

GIUSEPPE PIRAS

Towards the Autonomous Building Ecosystem

Semantic Interoperability,
GraphRAG, and the Future
of Cognitive Digital Twins
in the AEC Sector

preface by Zoubeir Lafhaj

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Preface

There is an old irony at the heart of the construction industry. The sector that builds the physical infrastructure on which every other economic activity depends has, for decades, been named among the least productive, the least digitalised, and the most resistant to systematic improvement of any major industry. For those of us who have spent our careers trying to bring Lean principles into European construction, this irony is not abstract. It is the daily reality of a fragmented, project-based industry in which tacit knowledge resists codification, in which supply chains are reassembled from scratch on every project, and in which the distance between what we know about efficient production and what actually happens on site remains, in too many places, discouragingly wide.

I open this monograph with that observation not out of pessimism, but because it is the context that gives the following chapters their meaning. Before saying what these technologies may change, it is worth being clear about what will not change on its own. Construction is not, and will not become, a factory. Its products are prototypes. Its workplaces are temporary. Its workforce is mobile. Its supply chains

are assembled for a single project and disbanded on completion. The stability, repetition, and standardisation that allowed Toyota to build its Production System, and allowed the Lean community to draw transferable principles from it, are precisely the conditions the construction site cannot fully reproduce. Anyone who has tried to run pull planning on a large infrastructure project, or visual management on a hospital refurbishment, knows this. The gains are real, but they are hard-won, partial, and fragile. When the project ends, much of the knowledge built with the team dissolves with it.

It is against this structural background that I read the technologies this book assembles, Agent-Based Modelling, Large Language Models, Retrieval-Augmented Generation, and the Cognitive Digital Twin. And it is here that I must state, plainly, the conviction from which I read them. The technology will advance. That much is certain, and it is not, in itself, the interesting question. Models will grow more capable, tools more powerful, automation more pervasive, whether or not any of us wills it so. What is not certain, and what will decide whether any of this improves the act of building, is whether we keep the human being at the centre while the technology accelerates around us. My conviction, deepened rather than weakened by every year of this work, is that we must. The decisive question in our industry has never been, in the first instance, technological. It is human and organisational.

This is the heart of what the Lean tradition has always understood, and what I want the reader to carry through these chapters. Construction is, before it is anything else, a human activity: a matter of people who must think to-

gether, decide together, anticipate problems together, and cooperate across the boundaries of trade, discipline, and contract. The more capable our tools become, the more, not the less, this depends on human judgement, human collaboration, and human formation. A technology that fails to change how people cooperate, how decisions are made, and how value reaches the person who does the work and the client who receives it, will be absorbed slowly, unevenly, and in ways that redistribute rather than create value. The interest of the chapters that follow, to my mind, is not that they promise better tools. It is that the mode of thinking they describe is unusually compatible with what the Lean tradition has argued for thirty years: that waste in construction is a property of the connections between people and tasks, not of the tasks themselves.

Chapter 1 traces the intellectual genealogy of that mode of thinking with real historical care. The cellular automata of Ulam and Von Neumann, Schelling's segregation model, Reynolds' Boids, and Helbing's Social Force Model are, at their core, models of how local interactions between autonomous agents produce emergent global order. In different language, this is close to what Koskela described when he characterised construction as a flow system in which waste arises from buffers, waiting times, information asymmetries, and handover failures. The connection is more than analogy. Location-Based Management, which schedules work as flows of crews through physical space rather than as sequences of tasks in a Gantt chart, is already, implicitly, an agent-based model: it treats crews as agents moving through a structured environment under local rules and predicts system-level performance, productivity, conflict, idle time,

from their aggregated behaviour. What Chapter 1 shows is that an intuition long embedded in Lean practice can now be given formal computational expression at a scale and fidelity previously out of reach.

Chapter 2 carries this into engineering practice, and it is here that the implications are most immediately legible for the Lean practitioner. The central claim of Lean construction is that waste is informational before it is physical: the defect, the delay, the rework, the idle time are downstream consequences of upstream failures in planning, communication, and knowledge. The Last Planner System addresses this at the level of weekly planning; BIM at the level of design coordination; Integrated Project Delivery at the level of incentive alignment. What LLM-based systems begin to address is the layer beneath all of these, where a practitioner must navigate thousands of pages of specifications, codes, subcontract conditions, and drawings to make a decision that is at once technically correct, contractually sound, and buildable. I would only add the caution that runs through all of my work: such systems are worthwhile insofar as they support the judgement of the professional and the companion on site, and free them to think and to cooperate, not insofar as they displace them.

Chapter 3, on Retrieval-Augmented Generation, speaks to the concern that should trouble anyone watching AI enter professional practice: reliability. The Lean tradition is not, at heart, a tradition of technological enthusiasm. It is a tradition of disciplined attention to the conditions under which reliable performance is possible. The Toyota Production System was not built on faith in machines; it was built on the systematic removal of the conditions that cause

failure, and on making problems visible rather than hidden. RAG applies that same logic to AI-assisted reasoning. By anchoring outputs to verified, traceable sources, by making a model's citations auditable in the way a structural calculation must be auditable, it turns generative AI from a tool that is powerful but opaque into one that is powerful and accountable. For the professional who has to sign a compliance check or a cost estimate, this is not a technical nicety. It is the line between a tool that supports human responsibility and one that quietly erodes it.

