematics while adapting earlier methodologies of Elementarism in the 1920s and its cybernetic reinterpretations of the 1960s.

Elementarism emerged as a reaction to Neoplasticism which developed a universal language that gradually gave rise to Modernism. Elementarism incorporated dynamic configuration of the human experience of movement, instead of the static balancing of universals found in De Stijl theory and practice. Within this framework, innovative geometric concepts of Elementarism emerged such as the combination of shapes and rules for optimisation, as an analogue to the nature of computation and recent developments of Non-Standard Architecture in which parametric data model materialised.

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[254] Melika Aljukic et al., "ARACHN[OL]OIDS," *Architectural Association Design Research Lab (AADRL)*, accessed January 15, 2020, http://drl.aaschool.ac.uk/portfolio/spoon-benders/.

The complexity emerged as a result of basic operations on the elements such as repetition, arithmetisation and simulation. The Non-Standard architectural robot was generated by adding additional linkage and altering the kinematics embedded in kaleidocycle geometry. Thus, Non-Standard behaviour was generated from sinusoidal movement of the kaleidocycle (Video 6.62) that is governed by a circular function (Figure 6.62).

The kaleidocycle and two kinematic sets with different behaviour were obtained by dividing the cube (Video 6.63). Spatial analysis of the kaleidocycle geometry with the six-linkage tetrahedra informed the strategy for shell fabrication[255] (Figure 6.63). The ruled surface was defined by altered seven-axis linkage revolving in space. The Non-Standard geometry was identified by this thesis within the ruled surface of the straight lines or rulings of seven-axis linkage that generated asymptotic curves and parametrised the configuration, rendering it calculatable for translation into a buildable form. The deployment of asymptotic curves for load-bearing structures constitutes novel geometry in architecture as it has not yet been used in architectural projects featuring geodesics and principal curvatures. One of the advantages of asymptotic curves is straight unrolling and orthogonal nodes within shell geometry that advance the potential realisation of Non-Standard Architecture. Within a ruled surface, the straight or ruled lines generated produce asymptotic curves and parametrise the configuration, making it calculable with the necessary precision for translation into a buildable form.

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[255] Melika Aljukic et al., *Architectural Association Projects Review 2012: ARACHN[OL]OIDS*, accessed January 20, 2012, http://pr2012.aaschool.ac.uk/students/Spoon_Benders.

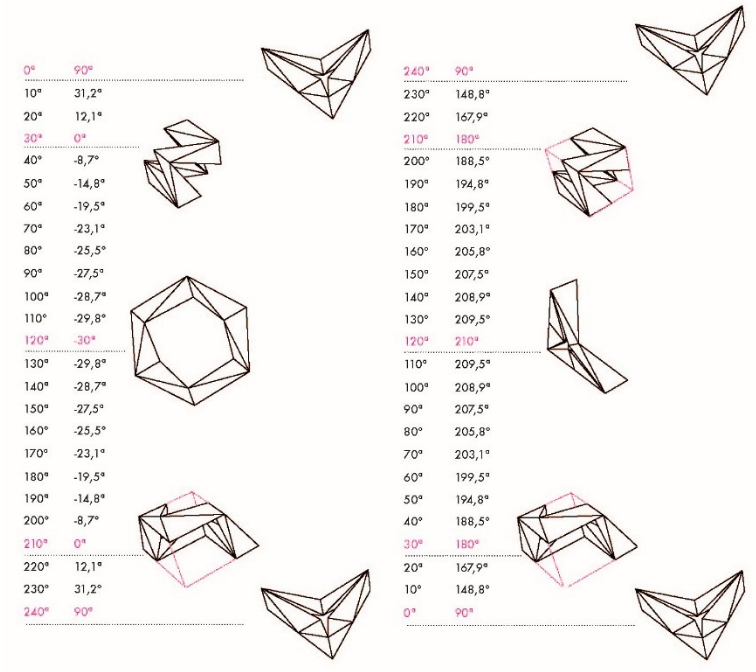


Figure and Video 6.62. Analysis of kaleidocycle geometry inversion. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

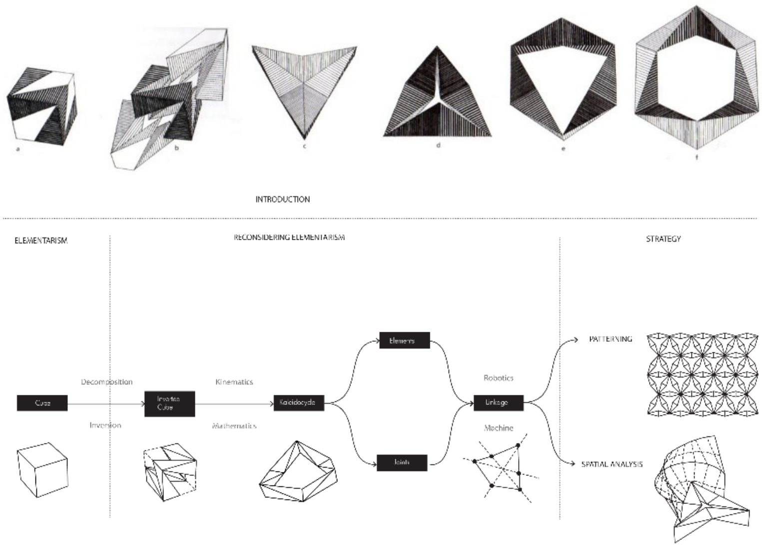


Figure and Video 6.63. *Above*, Spatial analysis strategy of the cube into sixfold linkage with one degree of freedom; *Below,* Cube translation into kaleidocycle and integration of kinematics into the geometry of kaleidocycle for shell definition. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

6.6.1 Spatial Definition of Shell

The method to analyse and simulate geometry of the kaleidocycle in a parametric data model is characteristic of the Second Digital Turn (Figure 6.64). The robotic apparatus was developed using Bricard Linkage – a closed-loop overconstrained spatial mechanism composed of six hinge-jointed bars. The 6R-Bricard Linkage is found in a six-axis kaleidocycle, and it represents a closed loop that works with an offset, which gives mechanical properties to the kaleidocycle model (Video 6.64). Non-Standard construction was analysed through variations by integrating a different number of linkages and joints with different degrees of freedom. The project automation introduced a novel method for simulating Non-Standard Architecture. Compared to 6R-Bricard Linkage that generated a closed space (Figure 6.65), 7R-Linkage showed the resultant meshes (Figure 6.66), which defined the shell as a three-dimensional ruled surface of third order (Figure 6.67). The robotic apparatus designed was automated by algorithmic input on the seven rotary actuators in place. The system had resources integrated, including material and structural properties to unfold and release. The robot prototype simultaneously integrates the design concept, material, manufacture and construction.

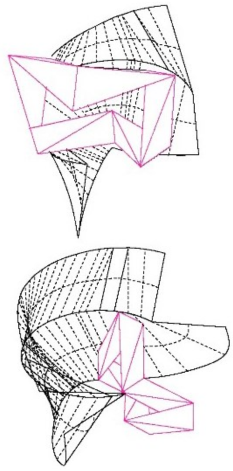


Figure 6.64.

Video 6.64.

In sum, the developed prototype contributes to the realisation of Non-Standard Architecture by introducing novel automation into construction and addresses the persistent limits that have so far constrained the full development of parametric possibilities in architecture. In a significant way, this increase in quality also enables the introduction of a dimension of craft, which is normally absent from automated industrial manufacturing

Figure and Video 6.64. Spatial analysis strategy of kaleidocycle. Surface definition generated with kinematic sets of different behaviour obtained from the cube volume. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

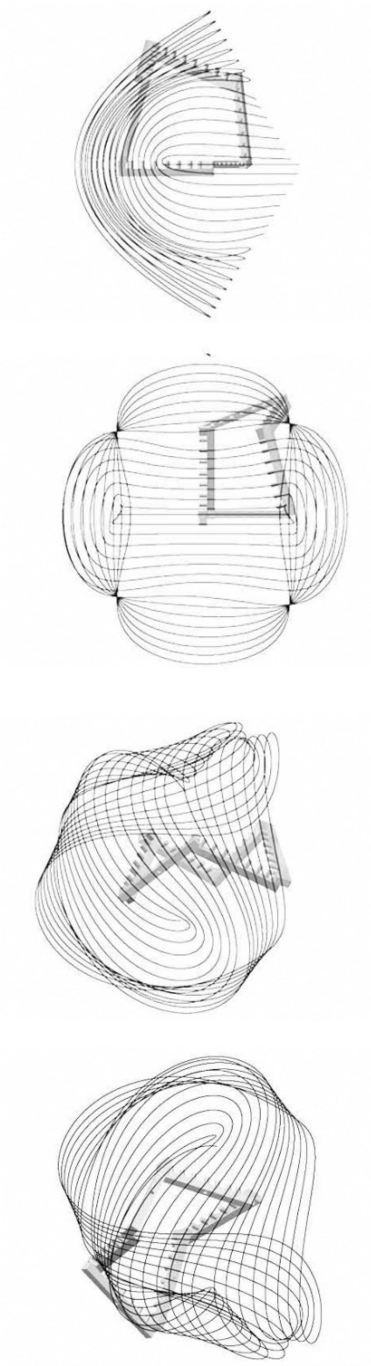


Figure and Video 6.65. Spatial analysis of the ruled surface of degree 3 created by a regular 6R Bricard Linkage simulated in a constrained environment. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

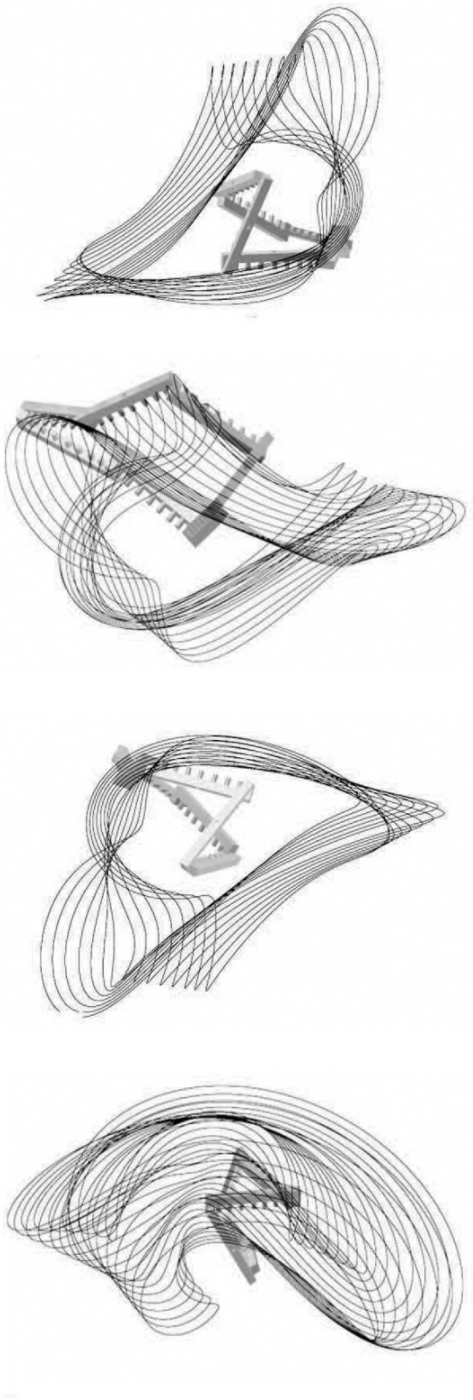
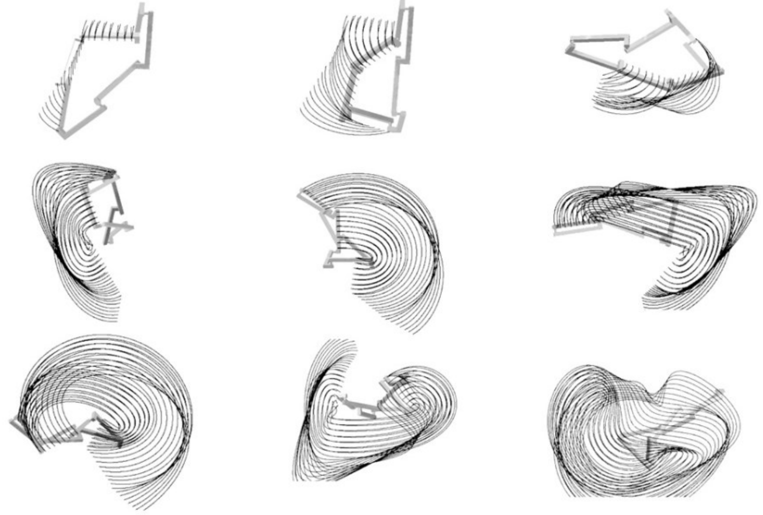


Figure and Video 6.66. Spatial analysis of the ruled surface of degree 3 created by a regular 7R Bricard Linkage simulated in a constrained environment. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).



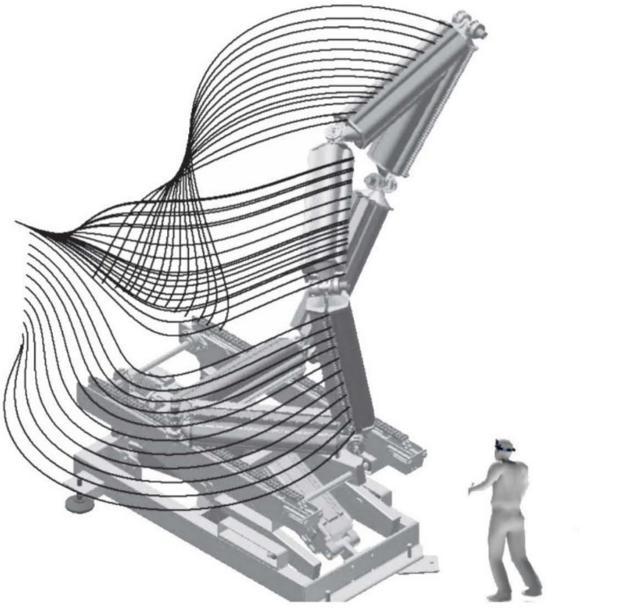


Figure and Video 6.67. *Above*, *ARACHN[OL]OIDS* robot prototype for shell construction. The seven-linkage robotic apparatus with revolute joints defines the shell as the three-dimensional ruled surface of the third order. *Below*, Robot prototype and machine simulation for the generation of surface geometry. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

6.6.2 *ARACHN[OL]OIDS* Architectural Codification

Geometric simulation of surface automation was investigated using the brainwave interface tool integrated with Arduino programming language to input information parameters for the geometry (Figure 6.68). The neural interface is a new method of architectural codification for the spatial movement of geometries in real-time. The brainwave reader interface was created from a sixteen-electrode device that read external cortex brainwaves from the human brain. The user interface of system variables was controlled through visualisation. Resulting experiments showed a neural interface requiring linear concentration and control for a result in directing simulation through a brainwave reader. The method involved processing an algorithm to link the neural signals with the automated linkage. The physical linkage obtained the command task through Arduino and performed accordingly in real-time.[256]

Figure 6.68.

