How to Plant a Subway System

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Abstract: We speculate on a possible CAAD future that deploys and extends paradigms of natural growth and cellular development to an extent that would allow the *planting* and *growth* of man-made structures. This approach is based on the translation and expression of digital data structures into artificial physical form and the building of structures by decentral means. In such a scenario, generative and evolutionary architecture could seamlessly blend into building construction. As a discussion of as yet unavailable future technologies and methodologies the proposed remains at a "sketchy" level and must largely limit itself to preliminary and speculative considerations. In order to restrain the scope of this paper to the area of building design and construction, we focus on subway development and discuss possible cellular approaches to this particular field emphasizing aspects of functional aesthetics. We encourage the reader to take this example as a point of departure only, to generalise our explanations and to apply them to other building types. We support our discussion with findings made in software simulations of human-designed cellular growth processes.

1 INTRODUCTION

Since the ancient pyramids, Man has built by applying external forces (levers, cranes etc.) to passive matter. Design is still focused on developing external blueprints that are interpreted by subsequent construction or manufacturing, and not embedding form-giving information into the physical substance of the object as it happens in Nature. Contemporary construction robotics does not challenge this perception and still applies external forces to put into practice external blueprints by centralised means. While aesthetic, and increasingly also structural, aspects of architecture have traditions of finding inspiration in Nature, architectural function and behaviour have been influenced by natural paradigms only to a very limited extent. We argue that taking inspiration from Nature for the design of small-scale material behaviour could yield similarly strong impacts and benefits for the architectural field as borrowings from larger-scale natural aesthetics, structures and behaviours. This implies a shift from externalised data representations (models, plans) and processes (computation) to designs incorporating computational capabilities and data storage for cellular containment and manipulation of soft building models. The discussed principles, once available, could be applied to the development and maintenance of *all* types of architectural or urban structures such as bridges, residential projects and so forth. We choose subway systems for this discussion, firstly, because the scale of this type of macro-project is well suited to demonstrate that the techniques discussed on the following pages are not subject to limitations of physical dimensions or logistic scope. Secondly, predictive procedures and explorative elements of tunnelling work provide an excellent milieu for the discussion of the *epigenetic* and autonomous *in-situ* planning capabilities required by developmental systems.

The project from which this paper emerges is concerned with cellular developmental growth in architecture from a primarily information-architectural and theoretical perspective. It is not the purpose of this paper to rigorously investigate all aspects of how developmental processes could be applied to building construction. Its purpose is rather to demonstrate the relevance of developmental principles to practical future planning, building and construction. Since this relevance might best be demonstrated by showing financial viability and proposing a potential market, we will proceed with a brief discussion in economic terms. Our argument is less concerned with maximising the (often intangible) macroscopic merits of subway development but more with understanding developmental models of artificial morphogenesis to help in minimising macroscopic cost and the economic risks associated with subway development. Built to improve and enhance urban transportation infrastructures, subway systems are often solely or significantly supported by public authorities and expected to pay-off in ways that cannot always be expressed in terms of their monetary value, such as improvements in surface traffic situations, general convenience, road safety or indirect stimuli to urban development and economy. This does not, however, mean that subway development is independent from financial constraints and the general pressure for cost-effectiveness. From the perspective of a tunnelling contractor, for example, the cost of a project must of course be calculated carefully in the form of very clear figures that seek to guarantee successful and timely project completion as well as competitiveness. At the same time, unforeseeable factors such as geological uncertainties can be considerable and introduce a fair amount of economic risk. Along this line of thought, we propose cellular architecture primarily as a means to reduce (ultimately or mostly economic) demands and risks. The tight project budgets of large-scale development projects typically prohibit thorough searches for alternatives, except maybe within the very early stages of the design process. For this reason, we believe that examining the questions at hand independently from actual projects is an appropriate choice. Getting to the “right” solution very quickly is imperative in actual projects, especially at very large scales, which often leads to uninspired and overly conservative designs lacking in creativity. Concentrating on the problem of artificial growth, this paper ignores other capabilities of natural cellular structures such as replication and self-repair – despite the fact that the latter characteristic in particular bears significant potential with respect to system operation and maintenance. We are interested in applied aspects such as the following: How can we speed up development processes in order to save direct costs (and interest rates)? How can we mitigate surface traffic nuisances, underground work hazards, risks from geological and other uncertainties during subway development? And how can design and construction approaches be integrated so as to streamline overall operations in future subway development? Which alternatives to contemporary practices might be feasible and in what ways might certain alternatives be more feasible than other ones? These questions naturally imply a tendency towards fragmented, bottom-up answers that cannot be conclusive. We will address them after providing a brief discussion of the historical/ theoretical background of this research.

