New Industrial Design Protocols for Carbon-Neutral Buildings

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21st century carbon-neutral architectural design and digital manufacturing processes must eliminate fossil fuel dependency and reduce the growing demand for land use. The need for change is crucial despite conflicting goals in developing core tasks for governments, society, and business. Another challenge is that the divide between design and construction has resulted in increased schedule delays and cost, because information technology, optimization, and digital production techniques are not well integrated. This essay explores parallels between computational and performance-based developed architectural design and manufacturing practices—here represented by projects of leading companies in Carbon-Neutral Design Coding and Digital Manufacturing. The essay interprets how the future of computationally developed carbon-neutral architecture will affect the design and industrial practice through parametric-topological and/or algorithmic modeling. The findings suggest that these tools offer new industrial design visions in the Human-Computer-Interaction with digital manufacturing systems for producing, assembling, and benchmarking carbon-neutral buildings.

INTEGRATED BUILDING PROJECT DELIVERY OF INDUSTRIAL-SCALED MODES OF PRODUCTION

One of the typical challenges in architectural design and manufacturing is the lack of an integrated computing infrastructure to support complex design, engineering, manufacturing and evaluation. The problem is compounded by the fragmentation in the architecture engineering and construction (AEC) industry, in which data and software tools are often heterogeneous. The sheer amount of information that is required to effectively design, manufacture, implement, and operate carbon-neutral buildings is overwhelming. For this reason, implementation often requires the use of collaborative, intelligent tools, components, and execution systems to manage the entire integrated delivery processes including the structure's entire life cycle. Today, thanks to 3-D/4-D design modeling and intuitive computer interfaces that are easy to use, it is possible to achieve the rapid conceptualization of different prefabricated and modularized carbon-neutral building designs at minimal cost. These features enable the user to simultaneously conceive, simulate, and validate several alternative solutions though the entire life cycle.

HISTORICAL DIVIDE: PARAMETRIC-TOPOLOGICAL THINKING VS. COMPUTER-AIDED DESIGN

Computational intelligence and parametric knowledge in design and industrial practice are not new. In fact, since the 1980s, 3-D-parametric and performance-based planning engineers and industrial designers have employed a completely different method-logical use of digital design tools in aerospace, ship-building, automobile manufacturing, and electronic industries than in traditional generative architectural Computer-Aided Design (CAD) and Building Information Modeling (BIM). During that early period, most large companies, such as Siemens, IBM, and Boeing, and even smaller organizations like Bentley, SONATA, Reflex, CHEOPS, GDS, GE/CALMA, developed their own 3-D and 4-D-parametric software for designing, manufacturing and prefabrication, life-cycle-testing and optimization. This allows associative geometry for the manipulation of 3-D/4-D-parametric design models by changing variables and linking them to efficient manufacturing and life-cycle-product management.

Since 1984, CATIA Systems Engineering has developed solutions for modeling complex and intelligent products with parametric solid/surface-based packages, using NURBS for core surface representation that includes life-cycle-product management and digital manufacturing engines. For example the IBM and CATIA Dassault Systèmes Global Alliance life-cycle product-management software suites compete with Siemens NX, Tecnomatix, CAM express and SolidEdge, Pro/ENGINEER, Bentley, Autodesk, and others in the CAD/CAM/CAE market. Today, interoperable parametric software packages, such as CATIA Dassault Systèmes, SIEMENS PLM with its Tecnomatix Team center software,

GTeam-BIM, enable multiple input routines including climate, building systems, materials, energy use, CO2e, fluid dynamics, codes, zonings, cost, liability, etc. These assist and trigger semi-automatic performance-based form finding with multiple design constraints and parametrical-topologically coded ‘what-if’ life-cycle-scenarios for the whole product life cycle: from resource extraction, fabrication, assembly, and operation to future recycling or re-use. Currently available parametric BIM software meta-data packages allow companies to integrate 3-D and 4-D best-practice models, and large knowledge repositories. Users can define and parameterize variables at the detailed geometry level, and among objects, geometry sets, and libraries. Existing system and product files can also be referenced from other files to increase the reusability of designed parts and products that are used in complex assemblies, workbenches, STL-rapid prototyping, systems routing, fitting simulation, knowledge engineering optimization, material library, and catalog editor—to name a few. There is no longer a need for extensive and repetitive coding and scripting for this Intelligent Information Flow Management of reusable parametric models and creative design processes.

