Artificial intelligence as a tool for systemic modelling and simulation of architectural strategies for a sustainable future

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Abstract: *In this work, AI is examined as a tool for the simulation of climate scenarios and the systemic modelling of the future of the built environment under conditions of climate change. Rather than relying on numerical physical simulation, the approach is based on qualitative analysis using a set of possible future scenarios, in which the same building is considered within different climatic and economic contexts up to the end of the twenty-first century. The study examines how deteriorating climatic conditions redirect resources from development toward the compensation of losses and how this transforms the architectural environment over time. The paper discusses the potential for buildings to act as active participants in the carbon balance through mechanisms for CO_2 removal and long-term fixation. AI supports the analysis of causal relationships between climate scenarios, economic incentives, and architectural decisions in order to avoid systemically problematic strategies. The approach is applicable both in professional practice and as an educational exercise for architecture students.*

Keywords: CLIMATE CHANGE, ARTIFICIAL INTELLIGENCE, SYSTEMIC MODELLING, SCENARIO SIMULATION, BUILT ENVIRONMENT, CAPITAL REALLOCATION, SUSTAINABILITY

1. Introduction

The buildings we design and construct today will exist in the future – for another 80–100 years. This means that a significant part of the contemporary building stock will function under climatic conditions different from those of today. Scientific research in the field of climate change outlines several possible development trajectories, summarised in four main scenarios: RCP 2.6, 4.5, 6.0 and 8.5 [1-3] – from the most favourable to the most unfavourable in terms of global warming and the associated risks. Each of them assumes different emission dynamics, different final temperatures, frequency of extreme events and sea level changes by 2100, with estimates varying according to the models used.

In most studies, climate scenarios are used to analyse the physical behaviour of buildings [4-6] – temperature loads, humidity, extreme weather events, the impact of rising sea levels. However, these analyses rarely include the economic dimension of the problem. Each climate scenario implies not only a different physical environment, but also a different state of society, a different structure of public and private budgets, and a different distribution of public resources.

The link between climate change and the building sector can be examined in two main aspects. The first is related to the impact on the design, operation and long-term sustainability of buildings. The second is economic – the costs of adaptation, repair, maintenance and damage limitation [7,8]. It is precisely the second aspect that is often underestimated in strategic planning.

The main economic hypothesis put forward by this study is that, as climate conditions deteriorate, capital gradually changes its function: from capital for development to capital for compensating losses. This represents a fundamental change affecting the building stock, cities, public budgets, private investors and long-term economic growth.

Investment costs create future value – new buildings, improved technologies, higher quality of life and increased productivity. Compensation costs, on the other hand, do not create new value, but restore damage, limit losses and maintain minimum functionality. In more unfavourable climate scenarios, the share of the second type of expenditure increases significantly [7,9].

Under relatively favourable conditions (conditionally close to RCP 2.6), the majority of funds are directed towards new construction, value-added renovations and innovation. The economy operates proactively and works towards future growth. In intermediate scenarios (RCP 4.5–6.0), part of the investment resource is gradually "eaten up" by repairs after extreme events, increased insurance costs and adaptation of existing systems. The same funds begin to generate fewer improvements for the future, and the economy becomes increasingly reactive.

In severe scenarios (RCP 8.5), a qualitative change occurs: a significant portion of resources is directed not towards creating new value, but towards maintaining buildings in a habitable condition. Funds are invested in flood recovery, emergency reconstruction and temporary solutions. The economy shifts into maintenance mode, and growth is replaced by survival. This leads to a crowding-out effect – funds that could be directed towards education, scientific research, culture and high-quality architecture are redirected towards compensation and restoration.

The buildings designed today will fall precisely within this transition period (2030–2100), but they are created with today's standards, economic expectations and return models. As a result, we may see earlier economic obsolescence, a shortening of the real life cycle and the need for unplanned capital injections. In severe scenarios, there is also a risk of "locked-in capital" – significant funds invested in protective facilities and adaptation measures that do not generate income or increase productivity, but only delay losses.

It is in this context that there is a need for a tool that allows for a systematic examination of the interrelationships between climate scenarios, economic consequences and architectural solutions. This study proposes an integrated simulation framework, supported by artificial intelligence, which combines climate scenarios and economic dynamics into a common architectural analysis. The new element is the introduction of the economic transformation of capital as a central analytical parameter in assessing the future of buildings.

The study asks the question: how do different climate scenarios transform the economic function of buildings, and can artificial intelligence support the systematic modelling of this transformation?

This study therefore explores the potential of AI-supported scenario simulation as a conceptual tool for linking climate trajectories, economic dynamics and architectural strategies.

