The synthesis of data and material, which decisively failed to develop in the early digital age, is being realized – enticingly, playfully, and sensually – in today’s architecture. This becomes apparent in various medial, spatial and structural manifestations, whereby one premise persists: in the moment in which two seemingly separate worlds meet through the interaction between digital and material processes, data and material can no longer be interpreted as a mere complement but rather as an inherent condition and thus an essential expression of architecture in the digital age. A Digital Materiality is emerging, where the interplay between data and material is seen, then, in a new light, as an interdependent structuring of architecture and its material manifestations. Digital Materiality is thus not incidental, nor supplemental, nor is it a process of embellishment; instead it corresponds to an extensive collaboration, which can be analytically developed and implemented on an architectural scale. This leads as well to a new form of architectural expression and its material sensuality.

Today, at the threshold between the mechanical and digital age, it appears that a large part of contemporary architecture is determined by algorithmically established design procedures in which the constructive and building implementation is of insufficient significance and appears secondary; it is resolved only upon completion of the architectural design. With Digital Materiality something entirely different is introduced: instead of realizing a design, an image, or a drawing, a comprehensive design and building process is conceived. Here, the central issue is not the design of a form; rather it is the design of a production process that is informed essentially by the constructive organization of the material. Thereby conceptual commonalities between the construction of a building component and the programming of a computer become apparent; just as a computer program that conducts different operations in sequential order, constructive principles can be determined that define the production of architectural components as interrelated production steps.

The architectural creative intention is expressed in the setting of essential parameters and dependencies as well as by the actual design of a comprehensive building system. It unfolds fully through the constructive collaboration of highly diverse parameters of the design and its materialization. Thus Digital Materiality is characterized by material precision and clarity; it is uncoupled, however, from formal guidelines and relocated to another (constructive) level. It is a design and construction process controlled in all its details by the architect, a fundamental balancing or weighing of real possibilities, so to speak, during the process of making. Conversely, we are not talking about building systems that can be configured endlessly in the virtual space of a computer. Rather
the constructive logic of programming and material formation are linked to each other. The digital construction process reveals itself to be a constructive structuring, disengaged from the formal, the result of a “demystified” understanding of digital technologies and a freer, more autonomous use of the computer.⁶

Consequently, Digital Materiality allows one to combine the abilities and deficiencies of human beings and machines to deliberate advantage. In the digital age this means that while the machine with its numerical logic can rule over an infinitely large quantity of numbers, only human beings with their cognitive abilities and intuitive approaches can recognize meaning in them. The result is an added architectural value through the “interactive connection” of the human and the machine, who are not equal but rather “equivalent” partners. The added value points the way to completely new possibilities for a future constructional reality – not just quantitatively but also qualitatively. Thus Digital Materiality is far more than a mere rhetorical figure in the digital discourse; it represents an architectural vision.⁵

> New Modular Capacities in Space

The central problem is to what extent the difference between data and material, or digital and analogous realities, can be maintained, since Digital Materiality would seem to dispense with the frequently discussed dichotomies of programming and construction, of human beings and machines. Thus it recalls what Gottfried Semper pointed out long ago – the constructional requirements of architecture can be deduced primarily from different cultural and material models. According to Semper, the architectural result is formed by its own history, that is, by the process of its origin, the process of its making. It appears relieved of its original characteristic style of form and appearance, nearly emancipated. As Semper puts it, despite all these influences and transformations, in the end the different characteristics should remain recognizable and “owe their origin to the combined engineering arts in a primitive architectonic installation.”⁶

As do many other projects by Gramazio & Kohler, the project The Fragile Structure also demonstrates these principles.⁷ It makes apparent that Digital Materiality develops its greatest potential whenever the number of single components that stand in relation to one another is particularly high.⁸ In The Fragile Structure a robot freely stacks more than one thousand identical wood elements without additional fasteners, so that the issue of inherent stability takes on a decisive role in the design. As the dimensions of The Fragile Structure exceed by many times those of the working area of a

Facing page
Figure 20.1: View inside the architectural vision of the Flight Assembled Architecture installation. Image credit: Gramazio & Kohler and Raffaello D’Andrea in collaboration with ETH Zurich.
conventional industrial robot, the installation was assembled by a mobile robotic unit making use of caterpillar tracks.\textsuperscript{9}

The project \textit{The Fragile Structure} was built in a parking garage because it closely resembles a construction site; the slanted floor, freestanding columns, and limited ceiling height demanded continuous adaptations of the design towards the specific physical reality of the surroundings. Through the mobile robotic unit equipped with sensor technology, it was possible to scan the environment and quantify the geometric deviations to the idealized computer model and thus adapt the building process in real time.