6.6.3 Material Deposition End-Effector

The *ARACHN[OL]OIDS* Non-Standard architectural robot was envisaged for fabrication in lightweight materials with a material deposition end-effector for multiphase weaving in carbon fibres and composites (Figure 6.69). The end-effector was proposed as an air-jet insertion into each robot linkage prototype for parallel weaving of surface material. The ruled surface was automated by the trajectory of a rotating linkage revolving into the curvature with carbon fibre rods (Figure 6.70). The

Figure 6.68. Shell surface generated with seven-axis linkage *ARACHN[OL]OIDS* robot prototype using weaving method. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

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256 Melika Aljukic et al., "ARACHN[OL]OIDS", *AA Book 2013* (London: Architectural Association, 2013), 201.

Figure 6.69.

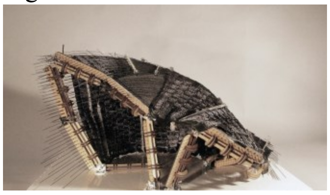

Figure 6.70.

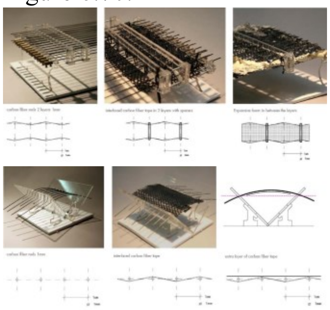

Figure 6.71.

Figures 6.69–6.71. Carbon fibre shell models and prototype tests with carbon fibre and resin. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

rulings of the surface were interlaced with the carbon fibre (Figure 6.71). The thesis envisages this Non-Standard architectural robot and material deposition end-effector adaptable and applicable to other materials such as functionally graded concrete over the identified rulings of the surface. For graded concrete, the material deposition end-effector would adapt an automated spray mechanism for specified concrete aggregates.

6.6.4 Non-Standard Structural Analysis

This first Non-Standard architectural robot prototype generated with a parametric data model and 7R-Bricard Linkage end-effector was defined as an architectural shell. Non-linear structural analysis was performed for composite elements where each layer was made of a different material with great heterogeneity of properties. A digital shell surface model (6.5 m high and 10 m wide) was integrated and assigned self-weight loads and wind loads for structural analysis (Figure 6.72). Structural model analysis results for the shell surface showed ruled surfaces producing relatively small bending moments, allowing for lightweight shells (Figure 6.73). The surface model was manufactured in polymethyl methacrylate (PMMA) with a rapid prototyping technique (Figure 6.74) to make precision components.

Figure 6.72. Seven-axis generated shell model. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

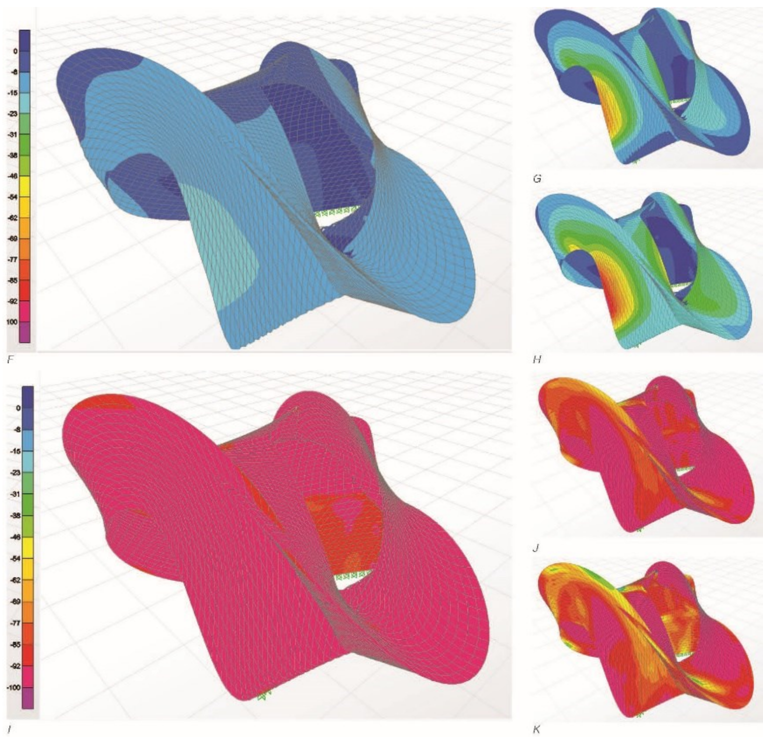

Figure 6.73. Structural finite element method shell analysis. *F-H,* Results: Displacement from wind (mm); *I-K*, Results: Stresses from wind (MPa). Structural analysis by Degree of Freedom Engineers. Prototype by Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

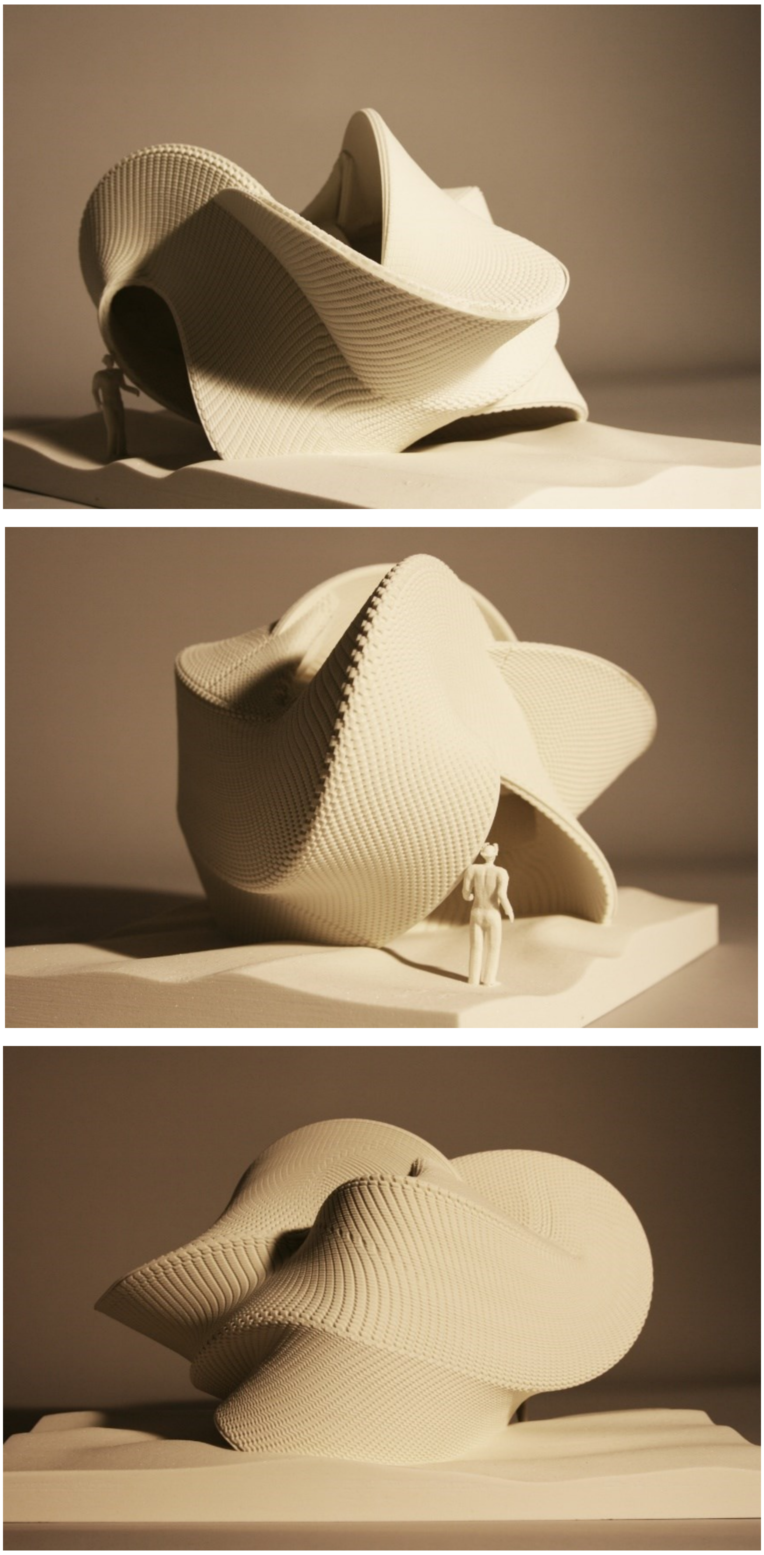

Figure 6.74. 3D printed shell prototype in polymethyl methacrylate (PMMA) with a rapid prototyping technique. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

6.6.5 Non-Standard Architectural Robot Variations

The *ARACHN[OL]OIDS* architectural robot was oriented towards integrative computational and fabrication methods with variations of simulations for Non-Standard surface geometry based on different degrees of freedom, changing rotary angles and altering elements. Codification of integrative computational and fabrication methods was generated as a simulation of the inversion kinematics using a combination of software including Rhinoceros, Grasshopper, Mathematica, Inventor and Processing programming languages for mass customisation of design. Automated variations explored different conceptualisations of Non-Standard Architecture. This was a new customised design of the robotic apparatus that differentiated automation from standard industrial six-axis robots. It enabled autonomous spatial definition of Non-Standard geometry for further customisation from increased degrees of freedom in the seven-linkage robot prototype, showing a number of different Non-Standard form modifications (Figure 6.75).

Variations on seven-axis linkage geometry were grouped into four key parameters: transitional freedom, rotational freedom, altering the elements and altering the rotary angle. In exploring geometric possibilities, ten architectural robot variations were created with changing degrees of freedom and their location that generate a ruled surface with asymptotic curves, which make the automated architectural robot Non-Standard (Figure 6.76).

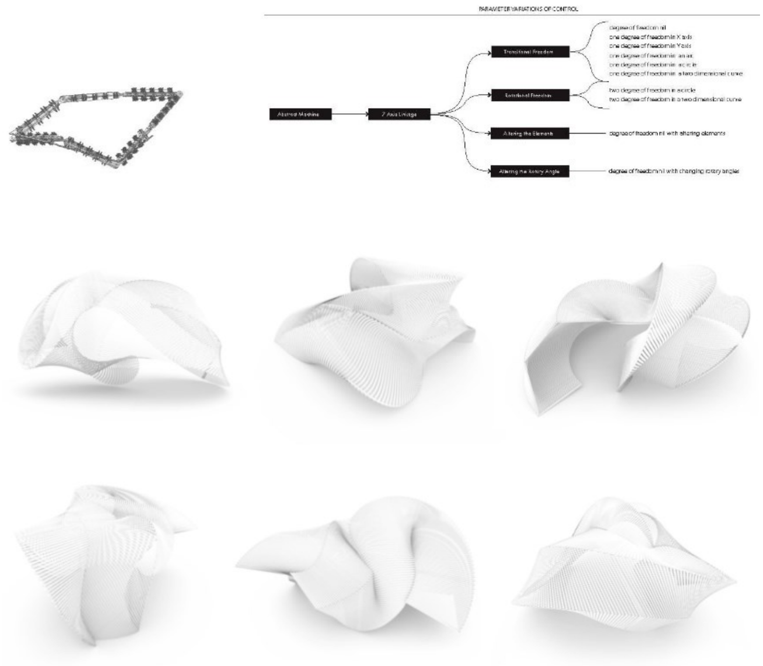

Figure and Video 6.75. Shell surface variations created with the strategy for angle degree adjustment of the *ARACHN[OL]OIDS* robot prototype. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

The final prototype was envisaged to be adaptable for different sites (Figures 6.77 and 6.78). The prototype was presented in January 2013 at the Architectural Association in London.[257] With advances in computational technology, robotic apparatuses enable the transition from digital design and prototyping to techniques of full scale, factory fabrication and on-site construction. Such optimal data can be used as input for abstract machines in the form of robotic apparatuses for geometrical definition.

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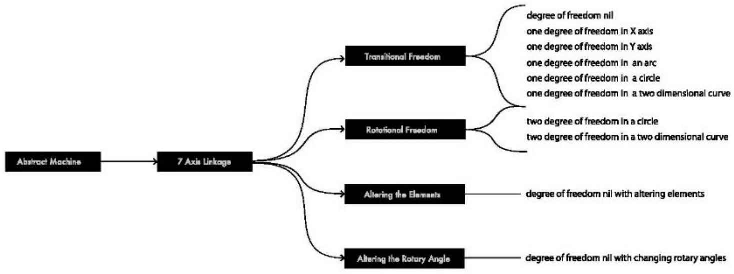
[257] Melika Aljukic et al., "ARACHN[OL]OIDS," *AA_DRL Phase 2 Final Public Jury 2017/18* (London: Architectural Association, 2013), 10.



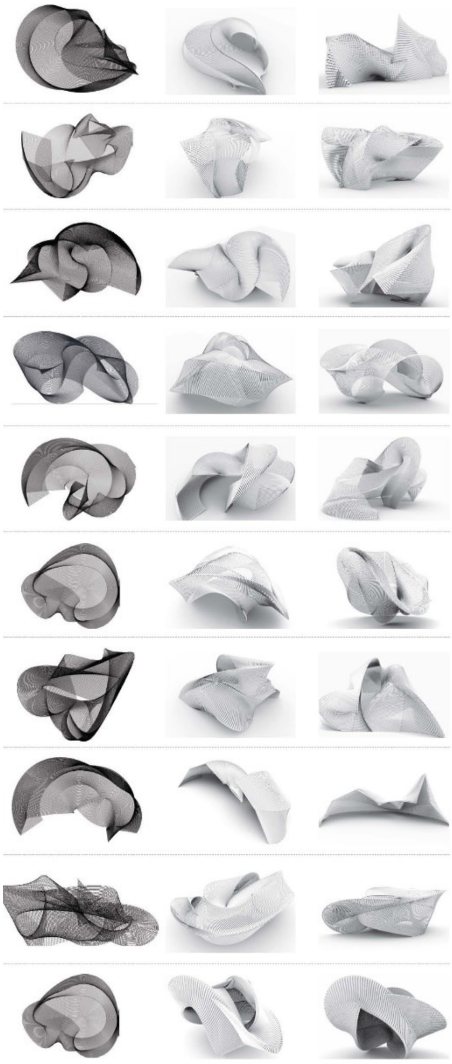


Figure 6.76. Shell geometry variations. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

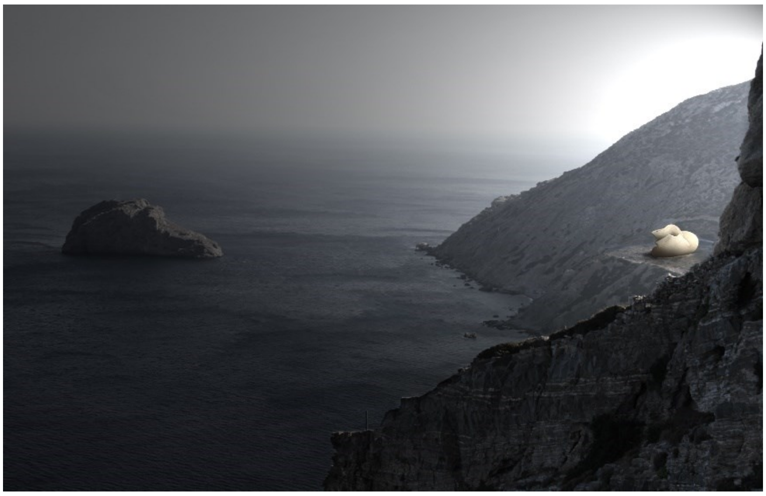


Figure 6.77. *ARACHN[OL]OIDS* prototype on site. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

Figure and Video 6.78. *ARACHN[OL]OIDS* prototype on site. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

Figure 6.79. *ARACHN[OL]OIDS* prototype on site. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

Figure and Video 6.80. *ARACHN[OL]OIDS* prototype on site. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

Figure 6.81. Presentation of the project *ARACHN[OL]OIDS* by Melika Aljukic, Margarita De Bruijn, Sreerag Palangat Veetil and Carles Sala at the Architectural Association in London, 2013. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

The *ARACHN[OL]OIDS* prototype experiments with lightweight intelligent materials and rapid prototyping technologies, assimilated with the power of computation.

