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How High will our Buildings Become?

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Abstract

We have clearly reached a point where the know-how and the budget of heightening buildings has been acquired almost everywhere, i.e., nearly all over the world. So one may be reasonably start wondering: How tall will the buildings in our residential neighbourhoods eventually become? Will the (upward) vertical expansion of buildings carry on forever? By exploiting several of the most basic and pristine principles of the neoclassical economic theory and of the mathematical theory of martingales, this paper argues (to wit, proves rigorously) that the acute perception (or, formally, the expectation) that we currently have as an answer to the previous question can hardly ever change in the long-run, by getting re-adjusted towards even higher buildings, no matter how much more pressing will the urbanised circumstances be in the earth's distant future. This then naturally brings us to the following conclusion: the expected average length of buildings is already (or will be quite soon) in a steady-state, so, in the long-run, our output (thus, our welfare and prosperity), which is (optimistically) expected to be (harmonically) strictly positively growing up to its own steady-state, cannot grow our buildings distinctively taller any more. Hence, according to this paper's neoclassical foundation at least, wealth and skyscrapers shall not be necessarily synonymous, and will not be going hand in hand in the future.

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1. Motivation, Idea and Method

In the outset, based onto our ubiquitous empirical observation and evidence (i.e., data and recordings) up to now, say that there is today a precise evaluation or assessment, equivalently an accurate estimation, of how high will the average building be in the near future, i.e., tomorrow, within the average non-rural residential place or part of the world. This computation, in other words, shall not be just a guess or a conjecture, but shall not be a back on the envelope calculation as well.

In the aftermath, based onto our intuition, which is unbiased when it is supported largely by our just yesterday experience, we presume that this anticipation (prediction or forecast) of ours will be being mechanically updated period-by-period, by consistently relying onto realised knowledge or information, towards a vertically longer average building, situated on the average urban district or periphery of the planet. This is because, heretofore, our buildings have been becoming just a bit taller from one period to the other.

Albeit paradoxically, or counterfactually, the neoclassical growth model, when appropriately combined, in this case, with the martingale theory of stochastic processes, foresees that, irrespectively of how far we keep going in the future, all our instantaneously formed expectations on this matter in any future time point will be just about the same with the original expectation that we have formed either presently or in any time point behind us as we stand in the future.

Thence in lay terms: our buildings, according to a martingale-blended version of the neoclassical growth model at least, will never virtually reach or scrape the sky, even if they potentially (i.e., technically and financially) could and are awaited to do so, as the nations of the world mature and advance, and their richness and well-being rise.

Forthwith, the preceding concluding paragraph encloses an intriguingly puzzling prospect for humanity, one that this paper actually goes about addressing. For the time being, of course, what this summarising paragraph contains is just a statement regarding people and their societies. With the advent of Economics, however, social (humanitarian) statements have been reconsidered and upgraded as far as their worth, value or prestige is concerned. Henceforward, for such statements: a statement becomes an argument if and only if a statement can be modelled and verified quantitatively (or mathematically); otherwise, any statement remains an opinion, and then it does not count as an argument.

The attendant text afterwards, therefore, is an attempt to formalise mathematically this surmise and transform it into a valid (i.e., proven) claim.

2. Mathematical Formulation

Start by positioning ourselves in the present, i.e., at $t = 0$, given an indefinite past or history behind us.[1] Suppose then that time runs ahead of us discretely and without an upper bound, so that $t = 0, 1, 2, \ldots$[2]

Let subsequently, at any $t \in \mathbb{N}$, $B(\bullet) \geq 0$ denote the quantified residential building (i.e., constructing or re-constructing) activity of the developers around the world. Across the miscellaneous regions world-widely that are to some degree densely populated (tight villages, towns, cities and metropolitan areas), to be more precise, consider that the developers have at their disposal a more or less persistent in time (namely, a time invariant or atemporal) technology relation(ship), which is represented in the usual neoclassical economic theoretic manner by some production function

$$B : \mathbb{R}_+^2 \to \mathbb{R}_+,\ B(R_t, G_t) \geq 0,$$

where G stands for 'geography' and R is used for 'resources', and which function may be defined by multiple analytically-equivalent formulae, as long as each one of them satisfies some set of (well known) normative mathematical-economic properties, namely, it is 'well (mathematically-economically) behaved'.