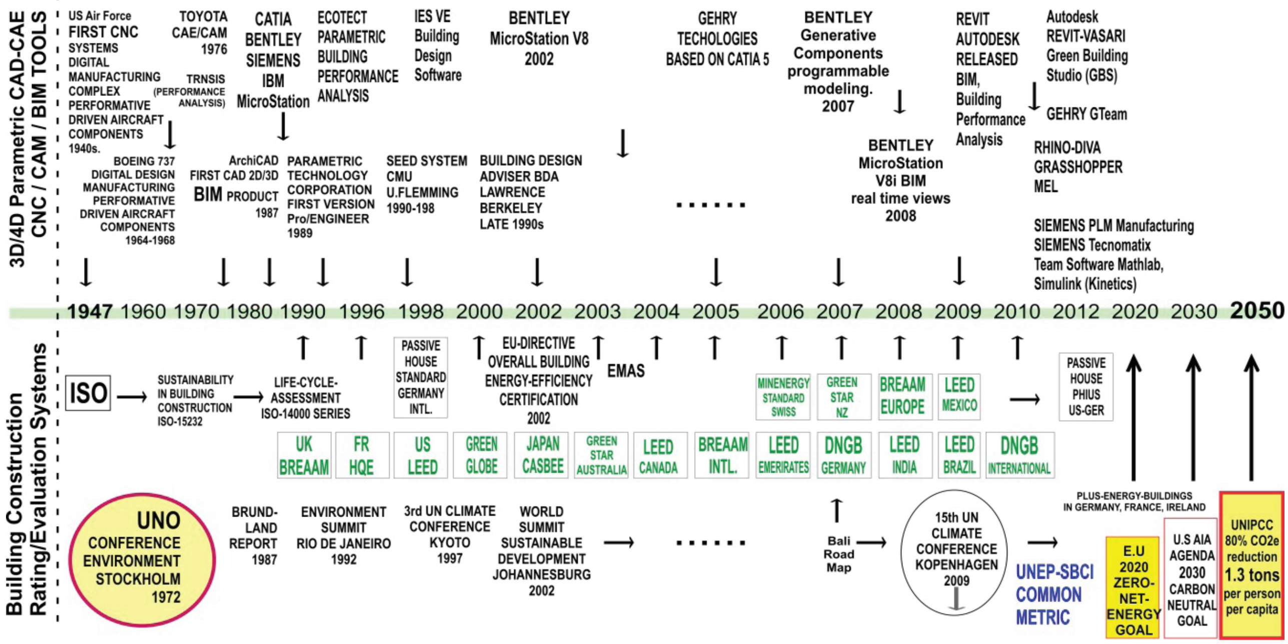

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Figure 1: Time line comparison of the parametric life-cycle and manufacturing design software development in context to the sustainability and carbon-neutral building conferences, directives and rating systems. Diagram: Author, 2012.

PARAMETRIC-ALGORITHMIC APPROACH FOR CARBON-NEUTRAL DESIGN AND DIGITAL MANUFACTURING

For the first time, students and architects are able to explore an algorithmic design approach that applies computational methods including digital manufacturing practices. New ways of simplifying and customizing software with varying degrees of complexity and compatibility between different programs is now possible without requiring students and architects to become computer programming experts. There is a growing interest from architecture students and faculties that are currently using scripting techniques such as MEL, Grasshopper, or Rhino-DIVA. There are also a large number of architecture schools that are adopting parametric software such as Revit-Vasari or Autodesk Inventor / Alias with Ecotect and the Green Building Studio® web-based energy, water and carbon neutrality analysis software. In industrial design and engineering schools, large-scale companies typically use SIEMENS PLM with Team center® software's integration for Matlab. This software integration enables Matlab, Simulink and Stateflow models to exchange and manage information with Siemens Teamcenter's systems for kinetic architecture. Users can generate Math-Works models and design codes into complex systems architectures that product teams can leverage to understand how software, electronics, and mechanical systems work together in a complex mechatronic product or infrastructure to match all the performance and carbon neutrality requirements. The afore mentioned compatible software combinations are used to analyze and benchmark building performance that can result in significant cost savings and resource reductions, mainly, because the market of reducing GHGs and the net-zero-energy building (NET-ZEB) directives in the European Union, Asia and in the USA dictate it. (Fig. 2)