On the basis of this experimental work and additional applied workshop research, the thesis contends that the customisation and optimisation made possible by robotics in architecture have conceptual, political and strategic potential. The potential is for autonomously automated architecture which integrates automation as part of the construction and addresses the potential limits that have so far constrained the full development of parametric possibilities in architecture. As a counter to mainstream developments in machine learning and human–machine interaction, the prosthetics of future machines extend the limits of human physical capacities. This notion of functional redefinition upgrades architecture to a state in which it becomes the anterior prosthetic extension of the human body itself.

6.7 Case Study: Functionally Graded Materials and Non-Standard Architecture

The case study on functionally graded materials and their application in robotics investigates a distinct field of little research, in particular, the use of functionally graded concrete to realise Non-Standard parametric forms in architecture. The thesis extends a body of work undertaken since 1963 by Frei Otto, specifically on optimisation in lightweight construction and form finding at the Institute for Lightweight Structures and Conceptual Design in Stuttgart. Functionally graded concrete has been investigated under the direction of Werner Sobek since 2006. The technology of graded materials provides an innovative possibility to align the internal composition of a concrete component with defined structural and thermal requirements. The research by the Institute for Lightweight Structures and Conceptual Design on functionally graded concrete indicates opportunities for environmental sustainability by the design optimisation of linear elements like graded precast floors which reduced component weight by 42%, compared to a normal concrete floor slab with a 5 m span. In addition, permitting more significant deformation and using a textile carbon-fibre reinforcement, grading enabled a mass element reduction of about 60% while providing the same load-bearing capacity as a solid floor slab. Correspondingly, the method was associated with lower CO^2 emissions.[258]

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[258] Michael Herrmann and Werner Sobek, "Functionally Graded Concrete – Numerical Design Methods and Experimental Tests of Mass-Optimised Structural Components," *Structural Concrete* (Berlin: Ernst & Sohn, 2016), 1.

6.7.1 Non-Standard Graded Protocol

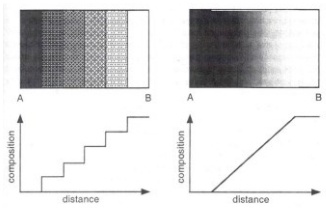

Figure 6.82.

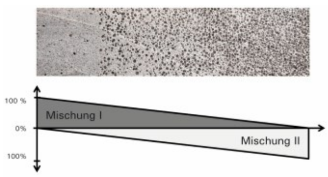

Figure 6.83.

Figure 6.82. Continuous and multilayered grading. Yoshinari Miyamoto et al., *Functionally Graded Materials: Design, Processing and Applications* (Boston: Kluwer Academic Publishers, 1999), 53.

Figure 6.83. Graded concrete. Michael Herrmann and Werner Sobek, "Development of Weight-Optimised, Functionally Graded Precast Slabs," *Building Future* (Stuttgart: ILEK University of Stuttgart, 1998), 5.

This thesis chapter contributes to the evolving technology of optimisation developed at the Institute for Lightweight Structures and Conceptual Design in Stuttgart. The research contributes by undertaking work in functionally graded concrete to achieve Non-Standard forms that integrate both design optimisation and material optimisation with robotic automation.[259] The grading of microstructures is distinguished between continuous change in composition and multilayered interfaces between discrete layers (Figures 6.82 and 6.83). These variations of material distribution have structural implications reflected in the processing, modelling and behaviour of functionally graded materials. Linear functional graded concrete is research that began at the Institute for Lightweight Structures and Conceptual Design in 2015. The results by Michael Herrmann for linear graded elements indicate that applying gradient materials in architecture is sustainable based on mass reduction of material (Figures 6.84 and 6.85). The material also has multifunctional properties such as porosity which improves thermal properties within a single structural component. The current research has achieved optimised linear elements in functionally graded concrete, and this research applies it to nonlinear parametric forms. Topology optimisation is a process to achieve optimal material distribution within a defined design space. Material optimisation with functionally graded concrete involves a continuous change in one or several parameters

[259] Melika Aljukic, "Functionally Graded 'Non-Standard' Architecture," *Architecture Bulletin: Climate Crisis*, vol. 76, no. 3 (December 2019): 26–27.

– such as hardness, density, porosity or chemical composition of the concrete – over a defined length in at least one spatial direction.[260] Grading of material is determined by characteristics on the inside of the component of specific requirements, and the density that can be adapted based on the load conditions. Differentiable material parameters include porosity, fibrous content and fibre alignment, as well as the composition of different materials. Werner Sobek describes the purpose of grading concrete as a way to optimise the performance and minimise the weight of a construction component by using the same procedure to optimise its inside. The general idea of structural gradients was first proposed for composites and polymeric materials in 1972 to increase adhesion strength and minimise thermal stress in ceramic coatings and joints development for a reusable rocket engine.[261] The research technique for grading of concrete by the Institute for Lightweight Structures and Conceptual Design was based on a material distribution strategy calibrated by the Solid Isotropic Material with Penalisation (SIMP) method for topology optimisation. The distribution of the material in SIMP topological space aims to distribute material according to the structural properties required for architectural design.

Current developments by the Institute for Lightweight Structures and Conceptual Design have

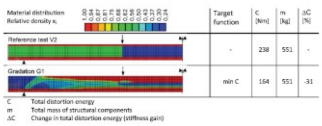

Figure 6.84.

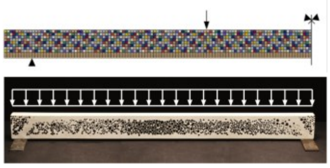

Figure 6.85.

Figures 6.84. and 6.85 Graded concrete. Michael Herrmann, “Gradientenbeton” (PhD diss., University of Stuttgart Institute for Lightweight Structures and Conceptual Design, 2015), 25.

[260] Michael Herrmann and Werner Sobek, “Functionally Graded Concrete – Numerical Design Methods and Experimental Tests of Mass-Optimised Structural Components,” *Structural Concrete* (Berlin: Ernst & Sohn, 2016), 1.

[261] Yoshinari Miyamoto et al., *Functionally Graded Materials: Design, Processing and Applications* (Boston: Kluwer Academic Publishers, 1999), 2.

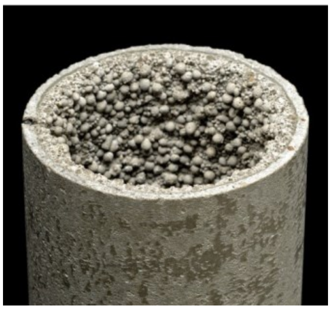

Figure 6.86.

Figure 6.87.

Figures 6.86. and 6.87. Concrete grading prototype with 150 mm diameter and 20 mm thickness. Pascal Heinz, Michael Herrmann and Werner Sobek, *Herstellungsverfahren und Anwendunsbereiche fur Funktional Gradierte Bauteile im Bauwesen* (Stuttgart: Fraunhofer IRB Verlag, 2012), 85.

achieved manufacturing processes for graded concrete by layered casting, controlled segregation and graded spraying. Layered casting is a discrete method that involves pouring into formwork concrete mixes in a layer by layer sequence. For this formwork, metal sheet dividers separate different concrete mixes. The continuous method of controlled segregation involves the separation of the concrete mixture through the introduction of centrifugal force and is therefore suitable for curved geometry. The experiment with controlled segregation for circular pipe with 150 mm diameter and 20 mm thickness (Figure 6.86) indicates a graded concrete distribution with variation value 0.41 w/z at 600 U/min rotational speed (Figure 6.87). Nevertheless, the controlled segregation method is suitable for specific circular geometry with the set of all points in the plane at a fixed distance from the centre.

This thesis extends the work of the Institute for Lightweight Structures and Conceptual Design by investigating the application of functionally graded concrete using an automated graded spraying method for Non-Standard architectural elements. Advantages of graded spraying include controlled concrete gradation to apply the material in thin layers on curved formwork that is not specific to circular geometry. The selected automated spraying end-effectors integrate encoded architectural information on optimisation of aggregates digitally, and thus are suitable for the architectural automation of functionally graded concrete.

6.7.2 Non-Standard Functionally Graded Concrete

To extend research by the Institute for Lightweight Structures and Conceptual Design, and to contribute a new dimension for parametric architecture, this thesis analysed graded concrete for a Non-Standard architectural prototype. The analysis was generated with topology and shape optimisation in Dassault Systèmes Abaqus Topology Optimisation Module (ATOM) programming language, which contains optimisation algorithms that can be adjusted for density layout of functionally graded concrete (Figure 6.88). Optimisation in ATOM programming language enabled processing of a very large number of design variables (100,000 to 1 million) in the prototype which is a characteristic of Non-Standard topological surface. However, the high cost of ATOM software made it difficult to access outside of specialised academia.

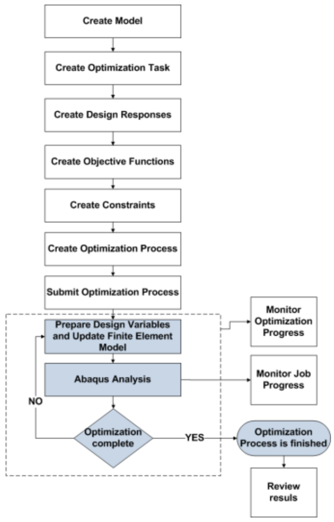

Figure 6.88.

The optimisation process was applied to parametric experiments on the numerical level, where structural components were studied as a simulation in the material model. For simulations performed on non-linear models, concrete damaged plasticity behaviour of concrete was applied in Abaqus, which is an elastoplastic damage model that captures the behaviour of reinforced concrete. Non-Standard geometry was analysed for concrete deformation, beam stress analysis, and maximum and minimum principle. For the graded Non-Standard digital model, seven variables of concrete material behaviour developed by the Institute for Lightweight Structures and Conceptual Design were assigned, starting with high-strength concrete aggregate (KAM) to lightweight concrete aggregate (RA) (Figure 6.89). The grading of the matrix was based on the arrangement of porosity, a range of aggregates and

Figure 6.88. Abaqus Topology Optimisation Module workflow. Dassault Systèmes, *Abaqus Topology and Shape Optimisation Module*, accessed June 8, 2019, http://www.simulia.com/download/rum11/GL/Sandeep-Urankar-ATOM-SGL-RUM-2011.pdf

Mischung	Betongefüge (Schliffbild)	$\rho_{tr,10}$ kg/dm³	ρ_m kg/dm³	$f_{lc,cu}$ N/mm²	$f_{cm,cyl}$ N/mm²	f_{ctm} N/mm²	E_c N/mm²	λ_{tr} W/mK
KAM		0,21	0,32	0,26	0,27	0,13	163	0,03
KLM		0,33	0,49	1,63	1,72	0,66	1023	0,09
G01LM		0,59	0,70	5,27	5,55	1,06	3044	0,17
G02LM		0,81	0,96	8,00	8,42	1,36	5232	0,27
G03L		1,00	1,11	6,83	7,19	1,98	7070	0,37
G05L		1,35	1,69	21,06	22,17	3,17	14040	-
G07L		1,77	2,07	33,22	34,97	4,58	22841	-
RA		2,08	2,23	57,46	60,48	6,16	35050	-

Figure 6.89.

				RA	G07L	G05L	G03L	G02LM	G01LM	KLM
	Material			RA	G07L	G05L	G03L	G02LM	G01LM	KLM
Basic	Rohdichte [kg/mm³]			2,23 E-06	2,07 E-06	1,69 E-06	1,11 E-06	0,96 E-06	0,70 E-06	0,49 E-06
Basic	E-Modul [N/mm²]			35050	22841	14040	7070	5232	3044	1023
Basic	Querdehnzahl			0,2	0,2	0,2	0,2	0,2	0,2	0,2
Compression	1	σ_c	[N/mm²]	22,98	13,29	8,42	2,73	3,20	2,11	0,65
Compression	1	ε_c^{in}	[‰]	0	0	0	0	0	0	0
Compression	2	σ_c	[N/mm²]	57,46	33,22	21,06	6,83	8,00	5,27	1,63
Compression	2	ε_c^{in}	[‰]	0,81	0,62	0,30	0,30	0,20	0,56	0,78
Compression	3	σ_c	[N/mm²]	57,46	33,22	21,06	6,83	8,00	5,27	1,63
Compression	3	ε_c^{in}	[‰]	3,5	3,5	3,5	3,5	3,5	3,5	3,5
Tension	1	σ_{ct}	[N/mm²]	3,80	2,83	1,82	0,75	0,77	0,53	0,21
Tension	1	u_t	[mm]	0	0	0	0	0	0	0
Tension	2	σ_{ct}	[N/mm²]	0,040	0,030	0,020	0,010	0,010	0,005	0,002
Tension	2	u_t^{ck}	[mm]	0,045	0,049	0,059	0,096	0,073	0,030	0,014
Tension	2	G_f	[N/mm]	0,085	0,069	0,054	0,036	0,028	0,016	0,003

Figure 6.90.

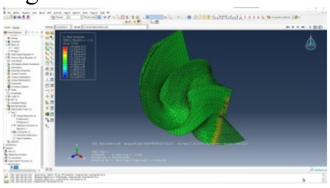

Figure 6.91.

Figure 6.89. Concrete prototypes. Pascal Heinz, Michael Herrmann and Werner Sobek, *Herstellungsverfahren und Anwendunsbereiche fur Funktional Gradierte Bauteile im Bauwesen* (Stuttgart: Fraunhofer IRB Verlag, 2012), 77.