The production factor G_t accounts for the urban geographical space or land (not necessarily the ground surface) that is used at the time point $t \in \mathbb{N}$ for construction activity. It cannot be sensibly belied that the urban land available for construction grows imperceptibly in time, if not practically being a constant (i.e., a time stationary) parameter in fixed supply, scilicet, a variable fluctuating with a quasi-flat secular time-trend. Pragmatically, one has no other option than treating the unlimited supply of people (or citizens) versus the limited supply of building land skeptically, if not as a dismal phenomenon, in urbanised habitable and labour environments. This is because as time grows and the population pressure continues, more and more building quantity $B(\bullet) \geq 0$ will have to be crammed into more and more confined geographical space.

The input $R_t \geq 0$ embodies the workers (of any level of skill and specification), the materials (natural or manufactured), the energy (renewable or non-renewable), the

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[1] Practically, nevertheless, the decision maker takes mostly advantage of and acts upon the information concerning her relatively recent experience.

[2] Why? The sustainable life of humans in the planet earth can be potentially continued for several more billions of years, which is the 'infinity' in practical terms. Moreover, people practically perceive the flow of time happening, either backwardly or forwardly, discretely, not continuously.

equipment (mechanical or not), the plants, offices and stations, the methods, techniques, technology and (creative and innovative) ideas, and generally all the possibly conceivable (beyond the geographical space) resources that are (all of them together) mixed and used (or employed) at the time instant $t \in \mathbb{N}$ directly or indirectly for construction purposes [i.e., for the realisation of the (re)construction output or product] by the private firms which operate in that sort of business. This quantified index (in monetary terms, or not) always takes up a large share of any country's Gross Domestic Product, i.e., aggregate income or output. Thus, it unabatedly occupies a considerable portion of the global production, notated as usual with $Y_t \geq 0$, $t \in \mathbb{N}$, as time elapses.

Both G_t and R_t are completely observable and can be gauged at every single $t \in \{0, 1, 2, ...\}$. Of course, for every $t \in \mathbb{N}$, the extant quality of (the quantities) G_t and R_t qualifies the (quantitative) output $B(R_t, G_t)$ as well. Product qualification here means being interested into building quality, not just into building quantity. More qualitative (skilled, specified, experienced, talented, upgraded, and so forth) quantities of G_t and R_t, $t \in \mathbb{N}$, are more productive, that is to say, produce more product under the same terms and conditions of employability, by exhibiting higher (positive) marginal products.

Next, for the sake of neoclassical economics, let the construction technology of the developers, B, be (represented by) a Constant Returns to Scale (or linearly homogenous) Cobb-Douglas (1928) construction function, defined as a consequence by

$$B(R_t, G_t) = AR_t^a G_t^{1-a},\ A > 0 \text{ and } a \in (0, 1), \text{ as } t \in \mathbb{N}.$$

Remark that the construction technology or function of the developers does not (indeed) shift over time, because the functional format of B is constant as time evolves, because A and a are constants in this algebraic expression. Moreover, B displays Decreasing Returns to Scale with respect to each production factor separately, which means that the inputs' (positive) marginal products are diminishing, namely, they are falling or declining within the duration of each separate time point.

We need to keep in mind that there is ample favourable mathematical-economic interpretation with respect to the specification of B as just above. Immediately below, the reader is reminded of solely a small fraction of it, the one that is to some extent useful herein.