In \textit{The Fragile Structure}, curved planes seamlessly merge into each other and span the distance between ceiling and floor; an interaction is set up between the rhythmic repetition of the additively assembled wood elements and their delicate dissolution into the spatially adapted, self-supporting entirety. Because of the porous assembly of the wood elements, a complex visual effect appears depending on the viewer's perspective and on light conditions. Of course this is evident only at a certain distance; if one steps closer the illusion dissolves, leaving only a multiplicity of geometrically discrete elements. This means that one is dealing not only with the appearance of a material compound structure, but also with a visual and, in the original meaning of the word, a "virtual" event, that is, with a kind of "virtual materiality." Consequently, in reference to \textit{The Fragile Structure}, it can be stated that such an architectural structure and its effect do not just inform each other, rather a further architectural potential of this structural and visual interdependency becomes tangible.

\textit{The Fragile Structure} was initially developed by means of physical prototypes. Early on, numerous robotically assembled scaled models were built, which allowed distinctly different building systems to be developed and validated in very rapid sequences - in an "evolutionary physical way." Moreover, the specific objective of an "untethered" structure that approaches a state of equilibrium made it difficult to accomplish this development work by hand. Through its constructional clarity and differentiated articulation, \textit{The Fragile Structure} shows how concrete materialistic-empirical research is granted an important place in the digital age. Its value accrues because this kind of architectural experimentation with programming and constructing not only forms complex compounds, linkages and aggregations; but also, within such a connection of data and material, these can now be implemented in a controlled way within a specific spatial environment.

\textit{> The Extended Operationality of Architectural Utopia}

As becomes apparent in \textit{Flight Assembled Architecture}, this strategy can go far beyond the scale of building components. The project for the Fonds régional d'art contemporain (FRAC) Centre in Orléans is the first architectural installation in the world that has been built by flying robots.\textsuperscript{10} In this case, several "quadrocopters" developed by Raffaello D'Andrea put together more than 1,500 elements to create a six-meter-tall complex vertical structure. The flight behavior of the quadrocopters is based on the algorithmic translation of digital design data, according to which they land on a platform where they pick up individual elements and assemble them, following an assigned construction sequence. Thus a geometrically differentiated structure is created where the individual building layers are mutually offset to present a six-hundred-meter-tall building that paves the way for entirely new scales of digitally fabricated architectures.

\textit{Flight Assembled Architecture} is not only an architectural installation, but rather a vertical urban utopia - a Vertical Village.\textsuperscript{11} With 180 floors and a usable space of 1.3 million square meters, the Vertical Village provides living space for more than 30,000 inhabitants. With its porous structure it creates the largest possible diversity of urban living.\textsuperscript{12} Consisting of vertical core structures and staggered-module chains, the \textit{Vertical Village} employs a grid-like organization that allows a great degree of freedom to vary the arrangements of the modules. However, the grid does not run horizontally as in a conventional city; rather it is turned vertically and is closed to form a circular unit. This results in a geometric compound that is the basis for the

\textbf{Figure 20.2:} \textit{Flight Assembled Architecture} installation, assembled from 1500 building modules at the FRAC Centre Orléans. Image credit: Gramazio & Kohler and Raffaello D'Andrea in collaboration with ETH Zürich. Copyright: François Lauginie, Gramazio & Kohler owns all rights of use.
particularly constructive, self-stabilizing properties of the entire structure. Moreover, in the transition from an ideal urban plan to a spatially differentiated and highly condensed urbanity, it also strives for nothing less than a revision of the organizational scheme of a city in the twenty-first century. The monotonous and often unbearable density of earlier times becomes an engine for a newly discovered urbanity.