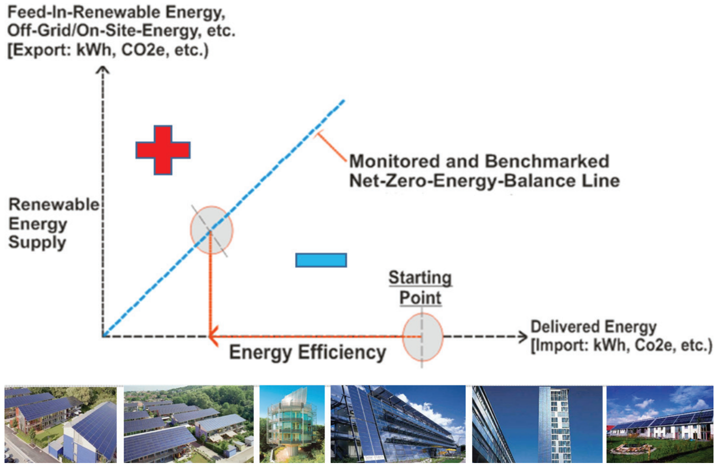

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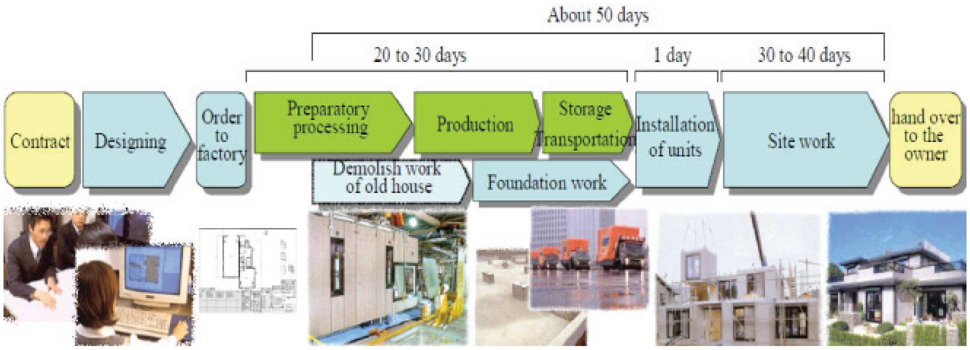
Figure 2: Net-zero-energy balance in 2018–2020 (E.U.). Below the diagram are examples of solar net-zero-energy buildings in Freiburg, Germany. Diagram, Photos: Author

NET-ZEB DIRECTIVES AND 3-D-PARAMETRIC MODELING TOOLS FOR DIGITAL MANUFACTURING

In November 2009, the European Parliament and the European Commission made an agreement on the recast of the Energy Performance of Buildings Directive (EPBD) to make it mandatory that all new buildings in the European Union must become nearly zero-fossil energy by 2020. France and Germany are moving beyond the E.U. requirements, mandating Energy-Plus Buildings in 2020, a standard Ireland aims for already in 2013. In the United States the American Institute of Architects' (AIA) voluntary '2030 Challenge' aims to achieve fossil fuel reduction for all new buildings by 90% in 2025, and become carbon-neutral by 2030. The goals of zero-fossil or carbon neutrality can be accomplished through innovative, energy-efficient design strategies, highly insulated buildings, and the use of smart building technologies, energy efficient appliances, and application of onsite renewable technologies. "A so-called net-zero energy building offsets its annual energy and water consumption demand from onsite emission-free sources through renewable energy mix such as solar, wind, biomass, hydroelectric, and geothermal including energy from renewable sources produced on-site or nearby."[1] During the operation of these buildings, greenhouse gas emissions to the environment are minimized or eliminated. The following diagram shows the general pathway to achieve a Net-ZEB in two steps. First, reduce energy demand by means of energy-efficiency measures. Second, only use renewable onsite energy to match the building energy load, or through other off-site energy carriers by means of credits to achieve the balance. (Fig. 2)