Figure 6.90. Michael Herrmann, "Gradientenbeton" (PhD diss., University of Stuttgart Institute for Lightweight Structures and Conceptual Design, 2015), 77.

Figure 6.91. Non-Standard concrete prototype optimisation in Dassault Systèmes Abaqus and ATOM, Melika Aljukic, 2017.

concrete.[262] For example, the concrete mix sample properties that contain expanded glass and aerogel can be optimised for structural capacity, while concrete mix, including aerogel, has minimum thermal conductivity. The functionally graded concrete process inputs parameters for tension, compression and elasticity of concrete behaviour into a parametric digital model for which specific aggregates are assigned (Figure 6.90.). The optimisation process with ATOM involved multiple objectives based on the specification for the construction of the prototype summed up to the objective of the optimisation (Figure 6.91). The results generated with the digital model require collaborative work with other disciplines such as structural engineering, which is a characteristic of the Second Digital Turn, in order to assign automation of Non-Standard prototype data from a digital platform to the concrete spraying process.

This research on parametric Non-Standard architectural components in functionally graded concrete aimed to minimise component weight together with optimised performance, topology and multiple shape potential. The outcome of the research was twofold. Firstly, it demonstrated the evolution of Non-Standard architectural codification and production processes, for example, with ATOM that can optimise Non-Standard complex geometry with multiple objectives, and potentially extend the capacity of existing skills and technologies to achieve innovative formal results. Secondly, it demonstrated environmental sustainability, where Non-Standard

[262] Michael Herrmann and Werner Sobek, "Development of Weight-Optimised, Functionally Graded Precast Slabs," *Building Future* (Stuttgart: ILEK University of Stuttgart, 1998), 3.

construction component weight, embodied energy and landfill can potentially be minimised without compromising performance, topology and shape optimisation.[263]

The thesis identified a limit in the codification of translation of an optimised parametric data model in assigning prototype data for automation of spraying parametric form. The engineering methods still need to develop a way to assign and distribute continuous topological and structural information through the spraying process on the parametric concrete prototype. This might require new software for automating the Non-Standard graded prototype and a specific end-effector to reach the required specifications. The spraying end-effector process was tested on the parametric form generated by the prestressed membrane without assigned optimised parametric data model at the Institute for Lightweight Structures and Conceptual Design in Stuttgart (Figure 6.92). Prototyping of functionally graded concrete was based on fine-grain concrete *Sica Matrix 2* on the textile membrane and reinforcement to achieve a Non-Standard form. The application of functionally graded concrete on Non-Standard elements involved spraying one mix on prestressed membranes (Figure 6.93). While this test demonstrated the application of functionally graded concrete on the parametric surface, more work is required to link the optimisation information of the parametric model to spraying automation in order to allocate high performance concrete in stressed zones and highly porous

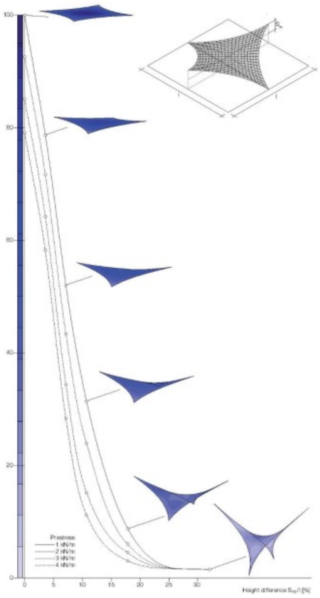

Figure 6.92.

Figure 6.93.

Figure 6.92. Comparison of the curvature-dependent deformations of various four-point sails with the same material properties, prestresses, spans and wind loads. Jan Knippers et al., *Detail: Construction Manual for Polymers + Membranes* (Basel: Birkhauser, 2011), 144.

Figure 6.93. Graded concrete surface generated with spray method on the arch-supported mechanically prestressed membrane. Institute for Lightweight Structures and Conceptual Design in Stuttgart, 2016.

263 Melika Aljukic, "Robotic Fabrication in Architecture," *Research Visions 2016: Bridging Research and Practice* (Sydney: University of Sydney, 2016), 13.

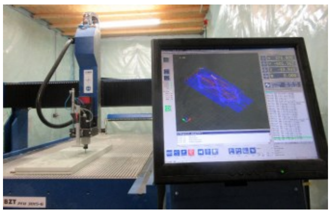

Figure 6.94.

concrete in regions with low stress, that is, to achieve fully stressed components with minimum weight in three spatial dimensions. Furthermore, the experiment was conducted for the functionally graded concrete lattice with openings integrating steel circular rod reinforcement. The automated spraying process indicates that spraying allows a maximum of 20 cm diameter of functionally graded concrete mix on circular steel reinforcement.

6.7.3 Non-Standard Graded Ultra-High Performance Concrete

Research undertaken for this thesis on grading ultra-high performance concrete mix with steel fibres aimed to optimise the concrete. The guideline for this optimisation aimed for precise allocation of graded steel fibres within a Non-Standard prototype with lattice openings. Assigning automation of graded parametric data still needs to be developed in structural engineering and fabrication, thus the prototype was tested as a continuous mix with steel fibres added in the Non-Standard mould generated on a three-axis CNC milling machine with SprutCAM programming language (Figure 6.94). An ultra-high performance concrete mix was created in the Institute for Lightweight Structures and Conceptual Design workshop from cement, sand aggregate (0.6–1.2 mm), superplasticiser, additive, admixture and steel fibres. The concrete mix specifications were based on high performance binder *Dyckerhoff Flowstone.* Combined high strength concrete aggregate and steel fibre concrete mix achieved strength over 100 MPa within 28 days.

Figure 6.94. Axis Computer Numerical Control (CNC) machine milling the formwork with SprutCAM coordinates by Melika Aljukic at the Institute for Lightweight Structures and Conceptual Design in Stuttgart, 2016.

The high concrete strength generated provides an advantage in building thin sections and long spans with the advantage of larger openings that result in lightweight, durable and sustainable structures. During the concrete curing process, superplasticiser and a low water cement ratio minimised the pores and high packing density which contributed to the high compressive strength of concrete (Figure 6.95). The steel fibres in the lattice prototype reinforced the ultra-high performance concrete enabling openings within a Non-Standard lightweight element. This research highlights the potential for grading of steel reinforcement within the ultra-high performance concrete parametric component, which could be developed for fabrication with the method of spraying as a feasible and sustainable technique, eliminating the need for formwork with the use of prestressed membranes. The high compressive strength and improved durability of concrete provides lightweight, durable and sustainable Non-Standard Architecture.

Figure 6.96.

Figure 6.95. Prototype of steel fibre reinforced ultra-high performance concrete lattice by Melika Aljukic, 2016. The prototype is a collection at the Institute for Lightweight Structures and Conceptual Design in Stuttgart.

Figure 6.96. Melika Aljukic exhibiting her research work as part of the Research Visions 2016 conference at the University of Sydney.

Figure 6.97.

The practical experiments undertaken for this thesis on the three-dimensional gradation of concrete using a spray process indicate that the spray end-effector method requires more development for the fabrication of parametric functionally graded concrete. Automated application of the functionally graded concrete parametric data model with the spraying process is yet to be accurately managed digitally. In conclusion, the Non-Standard grading process needs to be developed further to translate data from the assigned parametric concrete digital model to the aggregate information variables of the spraying automation process.[264] Research work by the author has been exhibited as part of the *Research Visions* conference at the University of Sydney in 2016 and 2017 (Figure 6.96 and 6.97).

6.8 Conclusion: The Limits of Architectural Automation

The theoretical component of this thesis identified that the limit of robotic fabrication in architecture and construction is in the development of technology tools and fabrication methods. The practical component of the research identified a method to overcome this limit and address some of the constraints that have prevented the realisation of Non-Standard forms in conventional architectural construction. The method aims to automate Non-Standard Architecture with functionally graded concrete from the digitised material prototype. These experiments show potential for an ecological approach in

Figure 6.97. Melika Aljukic exhibiting her research work as part of the Research Visions 2017 conference at the University of Sydney.

[264] Melika Aljukic, "Robotic Fabrication for Non–Standard Architecture," *Research Visions 2017: Bridging Research and Practice* (Sydney: University of Sydney, 2017), 10.

Non-Standard Architecture. The thesis contends that the achievement of Non-Standard Architecture is in the optimisation of material and the novel geometries required for formal and structural purposes. Functionally graded concrete is an ideal material for this purpose as it can be structurally optimised using a finite element analysis method and naturally incorporates insulation air gaps to create a monolithic material that performs sustainably in multiple ways: logistically, structurally and environmentally. Within this framework, the thesis showed that a parametric data model combined with a simulation protocol for functionally graded concrete has the potential to automate ecological Non-Standard Architecture defined as the Third Digital Turn of Non-Standard Architecture.

CHAPTER 7

The Third Digital Turn of Non-Standard Architecture

Deconstruction is justice.[265]

7.1 Introduction: The Third Digital Turn

Architectural history is characterised by pivotal shifts in thinking and practice that effectively reset agendas and redirect guidelines. These 'turns' in architectural theory and practice also have a juridical dimension. In *Force of Law*, Derrida defines the enforceability of the law or contract subject to the deconstruction of historical conditions as justice for improvements or modifications of the law in order to remain undeconstructible.[266] Matthias Fritsch notes that turn taking changes the question of the content of justice. By this, he means the sovereignty conceptualised as ethics of double turn-taking with future people intergenerationally taking turns among different overlapping and non-overlapping generations.[267]

The Third Digital Turn focuses on realising Non-Standard Architecture through algorithmic ecological automation which enables transition from the three-

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[265] Jacques Derrida, "Force of Law: The 'Mystical Foundation of Authority,'" *Deconstruction and the Possibility of Justice,* eds. Drucilla Cornell, Michel Rosenfeld and David G. Carlson (New York: Routledge, 1992), 14–15.

[266] Jacques Derrida, "Force of Law," *Acts of Religion*, trans. Gil Anidjar (London: Routledge, 2002), 233–243.

[267] Matthias Fritsch, *Taking Turns with the Earth: Phenomenology, Deconstruction, and Intergenerational Justice* (Stanford: Stanford University Press, 2018), 214.

dimensional digital logic of design and construction to the three-dimensional spatial construction advanced by robotics. Derrida affiliates the process of taking turns with democracy, whose autoimmunity cancels freedom and equality requirements.[268] Derrida's focus on deconstructive invention as a political function is because it bends the institutional rules through the notion of a 'democracy to come'; that is, through a sustained process of engagement and negotiation, rather than a resolved singularity that we might name 'democracy'. Derrida defines sovereignty to have the institutional character of a "machine" or a "prosthesis", rather than as something naturally given.[269] With the excess of sovereign right, Foucault identifies the postanimal as that which threatens the future of human life. Foucault points out the dangerous supplement appears "when it becomes technologically and politically possible for man not only to manage life but to make it proliferate, to create living matter, to build the monster, and ultimately, to build viruses that cannot be controlled and that are universally destructive."[270]

The Third Digital Turn proposes a reconsideration of architecture with current building practice proven to challenge the innovation faced with an industry working at

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[268] Jacques Derrida, "Force of Law: The 'Mystical Foundation of Authority,'" *Deconstruction and the Possibility of Justice,* eds. Drucilla Cornell, Michel Rosenfeld and David G. Carlson (New York: Routledge, 1992), 1.

[269] Jacques Derrida, *The Beast and the Sovereign, Volume 1,* eds. Michel Lisse, Marie-Louise Mallet and Ginette Michaud, trans. Geoffrey Bennington (Chicago: University of Chicago Press, 2009), 53.

[270] Michel Foucault, *Society Must Be Defended: Lectures at the College de France, 1975–76*, eds. Mauro Bertani et al., trans. David Macey (New York: Picador, 2003), 254.

the limit of legislated standards, driven by existing techniques. Thus, the thesis introduces the *Statutes of Non-Standard Architecture* to implement the legislated standards in the architectural industry. The Statutes of the thesis stipulate that the evolution of architecture must be the interplay between construction driven practice informed by experimental form finding research rather than being guided by particular interests in the form of an injunction and indifferent content. Consequently, this thesis suggests that the evolving limits of Non-Standard seriality, through experimental form finding of algorithmic design programming, have the capacity to contribute to a high standard of architecture practice through experimentation that is currently at the limit of codification of robotics in architecture. These contributions form part of the Third Digital Turn of Non-Standard Architecture.

The Third Digital Turn is a pivotal moment in the development of Non-Standard Architecture identified by this thesis. This moment is characterised by eclipsing the persistent limits of Euclidean geometry, Cartesian epistemology and Newtonian physics; the development of the sovereign capacity to manage Non-Standard, non-linear parametric form; and reimagining Non-Standard robotic automation beyond the constraints of the industrial six-axis robot. Ultimately, the full realisation of Non-Standard Architecture focuses on the need for substantial transformation in architectural governance within the regulatory environment of planning and building codes because these promote the same epistemological, logistical and technical bases of the regulatory environment. Planning codes have changed in line with the vision and lineage of geometrical development in architecture, and will need to continue to evolve in order to allow the evolution of ecological governance.

Section 7.1 suggests the limits to realising Non-Standard Architecture through concepts of sovereignty. Section 7.2 suggests how Non-Standard Architecture might be governed ecologically. Section 7.3 outlines the *Statutes of Non-Standard Architecture* that informs and responds to the architectural and urban dimensions of the potential crises evident in the quality of architectural and urban production, the climate crisis, pandemics and other consequences. Section 7.4 argues for emergent algorithmic parameters that can inherently define a new vision of Non-Standard architecture. The thesis argues that the inherent limit of architecture and urban design can only be answered by changing the epistemological, legal, governmental, logistical and implementational parameters that define technology as well as developing identified aspects of technology. Section 7.5 concludes the limit of the Third Digital Turn of Non-Standard Architecture.

The *Statutes of Non-Standard Architecture* includes specific design principles and protocols within sovereign State Government policy, specifically *State Environmental Planning Policy (State Significant Precincts)* evidenced in *Local Environmental Plans* that prescribe zoning and development controls as a framework for the way land can be used. The implementation of the Third Digital Turn within the sovereign environmental planning policy prescribed ecological governance and formulated the best guidance for further development of architecture and urban design. The *Statutes of Non-Standard Architecture* is expanded in the *Sydney Olympic Park Master Plan* which provides a comprehensive approach to the long-term development of Sydney Olympic Park. In architecture practice, the thesis research has contributed to the development of Non-Standard Architecture through several projects such as *ANZ Stadium* redevelopment and *Government Design Excellence* guidelines for towers;[271] and through a sequence of workshop and testing projects investigating the potential of Non-Standard automated robotic construction and Non-Standard automated functionally graded materials. These contributions suggest that a Third Digital Turn of Non-Standard Architecture is now underway.