2 AB OVO: 'TECHNICAL GAMETES', 'BRICK EGGS'

An early example of the vision of *planting* and *growing buildings* can be found in the speech given by Konrad Zuse at the granting of his honorary doctorate in Berlin in 1957 (Zuse 1993). Already then, referring to von Neumann's work on Cellular Automata and covering automated assembly as well as artificial self-reproduction, Zuse elaborates on the idea of a "technical gamete" (*technische Keimzelle*) that, containing a complete description of a full structure, would require only a supply of energy and raw material to build the structure autonomously. In *Calculating Space*, Zuse (1969) gives further early discussions on the relationship between space, matter, information and form. In contrast to the majority of his contemporaries working on similar ideas (such as von Neumann, Ulam or Codd, who were interested in cellular automata and self-reproduction from a much more theoretical standpoint without any ambitions to build physical manifestations of their ideas) Zuse focused on industrial applications and physical products. His amalgamation of an applied interest in built structures and a more abstract interest in cellular automata was, presumably independently, repeated by Smith (1976) who states: "We have taken the chemicals of living things and made vital parts of living things from them [..], but we have not yet generalized the secrets of living things to non-living creations of our own. [..] I see forests of inorganic trees. I see buildings construct themselves, growing from a single brick-egg each." Considerations of this kind can take two general directions: Natural organic material could be altered by means of genetic engineering to develop useful, designed environmental structures and artefacts. Since this direction has difficult ethical and technical implications, we confine ourselves to the safer and more controllable second alternative which also appears to be given Zuse's and Smith's implicit preference: the production of artificial tissues of cell-like robots, capable of performing developmental processes, such as those we observe in nature. Evolutionary theory, in particular the Neo-Darwinian view, has been the subject of considerable criticism during the past years. After the discovery of DNA as the carrier of genetic information in the 1940s and 1959, it was helpful to explain and to understand a number of phenomena. Since then, the DNA paradigm has inspired ideas in other disciplines such as design (Frazer 1995). Due to its failure to answer some questions concerning natural reproduction, however, this theory was increasingly recognized to be incomplete. It, for instance, neither encompasses the actual *principles* of selection, nor the occasionally very close relationship between phenomena on individual (ontogenetic) and population (phylogenetic) levels nor the emergence of radically new body plans. As it does still explain a great number of phenomena well enough, biologists have not entirely dismissed it, but extended it by so-called developmental theory. This branch of biology examines the developmental process that allows zygotes to develop into fully-grown multi-cellular organisms by means of cell division, cell crawling, tissue differentiation, programmed cell death and the regulatory systems governing these processes. As a result, biologists concerned with growth, reproduction, inheritance and so forth today apply a combined set of theories, which they informally refer to as "evo-devo". The further extension of these concepts in design was suggested in Fischer et al. (2002), in which a more detailed account on the fusion of evolutionary and developmental concepts in biology is also given. In this paper it was also demonstrated how form and behaviour can be "bootstrapped" using cellular growth and how the expression of local attributes of developing designs is possible based on the spatial and/or temporal identities of cellular members. From the point at which cells are placed into the ground, they have to proliferate and cover the area of the entire subway system to form an explorative and, increasingly, a structural apparatus. This process can be seen in analogy to the growth of plant roots under ground. Whereas most plant roots tend to develop centralized topologies, subway systems frequently also necessitate other organisational types, as exemplified by the London Underground's ring-shaped Circle Line.