But is this possible? The major question is, how can 3-D/4-D-parametric modeling and digital fabrication tools assist to reach these goals of designing, manufacturing and operating carbon-neutral buildings? How can carbon-neutral buildings become a curriculum standard and practical routine in both education and the profession? To date, the basic curricular design process components with integrated project delivery metrics for a robust parametric 3-D-net-zero-design regulatory framework are either incomplete or missing in most accredited architecture schools. However, some schools have begun to integrate numerous parametric carbon-neutral design tool



resources into their curricula, but the visions are very limited. Most studios are still too focused on the aesthetical representation of buildings and still have not abandoned the CAD metaphor.

A major advantage to parametric-topological environmental design for NET-ZEBs is that it links variables, dimensions, and materials to geometry in a way that when an input or simulation value changes, the 3-D/4-D model automatically and simultaneously updates all systems and components. As a consequence, developed 3-D/4-D models become manageable for designers to conduct various 'what-if' scenarios to optimize and change specific parameters and benchmark indicators as needed. Such interoperable software frameworks enable multi-domain collaboration at the outset, while reducing the need for acquiring deep trans-domain knowledge; the result is the participation of multiple contributors to the entire design and project-integrated delivery process toward the mandatory net-zero-energy directives for the E.U. and United States slated for 2018 and 2030, respectively.

THE FUTURE OF DESIGN CODING

The design coding and simulation of any product, infrastructure or building on computers can be achieved long before anything is built. As mentioned before, these parametric 3-D/4-D or even 5-D virtual models contain thousands of associated parameters, most of which are from real infrastructure or building models. Many software companies such as SIEMENS or Dassault Systèmes are developing these parametric tools and processes beyond meta-heuristic techniques for environmental design in order to augment the traditional analog heuristic methods or practical rules of thumbs used by academic and professional project teams.

With 3-D/4-D parametric-topological modeling technology, even the most complex production and life-cycle processes can be visualized in detail, resulting in optimized configurations and the ability to rapidly adjust to client demands. During the Digital Mock-Up (DMU) studies, an entire building or factory can be virtually assembled to visualize the interaction of all production processes using an integrated data model. The objective is to realize how and in what sequence individual components can be assembled. A complete city infrastructure, factory, production plant, container, cruise ship or aircraft can be modeled with millions of parts designed and envisioned individually and in dynamically changing contexts. Parts of the design process, such as the HVAC, or routing of hydraulic and electrical systems, that were once performed through extensive physical mock-ups are developed through digital mock-up studies. The advantages of interoperable, digital data infrastructures are that they use synchronous technology for accelerated associated design, faster change, and improved reuse of imported existing architectural 3D-models. In this way, architects, designers, and engineers can become "topological operators with unlimited capability to optimize and test multiple scenarios."[2]

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It is obvious, that the practice of architecture in both educational and professional environments needs to embrace this level of product or industrial design thinking in order to survive and adapt to the challenges of creating, operating, and monitoring NET-ZEB buildings and infrastructures in the future.

WHAT IS DIGITAL MANUFACTURING IN INDUSTRIAL PRACTICE?

Digital manufacturing entails an integrated, computer-based system of 3-D simulation, visualization, analytics and various collaboration tools to simultaneously create product and manufacturing process definitions. Digital manufacturing evolved from manufacturing initiatives such as parametric design for manufacturability (DFM), computer-integrated manufacturing (CIM), flexible manufacturing, lean manufacturing, and others that highlight the need for more collaborative product and process design in architecture, aerospace, shipbuilding, and transportation. Digital manufacturing is a key point of integration between architectural 3-D design and various shop floor applications and equipment, enabling the exchange of architecture-related information between design and manufacturing groups. This alignment allows building manufacturing companies to achieve their time-to-market and volume goals, as well as realize cost savings by reducing expensive downstream changes. Digital manufacturing systems allow manufacturing architects and engineers to create the complete definition of a manufacturing process in a virtual environment, including: tooling, assembly lines, work centers, facility layout, ergonomics, resources and benchmarking. Simulation of production processes can be performed, with the intent to re-use existing knowledge and optimize processes before carbon-neutral buildings are manufactured. Digital manufacturing also allows feedback from actual production operations to be incorporated into the product-design process, allowing companies to take advantage of shop floor realities during the planning stage.