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[271] Sydney Olympic Park Authority, *Sydney Olympic Park Master Plan 2030* (Sydney: Sydney Olympic Park Authority, 2018), 93–95.

7.2 Ecological Governance of Non-Standard Architecture

The pivotal development of the Third Digital Turn of Non-Standard Architecture is the selection of ecological governance for organisation, optimisation and customisation of the process of automation in architecture. The thesis defines the Non-Standard Architecture of the ecological governance as a two-step process. The first step relates to form finding principles within the given constraints of a site, which then determines the inherent topological parameters of the architecture. This first step counters normative ideas of architectural *ex nihil* and of architectural sites as *tabula rasa*. The second step relates to the differentiated and ecological distribution of material, like functionally graded concrete, requiring digital and robotic optimisation processes, that can be achieved only by integrated advanced computation and automation to allocate material according to parametric specification rather than uniformly across a whole structure or structural component. The sovereign codification of the process, such as material grading with automation, initiates the Third Digital Turn.

Significant impediments to the governance and achievement of Non-Standard were found within the conservative methods of construction that, without automation, cannot achieve ecological Non-Standard architectural elements. The thesis foregrounded sovereign Non-Standard design method based on the strict codification of fortification of Renaissance cities. On that basis, the thesis contends that the Third Digital Turn can be achieved by reconsidering and reframing two key conditions of environments for architectural production.

The first is regulatory and focuses on the codes, rules and legislations that prescribe design controls and delivery of the built environment, from design to construction; the second is implementational and focuses on automation, robotics and material grading. As a result, six statutes for Non-Standard Architecture were defined by the author.

In contrast to sovereignty, the hypothesis of biodegradability is associated with the self-destruction of cultural objects,[272] that being recalled and identified become part of the archive. This phenomenon has accelerated with the development of technology in the form of the internet and digital archives.[273] Although the biodegradability of waste products can be calculated – for example, through heritage criteria requiring the demolition of concrete slab blocks to be addressed environmentally – sustainability, defined as environmental hospitality towards an anticipated future is incalculable. New digital forms of writing that emerged in architecture in the early 1990s have allowed increased precision and new capabilities of archive powered by new computer technology.

The potential of the digital is evident in parametric data coordination of Non-Standard Architecture in the Second Digital Turn. Stiegler described this new difference and differential infinite knowledge as the constructive negentropy of the economy-to-come in the Neganthropocene.[274] The current age of the Anthropocene

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[272] Jacques Derrida and Peggy Kamuf, "Biodegradables Seven Diary Fragments," *Critical Inquiry*, vol. 15, no. 4 (Summer 1989): 822.

[273] Michael Naas, "E-Phemera," *Eco-Deconstruction: Derrida and Environmental Philosophy,* eds. Matthias Fritsch, Philippe Lynes and David Wood (New York: Fordham University Press, 2018), 195.

[274] Bernard Stiegler, "Escaping the Anthropocene" (lecture, University of Durham, Durham, January 2015).

corresponds to industrial capitalism, where calculation prevails as the criterion of decision making and constitutes the advent of nihilism. Therefore, it is imperative to completely rethink the noetic fact such as architects actively engaged in modifying their environment in every field of knowledge in order to reinvent its technological apparatus of the Anthropocene.[275] With the digital object situated in a state of becoming, the task of transforming governance is based on the invention that responds to the needs of the population and the present and future architectural challenges.

[275] Bernard Stiegler, *The Neganthropocene*, trans. Daniel Ross (London: Open Humanities Press, 2018), 38.

7.3 Sovereign Non-Standard Architecture

This thesis effectively repositions an architectural discipline after implementing regulations though still within limits characterised by the Second Digital Turn of Non-Standard Architecture. The thesis relates the Third Digital Turn of Non-Standard Architecture to concepts of relationality and technics in terms of the design and material optimisation of architecture as a sovereign regulative practice. The notion integrates the capabilities of existing skills and technologies for design and production processes within a sustainable and ecological approach into guidelines for architecture. Non-Standard Architecture is repositioned by thesis contributions through construction driven work and academic experimental form finding. The construction driven work includes the work of my architecture practice and collaborative architecture work, including with Zaha Hadid Architects. The academic work includes my postgraduate research at the University of New South Wales, the Architectural Association in London, the University of Sydney, the Institute for Lightweight Structures and Conceptual Design in Stuttgart and other academic consultations during the research. The critical practice by Melika Aljukic Architect is the implementation of innovative Non-Standard Architecture generated from experimental form finding.

In the Sydney Olympic Park project for the NSW Government, the innovative methodology was used as a primary tool for delivering mandatory controls within *NSW Government State Environmental Planning Policy for State Significant Precincts* evidenced in the *Local Environmental Plans*. Novel aspects of the policy by Melika Aljukic were recommendations and principles that prescribed and revised sovereign controls for Non-Standard architectural design of Sydney Olympic Park. These were made possible with a parametric data model that characterises the Second Digital Turn, developed as an analysis tool to integrate design and propose a series of novel Non-Standard design guidelines for the Sydney Olympic Park site in coordination with the Sydney Olympic Park Authority.

The application of this research to design development and construction for large scale architecture projects tested the limits of realising the Non-Standard. What emerged as a persistent challenge to achieving Non-Standard objectives was identified as the limit of the regulatory environment and conservative construction practices. While the thesis research contributed to changes of governance regulation in the design stage, what the thesis advocates has still not made into the automated Non-Standard Architecture environment with the government's aim far from addressing the existing gap of the capability of building with robotic automation in the form of formal regulation. The thesis proposes six statutes of Non-Standard Architecture to realise the Non-Standard Architecture of ecological governance. The thesis argues that the inherent limitations that concern architecture as a topological politics of form and ecology can only be solved by reconsidering the existing regulations that frame technology. This includes formal methodologies in place in the form of a contract that prescribe these ecological regulatory frameworks as part of the Third Digital Turn of Non-Standard Architecture. The Statute aims to be a symbol of Non-Standard Architecture autonomous identity based on the Renaissance heritage of architecture and its development. The Statute is the basis of legal tradition for Non-Standard Architecture representing Non-Standard architects. Conceiving architecture in these terms means coming to the realisation of continuous adaptation and the profoundly important implementation in regulation. The Statute of the automated Non-Standard Architecture environment is outlined below. The Statute is a powerful symbol of Non-Standard Architecture.

7.2.1 *The Statutes of Non-Standard Architecture*

I: On Governance of Non-Standard Architecture

NSW Government State Environmental Planning Policy

The first *Statute of Non-Standard Architecture* concerns the design codification of sovereign Non-Standard Architecture. It prescribes parametric design guidelines for Non-Standard Architecture to be generated in the parametric data model. This thesis research evidenced the Statute through a case study of ancient planning evolution controls of the fortified Renaissance coastal cities of Korčula and Dubrovnik constructed in 1265 and by formulating the *NSW Government State Environmental Planning Policy for State Significant Precincts*. Melika Aljukic developed specific architecture design guidelines for the Sydney Olympic Park (State Significant Precinct). The review that contributed to this thesis underpinned matters of State for the Non-Standard project significance integrating the parametric control guidelines achieved with Non-Standard architectural principles, drawings and models. This policy was delivered through the primary instrument of mandatory development control – the *Local Environmental Plan*. New design control guidelines formulated prescribed specific controls for site configuration, floor space ratios, land use, building height, building zone setback control and event controls. The *Sydney Olympic Park NSW Government State Environmental Planning Policy (State Significant Precinct)* height of buildings map (Figure 7.1) reflects the addition of new height categories of 50 m, 74 m, 102 m and 149 m to reflect *Master Plan 2030*. The *Sydney Olympic Park NSW Government State Environmental Planning Policy (State Significant Precinct)* floor space ratio map (Figure 7.2) reflects the addition of new maximum floor space ratios of 2.2:1, 3.2:1, 3.6:1, 5.5:1 and 8:1 to reflect *Master Plan 2030*. The *Sydney Olympic Park NSW Government State Environmental Planning Policy (State Significant Precinct)* gross floor area map identifies the new floor space ratio categories for sites in Stadia and Central. The controls are summarised in the *Sydney Olympic Park NSW Government State Environmental Planning Policy (State Significant Precinct)*.[276]

The novel regulation was analysed in the parametric data model and included parametric design guidelines for increased height, new maximum floor space ratio and consolidation of sites. This implementation of Non-Standard architectural design principles as statutory in the form of two-dimensional drawing and three-dimensional model with novel techniques formed part of the Third Digital Turn of Non-Standard Architecture.

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[276] NSW Government. *State Environmental Planning Policy* (*State Significant Precincts*) *2005*, accessed August 13, 2020, https://www.legislation.nsw.gov.au/#/view/EPI/2005/194/part1/cl2.

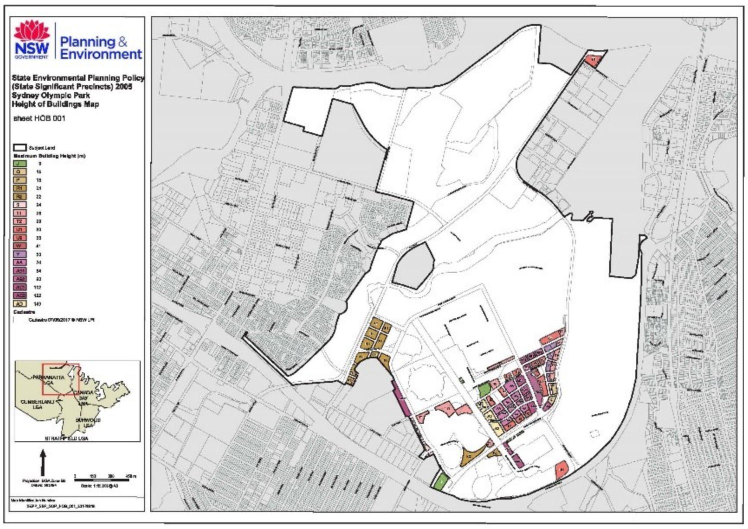

Figure 7.1. *Local Environmental Plan* for the height of buildings, State Environmental Planning Policy (State Significant Precincts) Sydney Olympic Park, accessed August 13, 2020, https://www.legislation.nsw.gov.au/#/view/EPI/2005/194/maps.

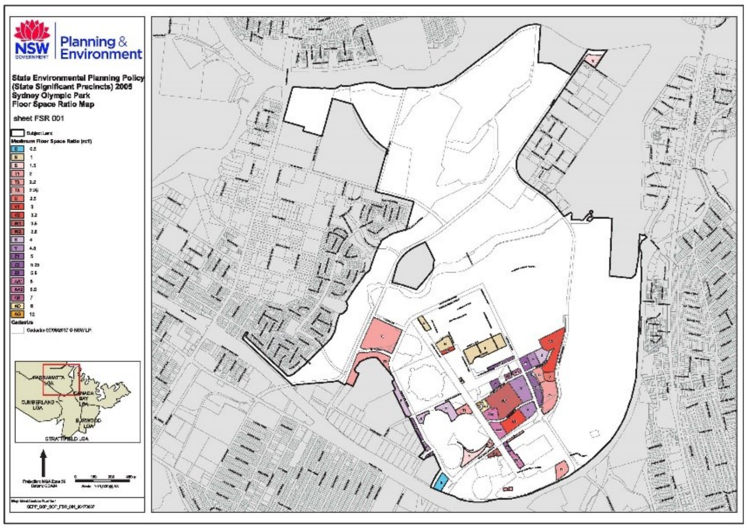

Figure 7.2. *Local Environmental Plan* for the floor space ratio, State Environmental Planning Policy (State Significant Precincts) Sydney Olympic Park, accessed August 13, 2020, https://www.legislation.nsw.gov.au/#/view/EPI/2005/194/maps.

NSW Government Design Excellence Guidelines

Specific objectives and built form were identified for the *ANZ Stadium, Allphones Arena* and *Coach Parking* site through design principles and parametric data model[277] (Figures 7.3–7.5). The parametric geometry for the *ANZ Stadium* was developed from the new design control guidelines. Non-Standard architectural design controls generated with the codification of parametric data model for *ANZ Stadium* are characteristic of the Second Digital Turn, whose implementation and revision of sovereign design controls[278] the thesis characterises as the Third Digital Turn. The proposed changes provided opportunities to activate the areas around the venues both during and outside of major events while retaining easy access for the high volume of pedestrians to and from the venues with a site link 20 metres wide (Figures 7.6–7.9). Proposed changes to the Stadia Precinct included expanding *ANZ Stadium* to allow infill development; creating new uses with the *ANZ Stadium* site to address and define street edges; changing uses from a Venue Expansion Zone to Mixed Commercial and Entertainment to encourage greater diversity; and setting a maximum height of 8–10 storeys for buildings to retain the visual dominance of the Boulevard light structures and the profile of *ANZ Stadium;* changing the *Coach Parking* site from parking uses to Mixed Commercial uses to complement events and future

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[277] Sydney Olympic Park Authority, *Sydney Olympic Park Master Plan 2030* (Sydney: SOPA, 2018), 131–170.

[278] NSW Government, *State Environmental Planning Policy (State Significant Precincts) 2005*, accessed August 13, 2020, https://www.legislation.nsw.gov.au/#/view/EPI/2005/194/part1/cl2.

Figure 7.3.

development around the *ANZ Stadium* and adding through site links; and increasing maximum building heights and development densities for the *Coach Parking* site to form an acoustic buffer for the Carter Street Precinct.

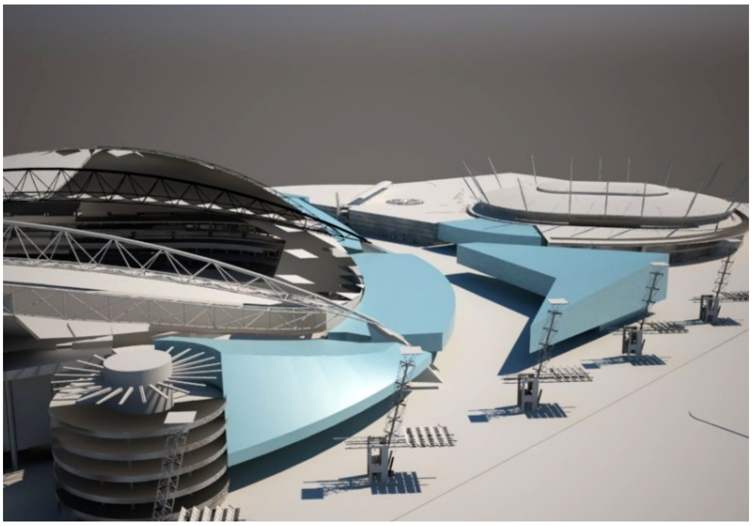

Figure 7.4. Design guidelines for *Stadia Precinct – ANZ Stadium, Allphones Arena* by Melika Aljukic for the NSW Government Sydney Olympic Park Authority. Melika Aljukic, Sydney Olympic Park, 2016.