Figure 1 Reaching Out: Plant Roots and Zuse's "Metropolis"

In a school project, Zuse developed an urban traffic routing scheme for his vision of a "Metropolis" that integrates centralized and circular elements (Figure 1 right). Such topologies, and useful distributions of subway stations, can be achieved by various means. Cell insertion points could coincide with future subway stations. Developments from multiple insertion points could then join underground to combine into circular topologies. Turing (1952) has discussed morphogenetic principles to express local attributes (such as a station) by decentral means in homogenous circular systems. These are applicable not only at molecular or cellular, but also on architectural, scales. Cairns-Smith (1982) describes the pathway from mineral crystals to organic molecules, and subsequently the emergence of DNA as the *genetic takeover* in the history of life. He describes this takeover as a milestone in the evolution of a system for plan-based development and reproduction that has eventually gained the capacity to sustain itself without the presence of some of the mechanisms from which it has emerged. The principles described here anticipate another "takeover" that will not evolve chemical compounds into vastly more complex and flexible natural building blocks as the genetic "takeover", but one that will eventually evolve passive building blocks of artificial products into units with vastly more powerful capabilities. This second "takeover" has a history, going back to the early days of computing and the integration of Turing Machines into grids to form cellular automata. Von Neumann (1966) used cellular automata to demonstrate artificial self-reproduction in a theory that has later been refined by Codd (1968).

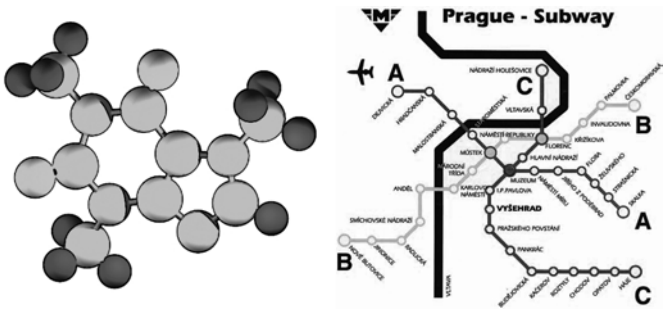

Figure 2 Diagrammatic Topology in Molecules and Metros: Caffeine, Prague

Considering designed artefacts and environments such as buildings in general and subway systems in particular as conglomerates of connected, interrelated sub-organs, and proposing to compose these organs out of cells, we implicitly consider them to be potentially realisable as multi-cellular "organisms". Growing such an organism would require the automatic proliferation of new forms of building bricks that are provided with a means for autonomous behaviour. As in higher natural cellular organisms we can observe self-reproduction on two scales (cell division and [a]sexual reproduction of organisms), these capabilities become potential options for man-made structures, too. Focusing on growth and development, this paper ignores those options at this point for the sake of simplicity. We assume that the artificial cells applied here do not share their natural counterparts' capacity to synthesise copies of themselves from raw materials. Instead, we suppose a continuous supply of industrially mass-produced entities, which will represent the cellular material of which the organism (subway system) is composed. In analogy to molecules and cells found in nature and their ability to assemble stable shapes and enclosures, we propose polyhedra capable of close packing for our purposes. Figure 3 shows close-packed polyhedra at different (architectural and molecular) scales of granularity. Due to its ability to form uniform close packing structures the rhombic dodecahedron appears to be an excellent choice for the geometry of this cellular entity. Fitted with computation-universal capabilities, communication facilities and a sensorimotor apparatus, these "bricks" or "cells" represent small robotic units that can move about, couple and uncouple following instructions from built-in computers. The actual size of such a cell would be determined by spatial requirements of internal devices (computers, motors, sensors, interlocking mechanisms) and internal structural components, which are mainly governed by inter-cellular mechanical forces expected during excavation work (determining the minimum cell size) as well as by the resolution at which a smooth approximation of line curvatures – according to dimensions of train cars, station locations etc. – can be achieved (determining the maximum cell size).