Current initiatives in the development of digital manufacturing tools involve improving the user experience, so that information is presented in the context of tasks performed, allowing users to make better decisions faster. Steps are being taken to provide direct connectivity with shop floor hardware, such as programmable logic controllers (PLCs), machine controllers, computer numerically controlled (CNC) machines and others. Unified platforms have also been developed to manage both 3-D software and manufacturing execution system (MES) information.

Figure 3: Process of Sekisui Heim's smart house making. Source: Masayuki KATANO, Housing Company, Sekisui Chemical Co., Ltd., Minato-ku, Tokyo, Japan. In: Structuring of Sekisui Heim automated parts pick up system (HAPPS) to process individual floor plans, 2006.

Figure 4: EMAS and ISO certified zero-fossil-energy Mercedes Benz Plant with CO2-neutral Co-Generation for electricity, heating and cooling in Rastatt, Ger-many. Image courtesy: Daimler Benz Sustainability Report 2011, http://sustainability.daimler.com

HOW DIGITAL MANUFACTURING STARTED

In the 1940s digital manufacturing started with CNC systems created by the U.S. Air Force for fabrication of complex performative driven aircraft components. Later in the 1970s and 80s worldwide CAE/CAD CAM was further developed and adopted by industrial designers and engineers in the automotive, aviation, and shipping industries. (Fig. 1)

In particular in the Japanese housing market, parametric 3-D-modeling, prefabrication and the use of robots is synonymous with innovation, sustainability, and quality. Since 1976 Toyota has been applying their lean computer-aided engineering (CAE) and manufacturing principles to their energy efficient housing division. Japanese companies such as Sekisui Heim work with finite component sets from which they offer their clients a controlled degree of customization while building high-quality designed building typologies in a fraction of the time taken by conventional site-stick- and built-methods. (Fig. 3) Most of these companies did not evolve from traditional craft-based construction firms, but instead were set up by building-material companies to create a showcase for their products and integrated building systems.

In the mid-1990s 3-D-parametric modeling and Building Information Modeling (BIM) with mass customization emerged to transform both industrial design practices and integrated project delivery. These new technologies dovetailed with CAE and CNC systems in the Japanese, U.S., and European prefabricated building manufacturing industries. Late 2000s robotics systems emerged as fully automated construction and deconstruction processes of high-rise buildings in Japan and Europe, and have since become more influential in resource and energy-efficient manufacturing, deconstruction, re-use, and recycling businesses.

In summary, increasing fabrication knowledge has reduced the gap between design, scenario testing, prototype, realization, operation, and life cycle. Today, parametric 3-D-feedback information enables rapid digital prototyping of scale models and is moving the construction industry toward ISO 14001 and EMAS certified full-scale automated fabrication of multiple products and carbon-neutral buildings.

PARAMETRIC MODELING AND MANUFACTURING: BUILDINGS, FACTORIES, AND AIRPORTS BY SIEMENS

The parametric multi-dimensional simulation tools of Siemens enable the design and digital manufacturing of all kinds of infrastructural and industrial buildings, and are useful in aviation, navy, transportation and automotive manufacturing. Product lifecycle management (PLM) and Technomatix Team software are assisting the modeling of the entire lifecycle of a net-zero-energy building and factory such as the Mercedes Benz plant in Rastatt, Germany. Whether applied to visualizing office management units or automotive production lines or planning entire factories, the simulation optimizes virtually every aspect of occupancy types and production. This includes design coding with total life-cycle scenarios based on resource-efficient CO2 reduction indicators with yearly mandatory ISO 14001 and