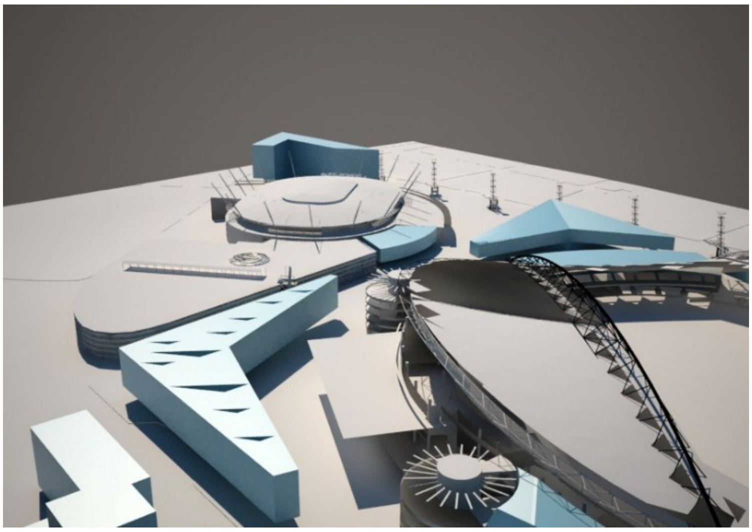

Figure 7.5. Design guidelines for *Stadia Precinct – ANZ Stadium, Allphones Arena* and *Coach Parking Site* by Melika Aljukic for the NSW Government Sydney Olympic Park Authority. Melika Aljukic, Sydney Olympic Park, 2016.

Figure 7.3 Design guidelines for *Stadia Precinct – ANZ Stadium, Allphones Arena* and *Coach Parking Site* by Melika Aljukic for the NSW Government Sydney Olympic Park Authority. Melika Aljukic, Sydney Olympic Park, 2016.

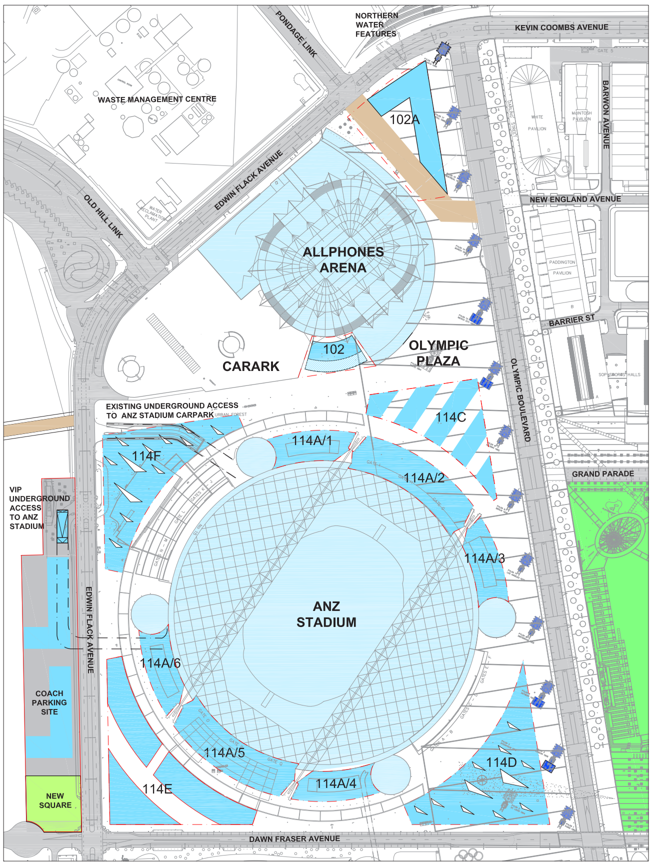

Figure 7.6. Design controls and guidelines for *Stadia Precinct* Ground Level – *ANZ Stadium, Allphones Arena* and *Coach Parking Site* by Melika Aljukic for the NSW Government Sydney Olympic Park Authority. Melika Aljukic, Sydney Olympic Park, 2016.

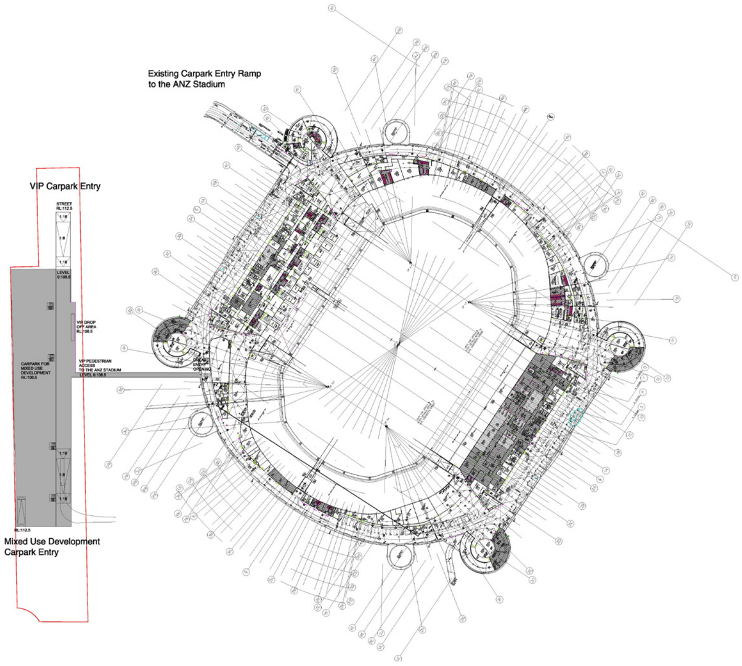

Figure 7.7. Design controls and guidelines for *Stadia Precinct* Underground Level – *ANZ Stadium* by Melika Aljukic for the NSW Government Sydney Olympic Park Authority. Melika Aljukic, Sydney Olympic Park, 2016.

102A
Height: 20m
FSR: 1.5:1
5 storeys: Ground level 6.2m to the pylons + 4 storeys above
Program: Hotel + New street connection between Edwin Flack Avenue and Olympic Boulevard

102
FSR: 2:1
4 storeys: Ground level 6.2m to pylons + 3 storeys above
Program: Cinema + External public screen + Public Seating in Olympic Plaza

114A/2, 114A/5
FSR: 1.5:1
2 storeys: Ground level 6.2m to the pylons
Program: Active wall edge

114/A3, 114/A6
FSR: 3:1
8 storeys: Ground level 6.2 to the pylons + 7 storeys above
Program: Active wall edge

114 C
Height: 15m
FSR: 2:1
4 storeys: Ground level 6.2m to the pylons + 3 storeys above
Program: Hotel

114D
Height: 15m
FSR: 2.5
4 storeys: Ground level 6.2m to the pylons + 3 storeys above
Program: Conference facility + External live screen

114E
Height: 15m
FSR: 2:1
4 storeys: Ground level 6.2m to the pylons + 3 storeys above
Program: Commercial office

114F
Height: 15m
FSR: 2.5:1
4 storeys: Ground level 6.2m to the pylons + 3 storeys above
Program: Sports club

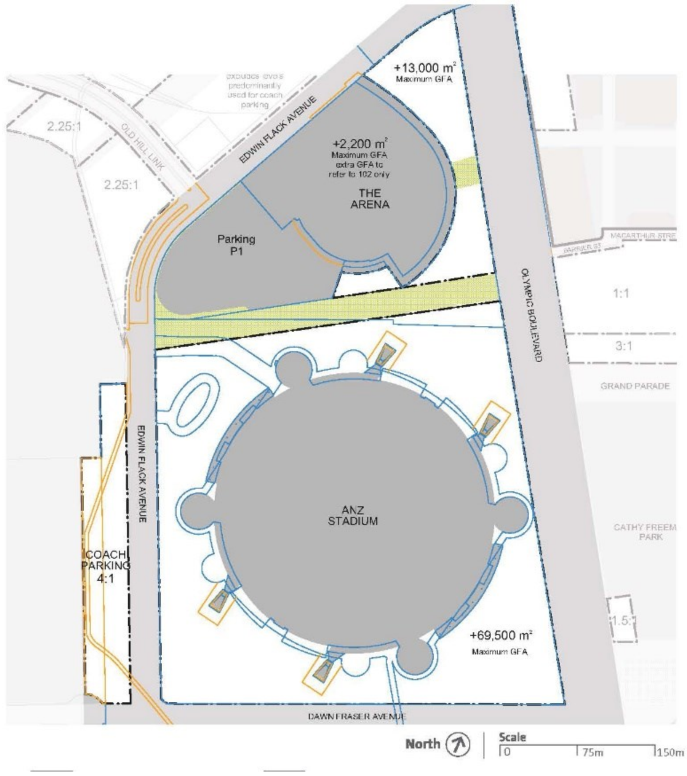

Figure 7.8. Floor space ratio for Stadia Precinct, Sydney Olympic Park. Sydney Olympic Park Authority, *Master Plan 2030* (Sydney: Sydney Olympic Park Authority, 2016), 146.

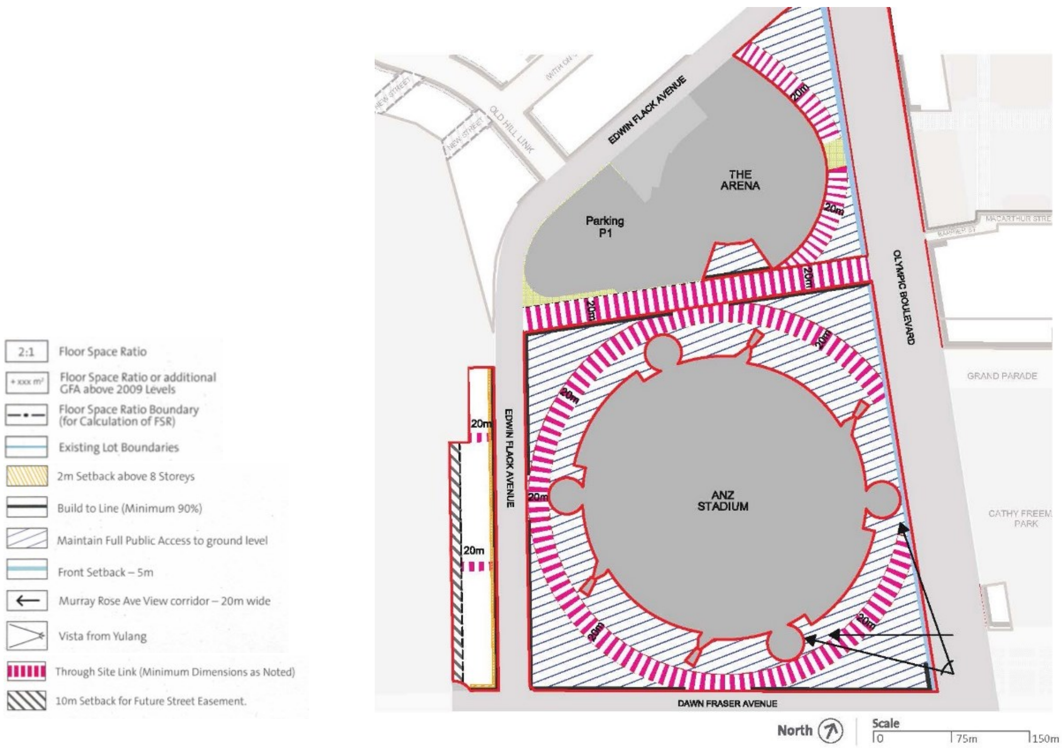

Figure 7.9. Building zones and setbacks plan for Stadia Precinct, Sydney Olympic Park. Sydney Olympic Park Authority, *Master Plan 2030* (Sydney: Sydney Olympic Park Authority, 2016), 149.

Another implementation of the Statute as part of the Third Digital Turn of Non-Standard Architecture was the design controls for the development of towers at Sydney Olympic Park by Melika Aljukic. The proposed *NSW State Government Design Excellence Requirements* guidelines were formulated with a parametric model to combine a series of design options for towers at Sydney Olympic Park. Design excellence guidelines identified floor space ratio, building height, building zone and a setback for site towers on each site (Figures 7.10 and 7.15). The design prescribed guidelines for a high standard of architectural design, materials and detailing as well as sustainable design principles in terms of sunlight, natural ventilation, wind, reflectivity, visual and acoustic privacy. The Non-Standard design controls for the future infrastructure emerged from the existing site condition and requirements. An important aspect of the design guidelines was the calculation of the potential site gross floor area for the design from which design guidelines were developed.

Figure 7.10.

Figure 7.11.

Sydney Olympic Park Master Plan 2030

Detailed planning design principles were provided for the future development of Sydney Olympic Park in the *Sydney Olympic Park Master Plan 2030*. The review of the Master Plan proposed a number of changes to reinforce activity in major streets. It continued to separate major land uses in the Town Centre with major events and sporting facilities, commercial uses close to the civic core and residential uses; integrated educational uses with existing sport facilities and commercial and retail uses to promote day and night activity.

Figure 7.10. Proposed built form for *Central Precinct* by Melika Aljukic and Sydney Olympic Park Authority, 2016. Sydney Olympic Park Authority, *Sydney Olympic Park Master Plan 2030* (Sydney: Sydney Olympic Park Authority, 2016), 1.

Figure 7.11. Proposed built form for *Central Precinct* by Melika Aljukic and Sydney Olympic Park Authority, 2016. Sydney Olympic Park Authority, *Summary of Proposed Planning Changes* (Sydney: Sydney Olympic Park Authority, 2016), 26.

Figure 7.12.

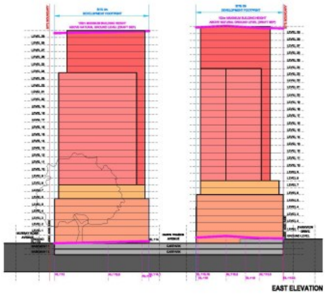

Figure 7.13.

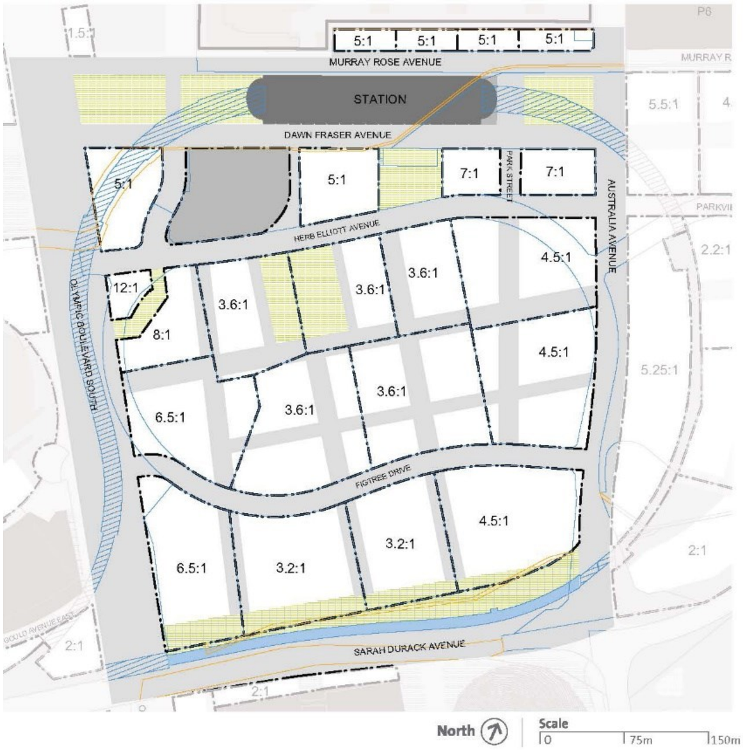

Figure 7.14. Floor space ratio for Central Precinct, Sydney Olympic Park. Sydney Olympic Park Authority, *Master Plan 2030* (Sydney: Sydney Olympic Park Authority, 2016), 146.