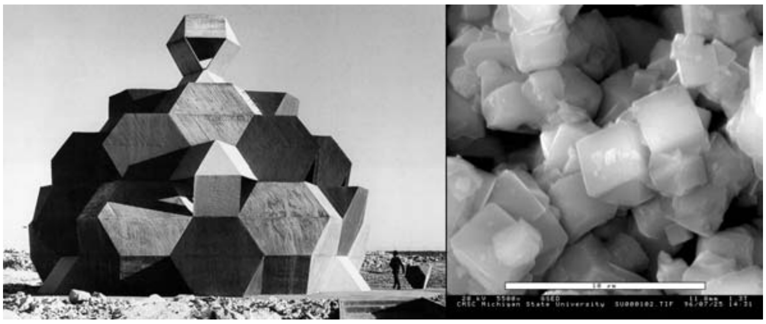

Figure 3 Polyhedra Packing: Architecture by Zvi Hecker and Zeolite Particles

Since at different locations and at different times during development, different activities need to be performed, cells need to support a variety of (sensor, motor, structural, logic) actions. It appears unrealistic to aim for technical solutions that would allow cells to express needed capabilities as they arise in analogy to natural cell type differentiation. Integrating support for all expected actions into all cells would result in immense extra cost, overall redundancy and impact on minimum cell size. Hence, to simplify and streamline their mass-production, programming and maintenance, a minimum number of different types of cells with different capabilities (excavating, providing structural support etc.) would need to be produced and provided to the developmental system. The requirement for specific capabilities would need to be reported to and satisfied by the cell production and supply system accordingly. Cells would find their positions autonomously in analogy to natural cell crawling mechanisms (compare Stossel 1994). Yim et al. (Yim 1997) have examined the logistics involved in shape assembly based on dodecahedral robotic units. Their report demonstrates motion-planning algorithms based on centralised co-ordination, to which a number of more or less decentralised variations can be found.

3 CELLULAR TUNNELING

Present construction techniques still largely depend on human presence. Natural cellular growth and development do not rely on external forces, observation or intervention, but are nevertheless capable of (epigenetically) coping with environmental factors in effective ways. If this capability could be applied to artificial development, one of the most important advantages would be that the presence of humans in the construction area could be rendered widely unnecessary. This reduces the general requirement to maintain liveable and safe conditions in the development area including the infrastructures required to provide light and air but also water drainage and so on.

Figure 4 Cut and Cover Execution of a Subway Station in Shenzhen (China)

One should expect the minimum size of tunnel opening(s) during construction to be determined by the largest object (material, equipment: train car, boring machine etc.) that needs to go underground. Practically, however, contemporary subway development does not even approximate this ideal situation. Very frequently, if surface and soil conditions allow, stations are executed as box constructions, resulting in very large cavities in urban contexts (Figure 4). The running tunnels between them are often aligned with streets and realised as cut-and cover constructions (in which case of course boring machines are not necessarily required). Such nuisances could be reduced if excavation were to be delegated to special-purpose variants of our cellular bricks, which perform digging work in a massively parallel, decentralised way. In this way, excavation openings could be minimised significantly to the diameter of two or very few cells plus some extra space that allows cells to roll about on each other. The result would be *drifts* or chains of cells of small diameters, which lead ahead of the full-scale excavation. This could happen at any stage during tunnelling to provide an explorative apparatus ahead of the tunnel to evaluate geological contexts and to allow the development to respond epigenetically to given situations. The result of this stratagem would be a far-reaching integration of structural components, proliferation robotics, predictive exploration and analysis devices as well as of all their behaviours. Figure 5 shows the computer-simulated development of a subway junction similar to that of Hong Kong's Island and Tsuen Wan MTR lines between the Central, Admiralty and Tsim Sha Tsui stations. At junctions of this type, where two lines meet, the two tunnels (one for each direction) of one line have to "twist". This twist allows passengers of each line to conveniently change to each direction of the other line on the same platform on one of two stations. The simulation shows how cellular tunnelling robots could satisfy the tunnel routing requirements described above step-by-step, expressing abstract cell-internal data and program structures as collective physical form. It is comprised of around 9000 cells of three types. Decentralised translation of data structures into cellular form opens a variety of technical options and strategies. The development of buildings from industrially mass-produced, crawling cells would come to pass as massively parallel robotic activity in which logic states inside the cells are translated into composite form. This translation process could apply many different strategies.