EU's Eco-Management and Audit Scheme (EMAS) certifications. (Fig.4)

In Germany all the Mercedes Benz plants and administration management facilities are certified in accordance with the new standard for energy management systems, DIN EN 16001, and with the ISO 14001 series and EMAS. Worldwide, all of the sites are regularly audited by external experts to assure that all the facilities are benchmarked against environmentally friendly production and processing technologies with operations-related environmental protection ISO 14001 criteria. At the net-zero-energy Rastatt plant, for example, geothermal energy and co-generation technology is being used in a new production hall in combination with a holistic concept. The latter covers the provision of heat and cooling, the operation of highly efficient ventilation systems, and the recovery of heat from production.

The intelligent design coding and simulation of the new factories on computers was done long before anything was built. These 3-D/4-D/5-D virtual models contain thousands of parameters, most of which are from real building systems, units, and machines. The models are used in calculating optimal performance arrangements, component assemblies, and transport routes. These simulations are replacing huge piles of paper plans of assembly instructions. 3-D graphics with augmented reality of individual work steps make assembly work simpler, faster, and more precise. All product life cycles are simulated from design to service, maintenance and facilities management benchmarking towards net-zero-energy standards. (Fig 5)

In general, the areas of product and infra-structure design and manufacturing in the aerospace, shipbuilding, and automobile industries have an advantage over the traditional practice of architecture firms. With 3-D/4-D-parametric modeling and digital smart-sensor infrastructures, industrial designers are able to produce a virtual mock-up of their entire product. A virtual mock-up allows for simulation of different carbon neutrality scenarios to test critical materials, systems, performance, and life-cycle constraints, without having to build a physical model. A complete aircraft can be modeled with millions of parts designed and envisioned both individually and in dynamically changing contexts. Parts of the design process, such as the HVAC or routing of hydraulic and electrical systems, once performed through extensive physical mock-ups, are now developed digitally.

MERCEDES BENZ MUSEUM

Parametric modeling has already been a critical tool used to design many complex projects around the world. The Mercedes Benz Museum project in Stuttgart (Germany) was based on'trefoil and clover leaf loop concept idea'. The 37,673 sf complex was designed by the UN-Studio Architects team of Ben van Berkel and Caroline Bros (Amsterdam, Netherlands). However, the parametric and topological 3-D/4-D-model of the trefoil idea was developed by Arno Walz, of the DP (DesignToProduction) team. Other team players included the structural engineer Werner Sobek (Stuttgart, Germany), climate engineering by Transsolar Energietechnik Mathias Schuler (Stuttgart), and the infrastructural design by David Johnston of Ove Arup (London).

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Figure 5: Parametric production lines and total life-cycle scenarios with SIEMENS-PLM and Technomatix Team software of the Daimler Factory in Sindelfingen-Stuttgart, Germany. Source: Image courtesy Siemens, Pictures of the Future, fall 2007.