*Flight Assembled Architecture* also represents a technological "intensification." Here the use of flying robots not only provides for the architectural implementation of design data, their accumulation and processing, but also results in the implementation of an actual, built installation. Far beyond that, the "quadrocopters" correspond to a model of thinking; they are a kind of "conceptional door opener" that can free one from the constraint of the present and facilitate instead a radical architectural utopia that excludes neither the possibility of material experiments nor a possible built reality of the future. Similar to the case of the industrial robot, which underwent a breakthrough in industrial automation several decades before its first application in architecture, the flying "variation" also represents an already established device that has been the focus of many research endeavors and is available on the commercial market. Similar to the industrial robot, the quadrocopter has a "generic nature." It is important to stress, however, that the quadrocopter has the capacity to leave the conventional work area of an industrial robot; the airspace not only corresponds to an architectural environment, it also becomes an all-determining design paradigm.

From its essential tendency to combine different technologies, perspectives, and potentials *Flight Assembled Architecture* generates – for the visitor – a near "state of hovering" between a real architectural installation and a utopia. Thus the installation – although on a scale a hundred times smaller than the projected Vertical Village – calls into question the supposedly distinct border between utopia and realities. Beyond that, the focus on the creation of a parallel reality, which is recorded with matching precision in *Flight Assembled Architecture*, thus becomes a systematic expansion of both the imaginable and the real.

At the same time, the boundaries between installation and building process, between architecture and robotics, increasingly dissolve here and themselves become an instrument that fathoms anew the "borders between the real and that which is conceivable" and present Digital Materiality in a new architectural "perspectivity." This indicates how we may understand and investigate robot-based design processes in the digital age of architecture. It registers that empirical and at the same time "speculative" character, without which the relation to architectural research would remain disengaged and distanced from both reality and future of building. Thus *Flight Assembled Architecture* is not restricted to a pure "projection or imagining of the future," rather it is propelled by a concrete "logic of making." In the history of architecture there has always been an impetus to tame the new and thus to transform a multiplicity of possibilities and risks into concrete realities. Consequently, utopia in architecture – beginning with ancient descriptions of ideal states and cities, biblical approximations, the first architectural theory by Vitruvius, the idealized medieval representations of cities, the ideal city, architecture of the revolution up to the early socialists, modernists, and postmodern subversity – has its firm place in the history of the built and planned environment. With this premise, the installation *Flight Assembled Architecture* shows that – as in all projects by Gramazio & Kohler – it is not a distinct architectural drawing or a pure picture-like vision that stands in the foreground; above all, it is a matter of pointing out, comprehending, and implementing an architectural process with all its spatial, functional, and aesthetic consequences. Thereby *Flight Assembled Architecture* opens up a radical material practice and comprehensive interdisciplinarity; at precisely this moment utopia becomes research into the future.

> The “Interactive Connection” of Man and Machine

In navigating through the world of digital design and fabrication, the question always arises as to why these tasks cannot be accomplished without a robot. Indeed, if viewed from a global perspective one must concede that it is easier for human beings than for a robot to produce a brick wall based on a simple, repetitive bond. What might be called the "operationality of the robot" pertains in situations of a certain complexity. This means that every material entity that can only be built precisely and efficiently with the help of a robot becomes at the same time the reason why the robot facilitates what human beings cannot do. A robot unfolds its potential precisely where an increasing number of complex spatial and tectonic relations as well as individual requirements justify its use.

As the following project, *Spatial Aggregations*, demonstrates, the question arises of how to fundamentally deal with architectural complexity; that is, the problem of the relation of spatial differentiability and functional performance. Initially this corresponds less to the efficiency, precision, and flexibility facilitated by the robot, than to the possibility of monitoring and controlling complex material processes. These can be sequentially developed and implemented on a larger scale and thereby targeted for particular architectural purposes. Only there, where these artifacts are materialized does the possibility emerge for an extended performative materiality in architecture. For the implementation of the project *Spatial Aggregations*, simple rod elements were used. These are connected point-like with each other, and a large quantity are assembled in a geometrically differentiated manner. This results in statically redundant, spatially differentiated load-bearing structures, which – in contrast to traditional framework constructions – are individually adaptable and capable of assuming diverse configurations. Through robot-based fabrication, it becomes possible to produce these rod structures without additional measurement or auxiliary structures; that is, the robot grabs a generic rod element, shortens and marks it before positioning it in space, according to the data describing the overall geometric layout as well
as the assembly sequence. In this sense, the assembly sequence exerts a decisive influence on the architectural design and building process; essential here are both the spatial accessibility and the structural stiffness generated by the connection of the individual elements.