2. Methodology

This study uses a qualitative, integrated simulation based on climate scenarios with a horizon until the end of the 21st century. The method is not a numerical physical simulation of building processes, nor is it a purely economic predictive model, but rather a conceptual analysis of the interrelationships between climate conditions, economic consequences and architectural solutions. The approach can be defined as exploratory – aimed at investigating structural dependencies and possible trajectories, rather than calculating precise quantitative values.

The simulation is carried out by sequentially applying the four climate scenarios (RCP 2.6, 4.5, 6.0 and 8.5) to the same architectural object. A conditionally selected contemporary building, designed in accordance with current standards and typical economic expectations for its life cycle, is taken as the starting point. To ensure comparability, all initial design parameters, structural characteristics and functional assumptions are kept constant, with only the climate and economic environment varying in accordance with the respective scenario.

For each scenario, the following sequence is followed:

change in the physical environment → impact on operation → economic consequences → change in capital allocation → transformation of the role of the building in the urban system.

The input assumptions include published climate forecasts, generally accepted economic relationships between damage from extreme events and budget expenditures, as well as assumptions about the investment cycle in the building sector. The comparison between scenarios is made by analysing the direction, intensity and quality of structural changes, rather than by absolute numerical indicators.

Artificial intelligence is used as a tool for structuring and analysing the cause-and-effect chain and for generating visual interpretations of the results [10]. Two independent large language models (ChatGPT 5.4 [11] by OpenAI and Gemini 3 [12] by Google) were used under identical input conditions, allowing verification of the robustness of the interpretation and reducing potential model-specific biases. The role of AI is analytical and interpretative – supporting the formulation and comparison of alternative scenarios, the tracing of systemic dependencies, and the identification of possible logical contradictions or undesirable effects.

The approach does not aim to predict specific quantitative values, but to clarify structural trends and the risk of shifting investment capital from development to loss compensation. The method is research and educational in nature and aims to develop a systematic understanding of the long-term consequences of today's architectural decisions.

The methodological framework is reproducible because it is based on clearly defined input parameters, including the selected architectural object, the set of climate scenarios and a predefined cause-and-effect logic. By maintaining the same initial conditions and analytical sequence, the simulation can be repeated or applied to other building types or regional contexts. Although the results are qualitative, the logical structure of the study enables comparative verification and adaptation across different disciplinary and geographical contexts.

3. Results

As a result of the integrated simulation based on the four climate scenarios (RCP 2.6, 4.5, 6.0 and 8.5), it was investigated how the same contemporary building would function and evolve in different climatic and economic contexts until the end of the 21st century. The visualisations are not quantitative forecasts, but rather a conceptual representation of the expected structural trends resulting from the respective scenario.

Each scenario is considered as a combination of physical climatic conditions and the corresponding economic environment. Thus, the simulation allows us to track not only the impact on the construction and operation of the building, but also the change in its role in the broader urban and economic context. The differences between the scenarios are not only expressed in the degree of climate pressure, but also in the way the distribution of resources changes – from investments in development to costs for adaptation and compensation for damage.

The visualisations and analyses presented below illustrate this transformation and outline the gradual shift in architectural function – from a source of added value to an object of maintenance and protection in more adverse scenarios.

a) ChatGPT 5.4 b) Gemini 3

Fig. 1. *Conceptual visualisation of the building under study in climate scenario RCP 2.6, generated as part of the integrated simulation.*

In the RCP 2.6 scenario (see Fig. 1), the visualisation presents the building in a relatively stable climate environment, where temperature increases are limited and extreme events are less frequent and less severe. The architectural object retains its original functionality and aesthetics, with a high level of maintenance and integration of sustainable technologies in the surrounding environment – photovoltaic systems, green areas, effective awnings and resource management systems. The building functions not only as a consumer but also as an active element of sustainable urban infrastructure, without the need for large-scale adaptation or emergency interventions. The economic context allows funds to be directed primarily towards development and improvement rather than damage compensation, supporting a proactive model of growth and environmental renewal.

a) ChatGPT 5.4 b) Gemini 3

Fig. 2. *Conceptual visualisation of the building under study in the RCP 4.5 climate scenario, generated as part of the integrated simulation.*

In the RCP 4.5 scenario (see Fig. 2), the visualisation shows the building under conditions of moderately increased temperatures and more frequent extreme weather events, which already require targeted adaptation. The architectural object retains its basic structure and function, but additional sustainability measures are noticeable in the environment – enhanced sun protection screening, more intensive landscaping for cooling, rainwater collection and management systems, and reinforcement of structural elements. Some of the resources are already being directed towards increased maintenance and preventive actions, which gradually reduces the share of investments that create new value. The building remains functional and integrated into the urban environment, but the economic model is beginning to shift from entirely proactive to balanced between development and adaptation.