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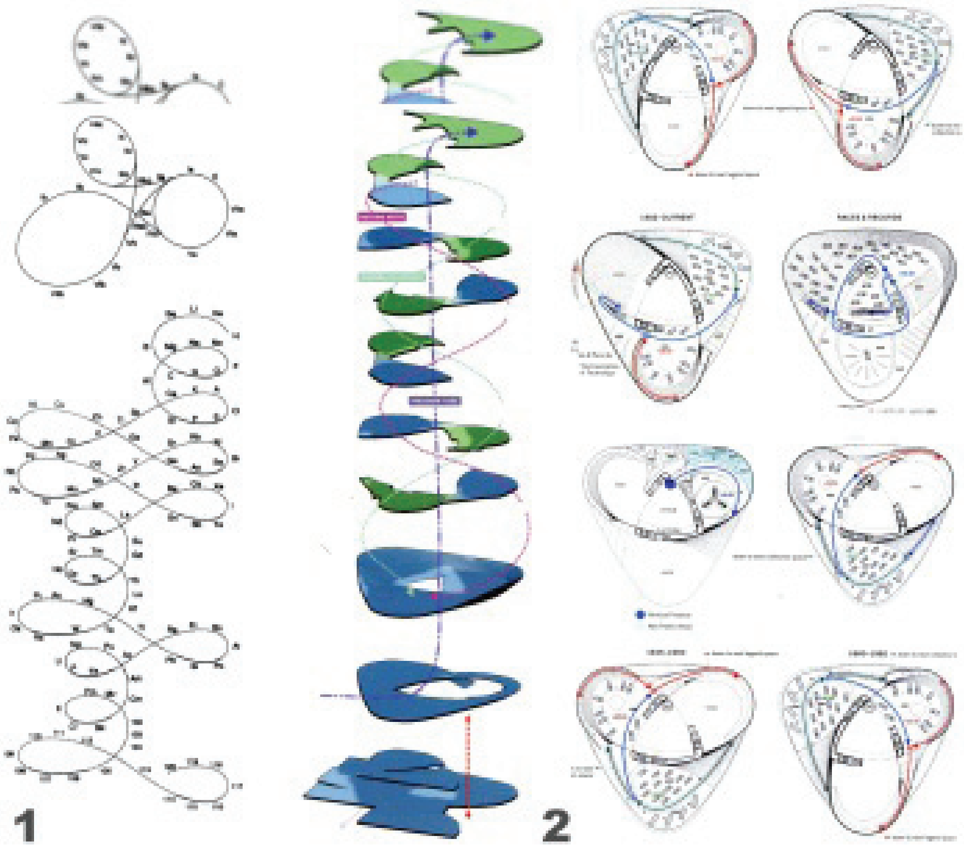

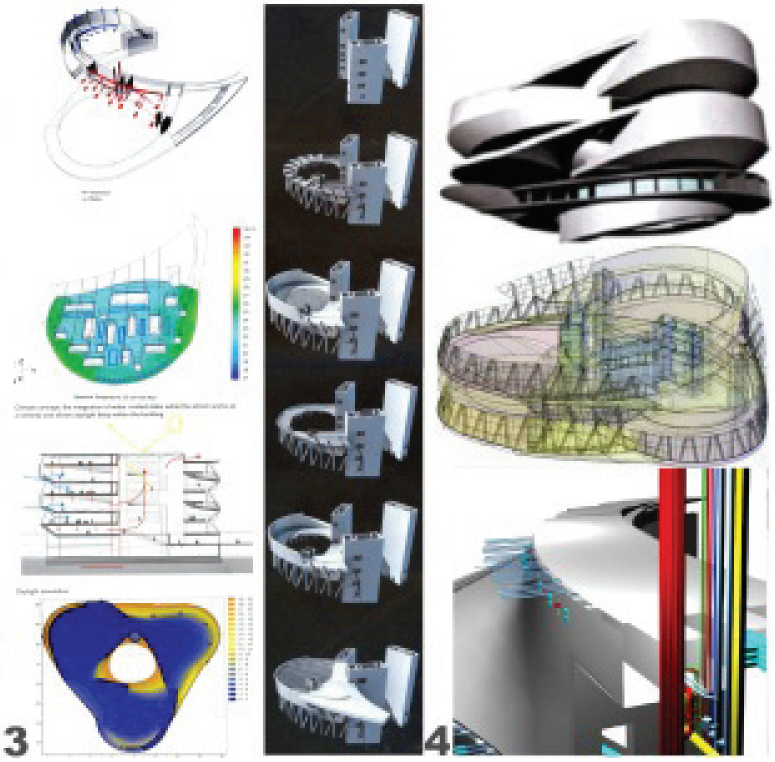

Figure 6: Arno Walz team's Parametric Master Modeling Stages: 1. Evolution of the trefold circulation idea of double curved ramps and enclosure systems; 2. Floor plan topologies with interior sequencing; 3. Integrated environmental control studies—passive and active systems; 4. Volumetric and topological modeling toward built ability, embedded manufacturing, and commissioning design coding. 5. Integrated MEP Systems and Mercedes branding of materials and surfaces

The team of Arno Walz is project driven and works to support the architect's ideas by exploring generative and analytical computational processes in intelligent coding design. The team has worked in a variety of other projects for established architects such as the parametric modeling of the construction in a series of associative topological protocols that aided the design and digital production and manufacturing processes for the architects Zaha Hadid, Daniel Libeskind, and Renzo Piano, among others. Arno Walz team has focused on spatial-topological systems, façades, performance analysis, and large-scale associated manufacturing processes of complex non-Cartesian forms and shapes. The team's objective was to develop methods that support complex designs and that explore the spatial and performative conditions, as opposed to exploring only specific geometric–aesthetic solutions for a project.