This process requires new decision-making mechanisms; most of all it requires an intensive collaboration of human beings and machines because the assembly of the rod elements is in no way a fully autonomous procedure. On the contrary, human beings become part of the mechanical process by inserting individual rod elements and installing them according to the previously applied markings. In this instance the robot merely positions them in space. The tolerances introduced through the human intervention are in the meantime compensated for by the other elements put in place by the robot. This example demonstrates the potential for future adaptive and recursive processes in digital design and construction procedures. The individual elements of Spatial Aggregations fit adaptively as described to form a coherent, differentiated and nevertheless harmonious whole so that even more unique and highly resolved spatial structures can be built. The goal therefore is not so much the pure, automatized materialization of a concrete, previously defined scheme, as rather a procedural investigation into the cooperation between the human and the machine during a complex constructive assembly process.

While experimental research in architecture in the 1970s was still entirely concerned with “natural,” self-organizing or purely industrial-modular building systems, a very interesting shift emerges here: Spatial Aggregations is probably an important trial not least of all because the interaction between human intervention and digital fabrication procedures can be directly connected – what emerges from Spatial Aggregations are highly resolved, spatially complex formations, the results of which can be predicted or simulated only conditionally; they become accessible only through real experiments and actual materialization processes.

In this, it must be stated that human beings will in no way be relativized by the robot; instead they will establish themselves as leading figures in a constructive reality between programming and fabrication. The implied turn towards the connection of digital fabrication and human intervention could prove to be so far-reaching that the central issue of our debate would consequently be the opposite; that is, through the use of the robot, the human experiences a far-reaching re-conceptualization in the “force field” of the architectural information age.

> The Return of the Machine

It is perhaps this conceptual connection of human beings and machines that imbues Digital Materiality with its expression and makes possible the introduction of the robot into the architectural discipline. As “multiple tool,” the robot allows one to execute diverse applications in a rapid and precise way, but above all, to work directly at the immediate interface between digital and material spheres and thus to exert decisive influence on the physical world through programming. Since the beginning of the 1990s, the robot has indeed become a primary tool of industrial and standardized forms of production, which throughout the entire twentieth century have been influential in our understanding of contemporary society and its stimuli for the design disciplines. However, the development towards an increasingly reflexive, individual and global “stratification” of cultural forms paradoxically represents an additional, almost complementary “turning point.” This explains why, in the future, the robot will be granted more rather than less significance: because the robot masters not only the language of unity but also that of diversity.

Unquestionably, the hardly noted dispute about the division of labor in the digital age of architecture belongs in this context; that is, the transformation of labor and its implications for architectural building processes. Particularly here, the use of the robot makes clear that instead of perceiving the robot in the context of industrialization or unleashed capitalist production of goods, it rather must be seen as an expression of a more fundamental process of the digital age: as an expression of a new digital “workability” that is, as a fabric of diverse relations that has not only dispensed with the difference between authorship and the actual producer, the production of an original and its copy, but it has also materialized in an architectural reality, which has already begun.

Figure 20.3: The robot made, complex structures “Spatial Aggregations”, assembled from a large number of straight rods. Image credit: Gramazio & Kohler, ETH Zurich.
As if this potential had always been present in the “DNA” of the robot, now comes a breakthrough that makes the robot the suitable tool, not only of a standardized but also of an individual and global world of production. Its “generic” properties handle the most diverse tasks with consistent efficiency, precision, and flexibility while always remaining open for additional adaptations, extensions and tasks. The same is true for architecture: the robot attains significance for the architectural discipline because it allows for the implementation of individual work processes instead of uniform, repetitive building sequences, and it realizes them on an architectural scale. Thereby the robot connects the (old) world of industrial logic with the (new) world of the information age, making it possible – between efficiency and precision – to technologically grant the general primacy of individualization.