a) ChatGPT 5.4 b) Gemini 3

Fig. 3. *Conceptual visualisation of the building under study in the RCP 6.0 climate scenario, generated as part of the integrated simulation.*

In the RCP 6.0 scenario (see Fig. 3), the visualisation shows the building under significantly more severe climatic pressure – higher average temperatures, more frequent heat waves and more intense extreme events. The architectural object retains its structural integrity, but the environment now bears the marks of adaptation under stress: additional protective elements, reinforced structures, technical cooling and water management systems, and more limited green spaces due to resource constraints. Part of the original architectural concept gives way to the need for functional sustainability. A significant portion of the funds is directed towards maintenance, repairs and damage prevention, which limits opportunities for development and innovation. The economy is operating in a transitional mode, in which the balance between investment and compensation is becoming increasingly fragile.

a) ChatGPT 5.4 b) Gemini 3

Fig. 4. *Conceptual visualisation of the building under study in the RCP 8.5 climate scenario, generated as part of the integrated simulation.*

In the RCP 8.5 scenario (see Fig. 4), the visualisation presents the building in an environment with high climate instability and frequent extreme events. The architecture is primarily subject to the requirements for survival and maintenance of minimum functionality. There are protective structures, temporary or emergency solutions, modified facade systems and adaptations that do not improve quality but limit risk. Green and public spaces are reduced or transformed into protective zones. A significant portion of resources is spent on damage restoration, insurance payments and replacement of existing elements, without creating new value. The economic context is dominated by compensatory costs, and growth gives way to a regime of maintenance and loss mitigation.

The analysis of the four climate scenarios shows a clear trend towards a transformation in the structure of building operating costs. As climate risk increases, the share of funds allocated to damage restoration gradually increases at the expense of investment in development and innovation. Table 1 presents a comparison of conceptual estimates of the cost structure obtained using the two independent AI models.

Table 1: *Comparison of estimates of the economic cost structure between the two AI models.*

RCP	GPT innovation %	GPT damage %	Gemini innovation %	Gemini damage %
2.6	75–80	20–25	80	20
4.5	55–60	40–45	60	40
6.0	35–40	60–65	40	60
8.5	10–20	80–90	15	85

The visualisations generated by the two AI models show a similar overall logic of development across the different climate scenarios, but differ in how they interpret the degree and character of architectural adaptation. In the more favourable scenarios (RCP 2.6 and 4.5), both models depict the building as well maintained and integrated into a high-quality urban environment. The main difference lies in the sustainability strategies: ChatGPT emphasises technological solutions such as energy systems, while Gemini relies more on bioclimatic approaches through vegetation and shading. As climate pressure increases in the RCP 6.0 scenario, the differences become more pronounced. ChatGPT largely preserves the original architectural form with moderate technological improvements, whereas Gemini suggests a stronger architectural transformation with a more engineering-oriented appearance. In the most severe scenario (RCP 8.5), the divergence becomes most visible: ChatGPT presents the building as still functioning under significant climatic stress, while Gemini depicts a more degraded environment and reduced maintenance. These differences indicate that although both models follow a similar systemic logic, they interpret the scale of climate risk and the resulting architectural transformation in different ways.

4. Discussion

The simulation presented shows that the differences between climate scenarios are not limited to the physical parameters of the environment, but lead to a qualitative transformation in the economic function of capital. The main systemic effect that emerges is the gradual shift of resources from investments that create new value to costs for adaptation, restoration and damage mitigation. This transformation has long-term consequences not only for the building stock, but also for the overall economic potential of society.

In more favourable scenarios, buildings can function as platforms for technological innovation, energy transformation and improving quality of life. In more severe scenarios, they gradually become objects of protection, where a significant portion of the invested capital does not generate new productivity, but only maintains minimal functionality. This raises the question of sustainability not only as an environmental but also as an economic category.

Of particular significance is the risk of "locked-in capital" – investments in protective measures and temporary adaptations that do not increase the long-term value of assets. At the macroeconomic level, this can lead to a crowding-out effect, whereby funds are diverted from education, research and quality urban development to compensatory mechanisms. This creates a cycle in which future growth is constrained by the need to cover accumulated losses.