Chapter 4 addresses what has, in my experience, always been the hardest problem in applying Lean to the existing building stock: knowledge continuity. The Last Planner System generates rich information about production flows, constraint causes, and plan reliability, and almost none of it is systematically captured and handed to the next team. Each project begins, to a striking degree, from scratch, re-discovering the same failure modes and relearning the same lessons. The Cognitive Digital Twin, as described here, is the most ambitious proposition in the book: that the knowledge produced by a building's operational life, its maintenance history, its energy behaviour, its structural response, can be continuously captured, structured, and made available for reasoning rather than merely archived. This is organisational learning, in the fullest Lean sense, applied to the built environment, and its purpose is not to remove people from the loop but to give the people who come next the knowledge their predecessors won.

The concluding chapter draws these four lines of argument into a synthesis, and I would ask the reader to hold that synthesis alongside a necessary honesty about what the

book does not claim. Most of these technologies are at early stages of industrial deployment. The gap between a proof of concept and reliable, scalable, affordable practice is wide. The organisational, cultural, and regulatory obstacles to adoption are, in many cases, more formidable than the technical ones that remain. The industry's record of absorbing innovation slowly and unevenly is reason enough for measured expectations. None of this diminishes the contribution; it locates it. The AEC industry has rarely lacked the motivation to improve. What it has lacked are tools adequate to the complexity of the improvement, and the discipline to keep those tools in the service of the people who use them.

If there is a single conviction I would like the reader to carry into these pages, it is this. The trajectory from discrete automata to cognitive buildings is not, on its own, a story of technological progress made inevitable and left to run. The technology will evolve; that is given. The real work is to ensure that it evolves around a human centre, directed by human choice toward the ends that have always mattered in construction: less waste, more cooperation, more value for the person who builds and the person who will live with what is built. As our tools grow more powerful, our need to think, to reason, and to collaborate as human beings grows with them. Technology can make the transformation possible. It cannot make it happen, and it cannot decide what it is for. That remains, as it has always been, a matter of competence, of formation, and of human will.

The chapters that follow make their case with rigour, with breadth, and with the critical awareness the subject demands. They are a contribution of lasting value to the literature of a field at an inflection point, and I commend them

to the reader, whether practitioner, researcher, or policy-maker, in the conviction that the future they describe will be worth building only if we build it with people, and their judgement, firmly at its centre.

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Chapter 1

Design, Construction and Digitalisation in the Construction Industry

The Evolution of Artificial Intelligence Techniques from the 20th to the 21st Century

The Agent-Based Modelling (ABM) represents today one of the most advanced paradigms for understanding, designing, and managing the built environment. Unlike traditional models based on aggregate equations or system flows, ABM adopts a bottom-up approach, in which global behaviour emerges from the interactions of autonomous and individual entities, defined as Agents. This methodology, in its various degrees of complexity, has had a significant impact on the tools and methods typically employed in architectural and construction design. Consider, in this regard, the goal-oriented functionalities of design software, such as the structural safety verification of models produced using Finite Element Method (FEM) software (Zienkiewicz *et al.*, 2013), which are substantially grounded in these principles. This advancement has enabled the tools employed not only to simulate the physical structure of buildings and their physico-mechanical properties, but also the complex dynamics of the human beings who inhabit them and the processes that govern their construction (Macal & North, 2010).

This process has deep historical roots, traceable from the earliest process automation systems of the first and second industrial revolutions to the first substantial application of digital techniques during the WW2.

Indeed, like the entire computing sector, the roots of ABM lie in logical and mathematical research oriented towards military needs. It should be noted that the foundational concept of discrete modelling emerged in the Los Alamos laboratories in the late 1940s, through the synergistic work of Stanislaw Ulam and John von Neumann (Von Neumann, 1966). While Von Neumann was engaged in designing a universal self-replicating machine, Ulam suggested modelling such a process as a collection of cells on a grid, thus giving rise to the first Cellular Automata (CA) (Wolfram, 2002).

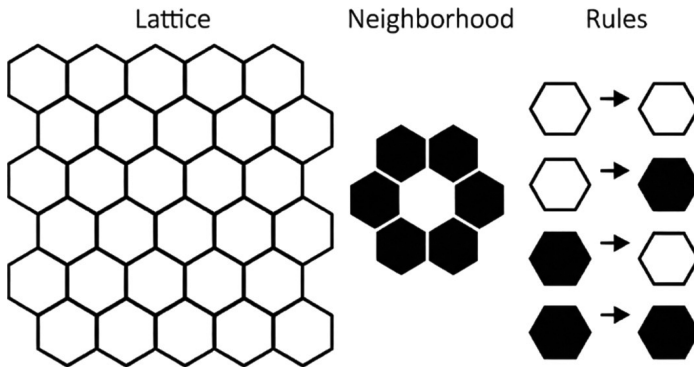


Figure 1. Illustrates the components of a cellular automaton: the lattice (i.e., the set of cells, each characterised by a state), the neighbourhood, and the local transition rules. The rules represent the communication between each cell and its neighbourhood; such communication is local, uniform across the entire lattice, and synchronous. The rules determine the global evolution of the system at each discrete time step (Delorme, 1998).