The concepts of the industrial division of labor, widespread to this day, are based on individual work sequences, on spatial and temporal surveys of human being–machine systems, which build largely on empirical knowledge. Frederick Winslow Taylor was the first to aim for clear rules and instructions for dealing with complex issues of the division of labor, exchangeability of single parts, and efficient mass production. Although production processes became considerably more precise and less expensive – the same is true for standardization, distribution, and the repair of industrial artifacts that were produced in this way – one always referred to the implementation of pre-defined objects and sequential procedures. However, in the post-mechanical age, the fixed adherence to sequential production of architectural artifacts and their limited variation have been dispensed with, so that “productivity” and “specialization” are no longer necessarily contradictory, rather they realistically depict the interconnectedness of information and technology. The sequential categorization of architectural production thus falls away, and with it the classic division of labor of the discipline. It is precisely here that the robot in architecture makes an important contribution, so that the sometimes dialectic and equally marginal influence of digital technologies on architecture now corresponds to a “reflexive” form, through which it gains considerable significance. In this process diverse influences and disciplines enrich each other and enter into a mutual connection – less because of increased sales or efficiency potentials than from an awareness of a culturally strengthened architectural production capacity.  

> Towards an Extended Performative Materiality in Architecture

For our present discussion, the great achievement is that the questions of efficiency, precision and flexibility can be simultaneously reinterpreted as a question of how to deal fundamentally with building. What is sometimes inconceivable in our current modes of thinking is that the robot-facilitated approach to a comprehensive technological fabrication capability corresponds in no way to a devaluation of human skills; quite the contrary, these can be considerably expanded through the “operationality” of the robot. Thus monitoring and control of complex material processes are not only improved, they can be implemented in a differentiated way and thereby targeted for architectural purposes. Within these conceptual goals, the robot no longer is tied to the making of things, it also connects with the thinking of things.

According to Mario Carpo, the consequence is that the division between the acts of designing and producing that has existed since the Renaissance dissolves. Thus, the “operationality” of the robot is not related exclusively to the material act of producing, of material operation, and of pure implementation, but rather equally to the way architecture is intellectually conceived, programmed, and designed. Carpo’s thesis gains analytic acuity when it is modified to say, conversely: programming can be interpreted as an “anthropological” form of designing, constructing, and materialization, so that it is ultimately questionable whether – in the synthesis of programming and robot-based fabrication – the intrinsic “self-referentiality” of human beings and machine becomes generally visible. Thus it can be stated: the robot is a fascinating instrument in architecture, particularly because it facilitates – removed from any determinism – the discovery of new constructive and spatial worlds, which in turn provide new insights for further discoveries. It remains to be seen how the robot will develop in the future. However, one thing is certain: in no way does operationality of data and material aim merely at digital aesthetics; it is far more than a short-lived chapter of the digital age. Rather it is a “perspectivity” that facilitates – from concrete technology-based examination of computer programming to fabrication with the aid of flying robots – an open, complex and tangible asset of architecture. The thrust of digital advancement in design and manufacture can be thus investigated and included in the content of the discipline; it becomes possible to spatially and materially relate these developments and thereby to make them culturally significant.

1 The merger of the terms “digital” and “materiality” can be traced to the essay “Digital Materiality in Architecture” in Fabio Gramazio and Matthias Kohler, Digital Materiality in Architecture, Lars Müller Publishers, Baden, 2008. Combining seemingly ambivalent concepts – the digital and the material – architecture is enabled to generate new constructive and sensual realities where data and material, programming and construction are interwoven by the techniques of digital fabrication. This allows the designer not only to control the architectural manufacturing process through design data and therefore to “inform” material, but also to express a new sensuality in the digital age of architecture, being characterized by an unusually large number of precisely arranged elements, a sophisticated level of detail, and the simultaneous presence of different scales of formation.

2 Central to this is an additive principle, which allows the assembly of complex architectural structures from single elements, and the control and manipulation of them so that new kinds of spatial and functional configurations can arise.