Figures 7.12 and 7.13. *Design Excellence Requirements* for tower development of Sydney Olympic Park. Melika Aljukic, NSW Government Design Excellence Requirements, 2016.

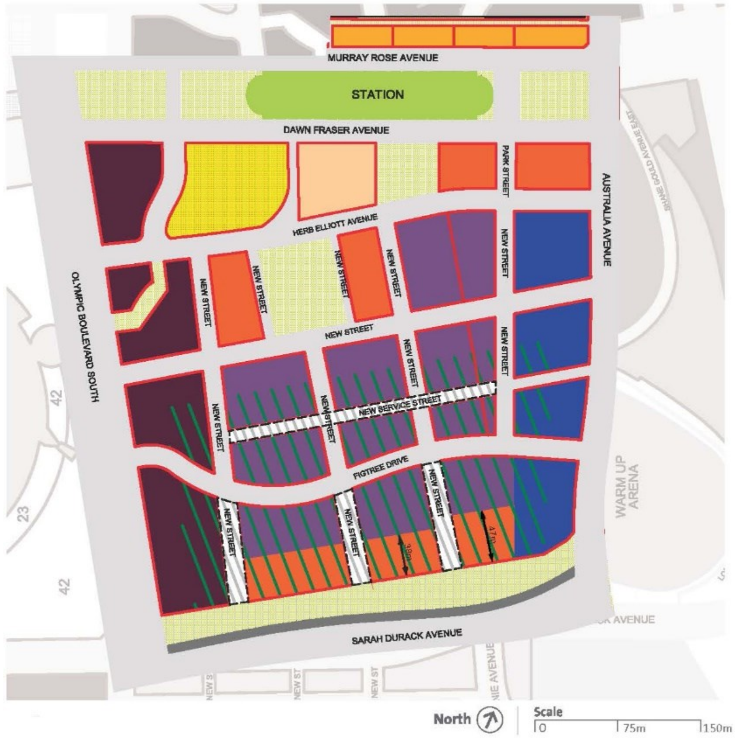

Figure 7.15. Building heights for Central Precinct, Sydney Olympic Park. Sydney Olympic Park Authority, *Master Plan 2030* (Sydney: Sydney Olympic Park Authority, 2016), 146.

Sydney Olympic Park Master Plan 2030 integrated civic and community uses through the Town Centre to complement retail and commercial uses, as well as opportunities for day and night time economy to support a range of activities before and after events. The review of the Master Plan proposed additional gross floor area for most land uses, equating to an extra 460,000 square metres of ground floor area. The potential for new residential dwellings increased significantly in line with the NSW Government policy to focus residential development around transport hubs. This led to a proposed reduction in commercial gross floor area.

The new built form aimed for both Non-Standard Architecture aesthetic and practical objectives where buildings contributed to a mixed use, compact Sydney Olympic Park Town Centre. The Master Plan aimed to use building design and location to screen residential developments from event noise, activate street frontages with uses that occur at the footpath level, reduce the impact of car parking on public areas by locating new car parking facilities underground, limit floor plate areas for towers over 25 metres high to maintain a skyline of slender buildings, and protect and enhance heritage and the Olympic legacy. The thesis claims this evolution and implementation of novel design controls that exhibit design excellence for NSW Government State Environmental Planning Policy for Sydney Olympic Park (State Significant Precinct), evident in the *Local Environmental Plan* and *Sydney Olympic Park Master Plan,* as the Third Digital Turn of Non-Standard Architecture.

II: On Codification of Automated Non-Standard Architecture

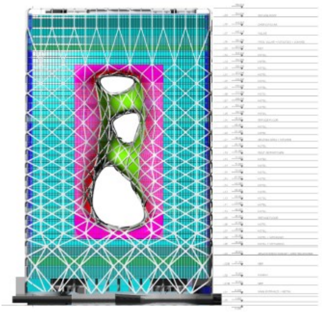

Figure 7.16.

The second *Statute of Non-Standard Architecture* refers to a novel method of parametric codification of architecture. This architectural codification prescribes a parametric data model as a new form of communication and collaboration between architects and engineers. Section 6.4 highlighted a case study where this aspect was critical, the *Morpheus Hotel* project, which documented the new tools and protocols of parametric prefabrication as part of a novel tower typology (Figure 7.16).

This process-based design approach from which the outcome emerged and evolved is germane to parametric architecture and is a characteristic of the Second Digital Turn of Non-Standard Architecture. The autonomous turn of the Second Digital Turn identified by the thesis beginning in 2012 introduced possibilities with novel methods of form finding and construction within the parametric model that, however, were constrained by the limits of robotic automation in the construction industry. This form of novel codification of architecture generated a gap between possibilities offered by digital technologies in architectural design and the current reality and capacities of the building industry to realise them.

Although the protocol for design and documentation of the architectural project is largely driven by digital and integrated parametric data models, the actual fabrication of components still requires a high level of skilled manual work. The thesis formulates the *Statutes of Non-Standard Architecture* for automation of construction driven by the integration of parametric data models that have the capacity to eclipse Second Digital Turn limits. The comprehensive

Figure 7.16. *Morpheus* parametric data model. Zaha Hadid Architects, 2013.

parametric model enabled the integration of all of the aesthetic, formal, structural and fabrication requirements through the collective form of communication and collaboration. Design and development of this new collaborative model as part of the digital process was pivotal for achieving the desired, novel architectural typology. With the increased involvement of co-laboratories of architects, engineers and other consultants across all stages of a project from design to construction, architecture has the capacity to increase the level of integration and quality of architectural outcomes.

III: On Rationalisation of Automated Non-Standard Architecture

The third *Statute of Non-Standard Architecture* refers to rationalisation of standards in contracts that frame the delivery of architectural and urban projects. This aspect aims to introduce high quality design principles and standards for architecture and the construction industry through novel automated construction methods. The Statute is envisaged to implement new technology generated from the pole of digital architecture based on the experimental form finding to describe the construction driven design method of building with automation that is parallel to the computation of architectural practice, specifically the algorithmic digital model. The automated architecture proposed by the thesis formulates specific architectural guidelines in contract documents that increase the involvement of an architect in an architectural protocol with the new tools. This *Statute of Non-Standard Architecture* proposed by the thesis includes a revision of the material specification for graded concrete as an ecological method.

This Statute on rationalisation of Non-Standard Architecture prescribes an update of existing mainstream construction practice with robotic technology. The research suggests that automated construction has the potential to reduce waste with precedents in Japan reducing site waste by 70% as a result of the high degree of prefabrication and on-site material management system.[279] The project program plan with an automated site indicates the highest labour reduction for facade installation, concrete, steel formwork and temporary safety-related installations. For instance, the construction project timeframe by Kajima construction company indicates that automated construction requires different methodologies and takes less time than conventional construction (Figure 7.17). The Third Statute of the regulatory environment identified by the thesis aims for a detailed process guideline in contracts to achieve higher standards with automation.

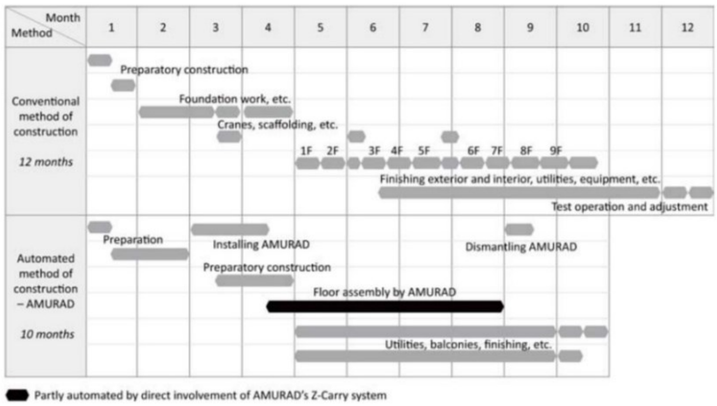

Figure 7.17. Comparison between conventional construction and automated construction with Advanced Technique by Kajima. Thomas Bock and Thomas Linner, *Site Automation: Automated/Robotic On-Site Factories* (Cambridge: Cambridge University Press, 2016), 178.

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[279] Thomas Bock and Thomas Linner, *Site Automation: Automated/Robotic On-Site Factories* (Cambridge: Cambridge University Press, 2016), 300.

IV: On Automation and Functionally Graded Materials for Non-Standard Architecture

The fourth *Statute of Non-Standard Architecture* is related to the implementation of automation ans graded material in architecture. The thesis proposes the application of specific aggregates and data analysis in a parametric data model to generate sustainable materials and automated methods such as stone stereotomy (Figures 7.18 and 7.19). The thesis extends current work in Non-Standard architectural forms to integrate material optimisation and efficiency as well as robotic automation for elaborate form finding (Figures 7.20–7.21). The protocol for grading material on a Non-Standard prototype requires specialised optimisation software Dassault Systèmes Abaqus with Abaqus Topology Optimisation Module.

The parametric Non-Standard architectural components in functionally graded concrete minimise component weight together with optimised performance, topology and shape potential. The necessary fabrication method for such construction is automated for both linear and Non-Standard elements. The case study performed for functionally graded concrete shows the limitations of the current development of functionally graded materials for Non-Standard Architecture. The experiments with the automated application of functionally graded concrete in the parametric data model with the spraying process need to be engineered digitally to translate data from the assigned parametric concrete digital model to aggregate information variables of the spraying process. The thesis stipulates that detailed aggregate guidelines and input parameters for material behaviour should be part of the contract specification.

Figure 7.18.

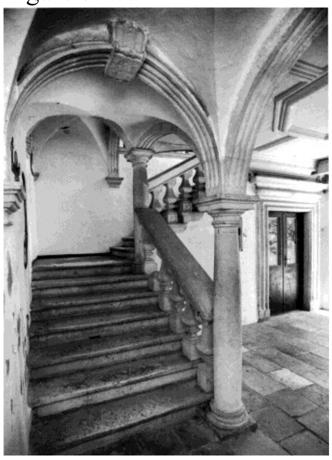

Figure 7.19.

Figures 1.18. Window with stone profiled frame in Korčula. Photograph by Melika Aljukic.

Figure 7.19. Stone staircase, *Palača Vodopić, Dubrovnik.* Katarina Horvat-Levaj, *Barokne Palače u Dubrovniku* (Zagreb: Institut za Povijest Umijetnosti, 2001), 158.

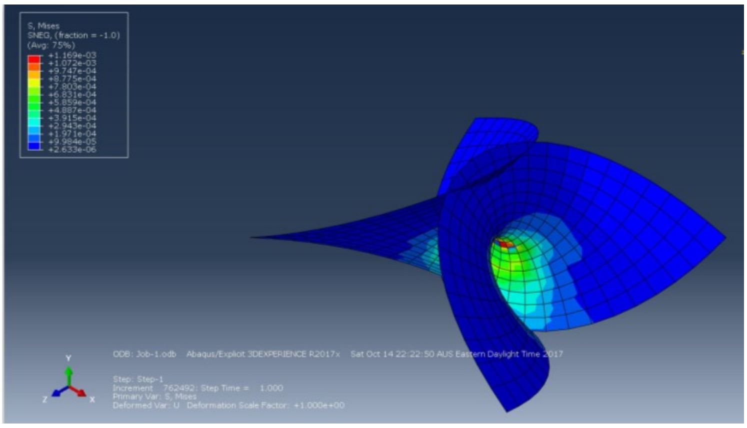

Figure 7.20. Analysis of Non-Standard surface in Dassault Systèmes Abaqus for application in stone stereotomy for Non-Standard architectural elements, Melika Aljukic, 2017.

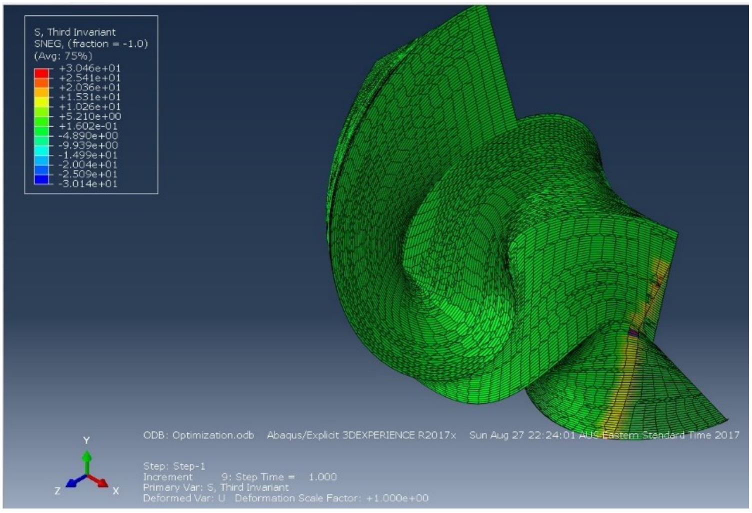

Figure 7.21. Optimisation of concrete Non-Standard prototype in Dassault Systèmes Abaqus with Abaqus Topology Optimisation Module. Melika Aljukic, 2017.

V: On Automated Non-Standard Architecture

The fifth *Statute of Non-Standard Architecture* is related to overcoming the limits of realisation in Non-Standard Architecture through automated architecture. The thesis identified differentiated speed between the digital and the possibilities of the industrial economy commitment. With the Third Digital Turn, the processes of algorithmic design and material optimisation encountered significant impediments to ecological governance and achieving Non-Standard since automated architecture cannot be created manually with unskilled labour. The thesis defines the requirements for automation of architecture as a regulatory environment for the implementation of new tools in the building industry to close the gap between architectural parametric digital technologies and the current capability of the construction building industry. Achieving architectural automation requires contractors to have construction capability of automation equipment and the capability to take digital architectural information into their software that can read architectural data without further translation and robotically automate functions without manual operations (Figures 7.22 and 7.23).

Figure 7.22.

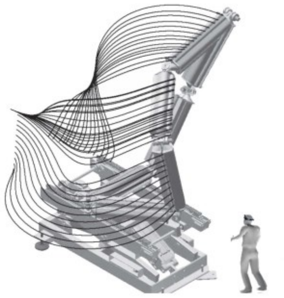

Figure 7.23.