In this context, the role of artificial intelligence is not to predict a specific future, but to support the systematic understanding of the interrelationships between climatic, economic and architectural processes. Through scenario structuring and comparative analysis, AI can identify logical contradictions, hidden dependencies and potentially undesirable consequences of otherwise locally optimal solutions. This makes it a tool for strategic thinking, not just technical optimisation.

This study is conceptual in nature and does not claim to provide a quantitative forecast. The limitations stem from the use of qualitative simulation and the dependence on assumptions about economic dynamics in different scenarios. Nevertheless, the approach outlines a framework in which future studies can integrate quantitative models, financial analyses and real data on building operation.

In this way, the simulation serves a dual function – analytical and educational – by helping to develop a systematic understanding of the long-term consequences of current design decisions.

This approach is particularly important in the education of architecture and construction students, including at the UACEG, where future designers form their professional thinking. Understanding climate scenarios should not remain an abstract topic in the field of climatology, but should be integrated into the design process as part of the architect's long-term responsibility. The realisation that the buildings designed today will operate in a different climatic and economic environment draws attention to sustainability as a strategic choice rather than a regulatory requirement. Including such simulations in the learning process helps students think beyond current regulations and investment frameworks, assess the risk of premature obsolescence of buildings, and seek solutions that reduce future adaptation costs. In this way, education becomes a tool for reducing future systemic risks through more conscious design today.

The development of more complex artificial intelligence models opens up the possibility for such integrated simulations to gradually move from qualitative to hybrid and subsequently to quantitative modelling. With reliable climate forecasts, real operational data from the building stock, insurance statistics and macroeconomic indicators, systems can be built that combine physical simulations of building behaviour, econometric dependencies and multi-criteria optimisation in a unified analytical framework.

Integration with the concept of digital twins of buildings and the urban environment is particularly promising. By linking real sensor data, operational indicators and climate forecasts, the digital twin could function as a dynamic platform for strategic planning, not just operational control. In this context, artificial intelligence can support not only the analysis but also the simulation of long-term investment strategies, including the assessment of trade-offs between initial costs and future adaptation needs.

It is also possible to use agent-based models that simulate the behaviour of different actors – investors, public institutions, insurers, residents – under different climatic and economic conditions. This would allow for a better understanding of systemic dynamics and potential non-linear effects, where locally rational decisions lead to globally unfavourable outcomes.

At the same time, the paradox that the development of artificial intelligence itself is associated with increasing energy consumption and carbon footprint should also be taken into account. Therefore, future integrated modelling systems should be developed with attention to their energy efficiency and real contribution to reducing systemic risk, rather than as an additional source of stress on the climate system.

In this sense, the present study can be seen as a conceptual basis for more complex interdisciplinary models that integrate architecture, climatology, economics and artificial intelligence into a common framework for strategic planning. Expanding such simulations would allow not only for more accurate assessments, but also for earlier identification of critical points at which the system transitions from a development mode to a loss compensation mode.

The time aspect of decision-making is also of additional importance. Architectural and investment choices are made in the short term – within a project cycle or investment framework of 5–10 years, while climate processes and economic transformations unfold over decades. It is precisely this time gap that creates systemic risk: decisions that are economically rational today may prove structurally vulnerable within the life cycle of a building. In this context, artificial intelligence can function as a tool for extending the time horizon of analysis, allowing for a comparison between short-term returns and long-term sustainability. In this way, AI becomes a means of reducing strategic myopia and integrating future risks into current design.

5. Conclusion

This study examines artificial intelligence as a tool for integrated simulation of the links between climate scenarios, economic dynamics and architectural solutions. The analysis shows that different climate trajectories lead not only to changes in the physical environment, but also to a fundamental transformation in the distribution of capital – from investments that create new value to costs for adaptation and compensation for damage in more adverse scenarios. In this way, climate processes become not only an environmental but also a structural economic driver that changes the logic of development in the building sector.

This change directly affects buildings designed today, whose life cycle will cover the period of the most intense climatic and economic transformations. The risk of premature obsolescence and "locked-in capital" calls for longer-term and more systemic thinking in the design process.

The proposed approach demonstrates that artificial intelligence can be used not only for technical optimisation, but also as a tool for strategic thinking about the future of the built environment. By integrating climate and economic scenarios into architectural analysis, it is possible to make more informed decisions today, based on an extended time horizon and an assessment of systemic risk. Such an approach is important both for professional practice and for the training of future designers, as it encourages the development of thinking that links climate, economics and architecture within a single logical framework.

More broadly, artificial intelligence makes it possible to identify earlier the critical points at which the system shifts from development to loss compensation, helping to support more sustainable development trajectories.

6. References

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