5 For more information, see Professorship for Architecture and Digital Fabrication, ETH Zurich, http://www.dfab.arch.ethz.ch (01.06.2012).
6 Cf. Semper, G., Der Stil in den technischen und tektonischen Künsten oder praktische Ästhetik, Band 1, Bruckmann, Munich, 1878, p. 7.
7 The project The Fragile Structure was developed 2012 at the ETH Zurich and realised with the support of Schüller Holz AG (Project leader: Luka Piskorec; team: Volker Helm, Selen Ercan, Thomas Cadalbert; students: Petrus Aemelahus Lindström, Leyla Ilman, David Jenny, Michi Keller, Beat Lüdi). For more information, see Professorship for Architecture and Digital Fabrication, ETH Zurich, http://www.dfab.arch.ethz.ch/website/europe226.html (01.07.2012).
8 Interestingly, this debate is directly related to the modularity of such systems. The Fragile Structure demonstrates that such a modular approach on the one hand incorporates the traditional logic of serial building systems; on the other hand, however, it articulates a wholly new state of affairs where such a generic and multiple construction system increases the integration of new freedoms and complexities. This is, however, less radical as it is generally propagated within contemporary architectural discourse on mass customization since it also leads in parallel to ever new convenations, serializations, and simplifications, even when this “return of standardization” is first out of direct visibility.
9 This implies that the traditional use of industrial ground robots in controlled environments is challenged by this project, in that a mobile robot unit is made capable of manufacturing digitally informed and geometrically complex building components, to a certain extent “in situ.” For more information, see “In situ robotic fabrication” (Echord/EU-funded research project), Professorship for Architecture and Digital Fabrication, http://www.dfab.arch.ethz.ch/website/forschungs198.html (01.07.2012).
10 This project is based on a collaboration of the Professorship for Architecture and Digital Fabrication (Prof. Gramazio, Prof. Kohler) and the Institute for Dynamic Systems and Control (Prof. Raffaello D’Andrea), both of ETH Zurich.
12 The question of the diversity and accessibility of urban spaces and their contents becomes a central theme of the Vertical Village, in as much as the embedding of four gigantic continuous public double-rings with a combined length of 1 km each, are found not, as usually is the case, on the lowest floor, but are spread across the entire height of the building volume, creating heterogeneous city structures. The public space thus spreads across the entire height. Together with the inner courtyard – with a diameter of over 300 meters, certainly comparable with a valley in a landscape – this creates the possibility of an urban generosity and permeability, which treats public life with all it offers, less as uniform, horizontal and insular and more as an essential feature. At the same time, a completely unique form of intimacy takes place. For through the sheer size and structure of the Vertical Village, the inhabitants and their comings and goings are only roughly visible from outside, whilst remaining recognizable as an intimate presence within the Vertical Village is created.
18 Conversely, it would make less sense to use robots producing standardized building components, even when this would be technically possible. For an architectural use of robots for such things, the essential complexity would be missing; quite apart from the fact that the human represents with craft skills developed over millennia, and the highly advanced technology of mass production, a far more efficient framework within which simple and similar components can be manufactured.
19 The project Spatial Aggregations was developed 2012 at the ETH Zurich and realized with the support of REHAU (Project leader: Luka Piskorec; team: Thomas Cadalbert; students: Petrus Aemelahus Lindström, David Jenny, Gabriela Schär, Ripple Chauhan, Evangelos Pantazis, Stylianos Psaltis, Rahil Shah, Stella Azariadi, Ivana Damjanovic, Hjalmar Schmid, Lukas Mersch, Katharina Schwiete, Enzo Valerio, Andreas Kissel, Kubrehret Patel, Christian Grewe-Rielmann, Sonja Cheng, Joe Liao, Yushi Sasaeda, Tarika Saajani, Janki Vyas, Bo Li, Yuji Mukaiyama, James Yeo, Eveline Job, Josephine Simonian). For more information, see http://www.dfab.arch.ethz.ch/website/europe228.html (01.07.2012).
24 What has not remained unknown is that Konrad Wachsmann’s Wendepunkt im Bauern (1959) is situated in a similar theme, as is the work of Pierre Néovi or Felix Candela. Here it is essential that Wachsmann had recognized early on the conceptual effects of industrialized production processes for architecture, and taken these beforehand for the digital age. Within this “Marxist” perspective, it is Wachsmann’s distinction between technology and the art of building which is essential to the debate conducted here, insofar as through the robot the “natural sense for material and joints” Wachsmann postulated appears to be newly articulated and experiences a new “turning point,” in the age of the viable individual and digital production of architecture.