Figure 7.22. Application of abrasive wire swing at the quarries in Carrara, Italy. Jelle Feringa and Asbjorn Sondergaaed, "Fabricating Architectural Volume: Stereotomic Investigations," eds. Fabio Gramazio, Matthias Kohler and Silke Langenberg, *Fabricate* (Zurich: Gta Verlag, 2014), 79.

Figure 7.23. Robot prototype for the generation of surface geometry. Melika Aljukic et al., *ARACHN[OL]OIDS* (London: Architectural Association, 2013).

The Second Digital Turn of Non-Standard Architecture introduced sophisticated computation and tools by integrating engineering logics and physical simulation for form finding and optimisation as part of the design process including the first Non-Standard architectural robot prototype *ARACHN[OL]OIDS.* Today the methods of manufacturing systematisation and optimisation have been implemented in Japan as optimisation with the automation ratio and human flexibility at the final production stage where high flexibility is required. The thesis proposes an update of existing mainstream construction practice to the prefabrication industry that embeds robotic technology. The automation of architecture requires further development and implementation of automation similar to, for instance, car automation assembly. Such manufacturing automation in architecture has the capacity to eclipse the limit of the Second Digital Turn on Non-Standard Architecture.

VI: On Implementation of Automated Non-Standard Architecture Research into Academia and Practice

The sixth *Statute of Non-Standard Architecture* refers to the implementation of research in academia and practice. The thesis positions the Third Digital Turn of the Non-Standard by implementing sovereign controls for architecture practice that prescribe Non-Standard project envelope design as well as methods of construction. In the Second Digital Turn of Non-Standard Architecture, computation routinely links members of design teams and the various professional specialisation and management teams through the parametric data model. The nature and structure of building practice must continuously evolve in response to this novel architecture computational design. Apart from the introduction of new tools for automation of architecture on a construction site, extending architecture computation to the capability of the construction industry will require an update of mainstream construction practices and a recasting of labour and employment models. Specific automated solutions have to be programmed to meet each project's requirements.

The principal feature of today's experimental architecture stems from the research-oriented forms of architectural design and innovation such as computationally advanced and speculative work in the academia that integrates design collaboration, networks, processes and experimental media. The research agenda is a platform for generating and testing ideas that become integrated into professional practice. For instance, automation opened the possibility of architecture modelling and simulation of different processes. This includes a method of functional grading of concrete that requires automated architecture. The thesis proposes regulating grading and optimisation tools as part of the regulatory environment in architecture. In such an environment, design and the design project as settings are open research with better communication between designers and collaborators, which can be considered in terms of both contemporary design systems and historical precedents in modern architectural discourse.

Studio 11 on the Third Digital Turn of Non-Standard Architecture is a Master of Architecture studio led by the author at the University of Melbourne in 2021. It incorporates thesis research into teaching architecture and urban design solutions for a project on a heritage site in the port of Dubrovnik. The studio considers novel architectural and urban design resolutions by applying new methods for the Dubrovnik port site within the planning of the city by the *Statute of Dubrovnik* in 1272. Each studio considers an architectural approach within contemporary architectural thought and practice while adding an innovative design aspect. The research is an observation tool for the potential manifestation of the transformation of architectural elements. The design outcomes demonstrate the possibility of Non-Standard Architecture in its Third Digital Turn.

7.4 Emergent Non-Standard Architecture

The Third Digital Turn of Non-Standard Architecture generates ecological architecture from within topological processes of specific design codification, grading material in parametric data models and automated fabrication. This thesis identifies topological parameters in the Second Digital Turn of parametric architecture, in which material and geometry are optimised and defined by algorithmic description. Topological space is also inherently ecological, as it defines the parameters within which an object can be modelled and that are integral to the object. Therefore, in topological space, an object generated is ecological since it is time and site-specific, residing in its relative position within an inherently complex, dynamic spatial milieu – whether that milieu is political, artistic or chemical.[280]

Topological theories by René Thom were pivotal to Non-Standard Architecture as they sought to describe a new science of form, an application of catastrophe theory to the evolution of biological and natural form. Furthermore, the autopoietic potential of matter by biologists Humberto Maturana and Francisco Varela explores a re-thinking of the concept of nature, extending the topological approach into architectural fields of materiality and the surface. Sociologist Niklas Luhmann defined autopoietic entities as closed or self-referential on the level of organisation, but open to environmental perturbations on the level of structure. Luhmann develops radically constructivist

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[280] Hanjo Berressem, *Felix Guattari's Schizoanalytic Ecology* (Edinburgh: Edinburgh University Press, 2020), 153.

sociology from within both autopoietic and cybernetic registers that define this process as "recursive" by using the results of its operations as the basis for further operations – that is, what is undertaken is determined in part by what has occurred in earlier operations.[281]

Cary Wolfe situates the theory of autopoiesis by Maturana and Varela within second-order cybernetics, developed by Heinz von Foerster, that can be characterised as a disciplinary matrix within which the study of the organisation of complex systems (cybernetics) includes, at a meta-level, recognising the existence of the observer-scientist as a complex system within the observed system itself. For Wolfe, Maturana and Varela's second-order cybernetics provides a means of moving beyond the traditional humanistic dualism of mind and body and its model representation into an approach that commits to the notion of cognition as embodied action. Hence, the autopoietic organisation continually self-produces according to its own internal rules and the requirements of second-order cybernetics.

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[281] Niklas Luhmann, "The Cognitive Program of Constructivism and a Reality that Remains Unknown," *Selforganization: Portrait of a Scientific Revolution*, eds. Wolfgang Krohn, Gunter Kuppers and Helga Nowotny (Dordrecht: Kluwer, 1990), 72.

7.4.1 Ecological Approach in Non-Standard Architecture

The Third Digital Turn applies topological optimisation as an ecological means to Non-Standard Architecture. This thesis extends the ecological governance for organisation, optimisation and customisation of the process of automation in architecture. This includes selection processes between the algorithm and the project, such as grading materials for parametric architecture and automation of architecture for construction. These characteristics of the Third Digital Turn of Non-Standard Architecture emerged from the Second Digital Turn that explored hybrids emerging through opportunities of novel digital design software as the engine of architectural experimentation. A computational approach in architecture design and documentation emphasised two essential features: firstly, a considerable continuity between material and information; and secondly, an ability to create organic organisations and behaviours through software and computing applications. This approach in architecture has led to a renewed interest in biological systems and a re-evaluation of what constitutes the terms of architectural form. The transformation of permanent, fixed material into mobile, dynamic fields of force and interaction is, in turn, related to form finding theories that rely on increasingly sophisticated digital design tools and programming techniques.

7.4.2 Emergent Algorithmic Discrete Aggregation and Topology Experiments

The emergent aggregation experiments on the discrete element, *Ecological Aggregation I and II* (Figures 7.24 and 7.25) and *Ecological Recursive Orientation* (Figure 7.28), are a comparison between the emergent diffusion-limited aggregation processes and kinematic vector model to simulate a large association of discrete components over the earth's surface. The diffusion-limited aggregation developed by theoretical physicists Thomas Witten and Leonard Sander in 1978 was given algorithmic function for recursive orientation of discrete elements. It was generated with a kinematic vector model of trigonometric function to establish a relationship between the components of a vector and its direction. The *Replicator* morphology principle demonstrated dynamic mechanisms of assembly, disassembly and re-usability that challenged mainstream notions and practices of traditional construction, with the algorithm that had potential to grow crystal-like structures, coral reefs and other natural systems. *Ecological Recursive Orientation* of the discrete tetrahedron element was defined by angle and distance calculations using an automated mathematical function with the conditional or termination criteria to limit the number of elements. As opposed to natural system growth, this prototype begins to integrate robotic kinematics of geometry that are essential for generating its simulation axis, end-effector position and motion of all the joints (Figure 7.26).

Figure 7.24.

Figure 7.25.

Figures 7.24 and 7.25. *Ecological Aggregation I and II*. Images produced by Melika Aljukic.

Figure 7.26. *Ecological Discrete Elements.* Images produced by Melika Aljukic.

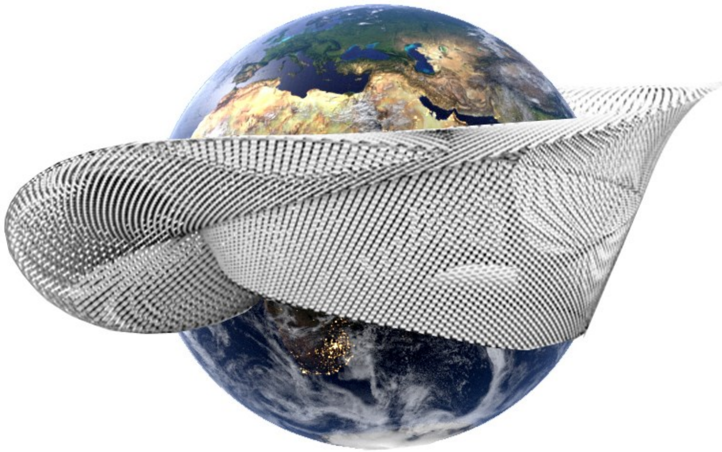

Figure 7.27. *Ecological Topology.* Images produced by Melika Aljukic.

Automated discrete elements revolve into the ruled surface with asymptotic curves to make geometry calculable for translation into buildable form. The concept defines automation of the discrete elements projected from the surface of the earth into its enclosing Non-Standard form (Figure 7.27). The options illustrate the different extent of the revolved surface form (Figure 7.29). The design method applies topology with the potential of ecological governance for functionally graded materials on parametric components. The material optimisation reduces the material from the conventional construction method. This efficiency of automated construction has the potential of Non-Standard Architecture.

Figure 7.28.

Figure 7.29.

7.4.3 Autonomous Non-Standard Architecture

On the discourse related to hybrid scientific models, Bruno Latour argues that political constitutions have "left out both scientific power and the work of hybrids" in order to claim transcendent authority.[282] Latour's approach includes forming hybrids out of politics and science. In order to achieve greater autonomy, and to conceptualise knowledge into universals, classical science has effectively isolated itself from social contexts.[283] Isabelle Stengers and Ilya Prigogine reflect on the conflict between the natural sciences and the social sciences and humanities. The reorientation of the classical view shows basic processes of

Figure 7.28. *Ecological Recursive Orientation.* Images produced by Melika Aljukic.

Figure 7.29. *Ecological Topology.* Images produced by Melika Aljukic.

[282] Bruno Latour, *We Have Never Been Modern*, trans. Catherine Porter (Cambridge: Harvard University Press, 1993), 14.

[283] Ilya Prigogine and Isabelle Stengers, *Order Out of Chaos: Man's New Dialogue with Nature* (New York: Bantham Books, 1984), 301.

nature considered to be deterministic and reversible to the contemporary view today of the role of irreversible processes, of fluctuations.[284] For example, irreversible processes include diffusion, radioactive decay, solar radiation and the emergence of the evolution of life. Frederic Bender argues that minimally, science and politics might need to accept the coexistence of reversible and irreversible processes in the world, in which the former is an approximation of the latter.[285] As such, ecology is neither in the past nor the future, but it is rather always right here, right now.[286] The architecture of ecological governance conceptualises a productive link between politics, topology, ecology and form. Ecology has been traced through the social, political and existential, which involves changes in production, ways of living and axes of value.[287] Response to the ecological crisis is on a global scale, with potential for an authentic political, social and cultural revolution, reshaping the objectives of the production of both material and immaterial assets.[288] Within ecology machinics, Cartesian thought is organised around sets of logical relations and formal distinctions that are differentiated from topological thought arranged around

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[284] Ilya Prigogine and Isabelle Stengers, *Order Out of Chaos: Man's New Dialogue with Nature,* 19–22.

[285] Frederic Bender, *The Culture of Extinction: Toward a Philosophy of Deep Ecology* (New York: Humanity Books, 2003), 257.

[286] Hanjo Berressem, *Felix Guattari's Schizoanalytic Ecology* (Edinburgh: Edinburgh University Press, 2020), 237.

[287] Felix Guattari, *Chaosmosis: An Ethico-Aesthetic Paradigm*, trans. Paul Bains and Julian Pefanis (Sydney: Power Publications, 2006), 119,134.

[288] Felix Guattari, *The Three Ecologies*, trans. Ian Pindar and Paul Sutton (London: The Athlone Press, 1989), 28.

local sets of signifying distinctions defined in terms of global space – Cartesian space is logical, topological space is ecological.[289] In this light, Non-Standard Architecture with topological characteristics is inherently ecological.

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289 Hanjo Berressem, *Felix Guattari's Schizoanalytic Ecology* (Edinburgh: Edinburgh University Press, 2020), 155.

7.5 Conclusion: The Limits of Third Digital Turn

The thesis positions the Third Digital Turn of Non-Standard Architecture in sovereign regulatory practice. The *Statutes of Non-Standard Architecture* is the transformation of the legal system specific to Non-Standard Architecture design and implementational guidelines. The thesis finds two components are necessary to overcome the limits of Non-Standard Architecture in the Third Digital Turn. First, implementation of automation, robotics, parametrics, grading concrete material and the adoption of non-Euclidean, non-Cartesian non-Newtonian epistemologies in the design of the technological apparatus is necessary. Second, admitting the above within the implementational context that frames delivery of the built environment through governance, regulation, policy, protocols in government, the industry, practice and the academy is necessary. Within this framework, automation provides a way to generate a process of negotiation, initiated by machines that generate models to negotiate through the invention of new ecological practices. Integrating these components, we can think new collectively, but only to the extent that we develop digital practices capable of producing a new ecological relation between individual subjectivity and collective thought, which this thesis proposes in the *Statutes of Non-Standard Architecture*: on governance of Non-Standard Architecture, on codification of Non-Standard Architecture, on rationalisation of Non-Standard architecture, on graded materials for Non-Standard Architecture, on automation of architecture and on implementation of research in academia and practice.

The thesis anticipates that the implemented design guidelines as part of the governance for Non-Standard

Architecture will formulate architecture, that is, the realisation of the Third Digital Turn of Non-Standard Architecture. Codification of architecture has already been integrated as part of the process-based design approach for digital parametric architecture. Further development of automated codification within construction driven design provides an opportunity to impact the protocol from design to fabrication. Thus, automation can be reconciled to the social aspects of architectural production by contributing to environmental sustainability. The programmatic and functional impact of Non-Standard Architecture is reconciled to the digitalisation of the architectural environment by seeking optimum design parameters enabled with novel software.

Nevertheless, experimental form finding is research-oriented architectural design focused on computationally advanced and speculative work. The arbitrary form as part of the emergent aggregation is reconciled to architectural aesthetics, expression and meaning by automated mathematical function and genetic algorithms for topology optimisation. Non-Standard Architecture recapitulates topology from global to local space, defining the historical and cultural.

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