The Mercedes Benz Museum's program ascends incrementally from ground level, spiraling around a central atrium by two intertwining ramps that spiral around three major cores. They create a unique spatial experience for the visitor, but are nearly impossible to describe in traditional heuristic designed floor plans and sections. The team of Arno Walz developed a parametric 3-D/4-D-/5-D-master model of the entire building to associate all topological performance parameters and coordinate all the subsequent planning and manufacturing steps of the numerous engineers and trades involved. Numerous scenario models and more than one thousand digital plans were generated from this dynamic master geometry during the design and manufacturing process. One of the major design challenges included the innovative design language of the sculptural appearance of the museum complex, because the architects linked their geometrical 3-D-model on the organization principle of the trefoil and on the clover leaf loop concept. Therefore, a special parametric design and digital manufacturing process needed to be developed to simplify the overall project delivery method of executing the double-curved concrete surfaces throughout the museum and synchronize all environmentally relevant design principles.

The double curved, smooth, fair-faced concrete surfaces of the complex geometry were beyond the scope of the existing formwork systems and manual (heuristic) planning methods. Arno Walz team developed a method that enabled the assembly of the double curved formwork to form planar boards. The panels—precisely pre-cut on a CNC-router—were bent to the desired shape *in situ* during the construction process, exploiting their elasticity. This manufacturing process involved cutting elastic elements in a planar in order to shape any required curvature. The design and construction technique was used for the majority of the façade's shuttering elements, as well as for those sections of the cladding that are double curved. The folding building surface is expressed in the concrete construction, in the environmental control systems, and in the daylight-redirecting devices.

CONCLUSION

Worldwide, it is apparent that the rapidly developing stages of parametric-topological tools, design protocols, coding and digital fabrication in the realm of Collective Intelligence—as a major carbon-neutral building design trend–driving process—will radically change the architectural, engineering, construction (AEC) industries and planning societies. It requires quick and informed changes within a framework of integrated and intelligent design workflows, linking synchronous technology design, practice, research, education, and carbon-neutrality benchmarking.

Intelligent protocols, design coding and digital manufacturing can help architects and manufacturers improve their productivity in both carbon-neutral manufacturing planning and production processes.

- Digital manufacturing allows one to execute production processes with real-time access to lifecycle data.
- Digital manufacturing enables product, process, plant, and resource information to be associated, viewed and taken through change processes, with a consistent and comprehensive approach to production design.
- Digital manufacturing allows part-manufacturing processes to be optimized within a managed environ-ment. One can produce flexible work instructions capable of displaying 2D/3D part information, along with the machining and tooling instructions.
- The simulation capabilities of digital manufacturing help reduce commissioning costs by validating robotics and automation programs virtually.
- Digital manufacturing systems facilitate the sharing quality of data across an organization by generating complete, verifiable CAD-based machine inspection programs for coordinate measuring machines (CMMs) and numerical control (NC) machine tools.
- Synchronous CAE technology editing tools speed up the simulation scenarios of multiple types of analyses with data from multiple CAD sources
- The real challenge, however, is figuring out how to alchemize all this knowledge into accessible and profitable information techno-logy of carbon neutrality business, education, policies, and practical implementation directives.

There is a fundamental change needed that requires nothing less than the complete retooling of the relationships and roles of educators, architects, engineers, and manufacturers, with 3-D/4-D/5-D parametric topological modeling tools, smart-sensor-infrastructures, semi-automated life-cycle-scenarios with integrated project-delivery, in order to collaboratively use the talents and insights of all participants in the design, manufacturing, and assembly processes of future carbon-neutral buildings. ◆

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