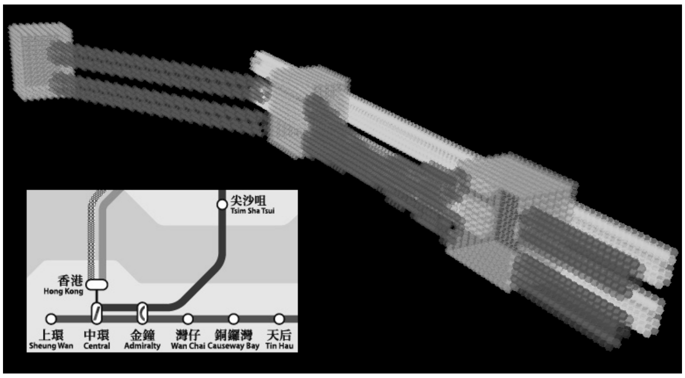

Figure 5 Simulation of Cellular Subway Station and Tunnel Development

“Logic state” refers to content, programs or data of computer memory. Since from an external perspective, programs and data can be regarded as equivalent, it does not necessarily matter if a cellular representation (or better: manifestation) is the result of a complex algorithmic program of pre-modelled data that was processed by a rather straightforward program. Yim et al. (Yim 1994) have described a simple scanning algorithm that identifies missing dodecahedral units by moving a virtual plane through a pre-defined 3D model of the final form. Many other strategies and various modes of interaction between programs, humans, models and data are possible and need to be addressed by future investigations. The challenge of manually or semi-manually pre-modelling rough building schemes poses more challenges, especially to the interface design field. A further issue is that of runtime adaptability. Will the unfolding of a cellular form rigidly insist on the manifestation of a pre-defined data structure or will it allow epigenetic adaptation to specific situations encountered during development? In the case of subway system development, the latter option could involve growing small pilot tunnels to evaluate media conditions. Based on such evaluations, the overall system would then be able to plan useful strategies as to how entire tunnel faces are excavated, how and when specific tool cells are requested and applied in mixed-face conditions and so forth. It would be interesting, in some cases, to use such explorative capabilities as can be observed in the growth of natural plant roots. In other cases, this stratagem would be less appropriate since the major components of subway systems must confront strong constraints (line routing, existing building structures etc.), which prohibit many of the developmental options of natural plants. Cellular building development and building by applying external forces and plans are not necessarily opposite or contradicting concepts. These two approaches can be combined in a variety of ways. It is for example possible to deploy non-cellular organs within cellular building organisms. Most projects of this type would probably benefit from hybrid or mixed-mode solutions. During the excavation of a subway system, for example, the use of cellular robots in mucking work will be very difficult and inefficient. Using traditional non-cellular equipment or "organs" such as traditional conveyer belts etc. in addition to the cellular developmental system would likely be a better choice. Alternatives of system centralisation vs. decentralisation, cellular vs. non-cellular building methodology and static data vs. algorithmically driven form generation should be seen as cooperating components rather than mutually exclusive polar opposites. Hybrid solutions would allow transitional changes from traditional tunnelling methodologies to the new paradigm to keep the impact of innovation calculable and schedulable. In order to reduce the costs of cellular developmental systems, it might also be necessary to recycle those components that are not used any longer after they have successfully accomplished their subtask. In some designs for example, once a member of a cellular tube system has found its position within the overall tissue, its motor capabilities are not likely to be used again (this would not be the case if its motor apparatus was planned to play a role in maintenance and reconfiguration after building completion). Once motor elements are no longer needed, they could use their own means to evacuate their cells. The mostly empty steel shells of a cellular structure with remaining sensory/logic/communication capabilities could then be filled with liquid concrete that is supplied from the surface. The result would be a reinforced steel structure consisting of concrete and re-used steel that was used as structural cell material during excavation and tunnelling. Sensory, logic and communication capabilities could be designed right from the start to also serve operational purposes after construction completion (monitoring traffic, tunnel condition etc.).

4 CONCLUSION

Discussing preliminary technical considerations we have shown that examples of growth in Nature could be extended to provide inspiration for artificial cellular design and construction paradigms and methodologies. Physical forms can self-assemble from cellular units at different scales and levels of granularity, potentially rendering the presence of human workers in the construction area unnecessary. This approach yields interesting clues as to how generative design, developmental evolutionary theory and construction methodology might amalgamate into one possible future direction of CAAD. It bears potential for reducing costs and negative impacts on contemporary subway construction, which would also apply if deployed in the design and construction of many other types of built structures at various scales (which would by the way be capable of universal computation and plan-based reproduction). We encourage the reader to generalize our scenario and to apply it to other design and construction challenges accordingly.

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