First off, A is the total productivity of the two factors together, which is a (quantitative) metric that captures the effective combined-usage of the quantities and the qualities of both factors of production simultaneously. Such a qualitative joint exploitation of the available resources occurs, for example, by exercising optimal business management, i.e., organisation and administration of all inputs, or by having placed the business into an optimal location, or by having secured optimal deals, i.e., by having made beneficial arrangements, with some level of the government. *De facto*, some of the explicit (re)construction product is to be attributed to this shadow factor of production, and A is set out to implicitly measure the level of this residual building output. If A were fully observable and not partially latent, then it could have simply been incorporated into every R_t (and/or to every G_t), as $t \in \mathbb{N}$. Major analytical prominence of B is also to be found in the fact that, given some finite (budget-constrained) construction cost for the developers, G_t and R_t are behaving like substitutes, or competitive inputs, into any alternatively pursued finite (technologically-constrained) construction level $B(R_t, G_t)$, $t = 0, 1, 2, ...$ In particular, B is a Constant Elasticity of Substitution (specifically equal to 1) production function. B is also a Constant Input Elasticity production function: as $t \in \mathbb{N}$, a measures the (percent) response of the instantaneous building output to the (percent) volatility of R_t, while $(1 - a)$ measures the (percent) sensitivity of the instantaneous building product to the (percent) variation of G_t. For $t = 0, 1, 2, ...$, the (relative) importance of R_t and G_t in the (re)construction activity is again measured by a and $(1 - a)$, respectively, but this time sideways, by releasing the market economy backdrop: as $t \in \mathbb{N}$, a is the share of R_t to the instantaneous building product, that is, a shows how much of the overall expenditure that is realised for $B(R_t, G_t)$ corresponds to expenses that are specifically taken for R_t; and analogously for G_t and $(1 - a)$. Within the global markets thereafter, since construction has seemingly become a highly competitive occupation, the homogeneity of degree 1 of B is typically used as a formal excuse for the zero profit condition that is uniformly applied to all the private firms in the business of (re)construction along $\mathbb{N}$, when they instantaneously act as common entrepreneurs, as they are trying streamline their economic activity under the neoclassical stereotype, out of which generic pursuit the unit or marginal rewards of the two types of resources (the family of the ones referring to land, against the group classifying the extra-geography ones) are equalised with their marginal products. This of course is realisable because B fulfils the familiar conditions of Inada (1963), which a stricter set of properties when compared to the much weaker ones that are originally, ordinarily and desirably sufficient. Ultimately, with the aforementioned profit-maximisation procedure, given the market prices of the production factors, the developers choose the optimal (qualitative) quantities of the two classes of inputs, instant-by-instant.

To make the notation more manageable at this point, set $D_t = B(R_t, G_t)$, for every $(R_t, G_t) \in \mathbb{R}_+^2$, for every $t \in \mathbb{N}$. Provided then that $G_t > 0$ for every $t \in \mathbb{N}$, straightforward algebra reduces B to a construction function or technology that is expressed in terms of geography, or 'per units of land'. Thereupon, we come up with the notion of the 'construction output (or product) per land', which is defined as follows:

$$\frac{D_t}{G_t} = A(\frac{R_t}{G_t})^a,\ A > 0,\ a \in (0,1),\ d_t := \frac{D_t}{G_t} \text{ and } \rho_t := \frac{R_t}{G_t},\ \text{as } t \in \mathbb{N}.$$

This is a fruitful and sensible action to take for many conceptual and, in the end, analytical reasons. *Inter alia*, one obvious rationale behind this analytical manoeuvre is that, since land has been assumed to be nearly fixed across the time-line, it therefore has limited significance inter-temporally, so it makes perfect sense to divide everything by it at every time instant, in order to underemphasise or even[3] disguise its trivial role and presence in the production process. In this way, evidently, the employment of the ratio $\rho_t(>1)$ is instead highlighted, which is the intensity of the bulky R_t (over the negligible G_t) in the construction activity, as $t \in \mathbb{N}$. At any $t \in \mathbb{N}$, consequently, there may be substitutability between the two inputs, but the building activity is permanently R_t intensive. In conjunction with (and by stepping upon to) the aforementioned explanations, there is now one more justification that needs to be predominantly stressed for the purposes of this paper. This has to do with the fact that, for every single $t \in \mathbb{N}$, the ratio ρ_t demonstrates and, effectively, quantifies the average height of the average building in the average urban area of the world. Why is this ratio an indicator (if not an actual measure, as time proceeds beyond the short and medium term) of the buildings' altitude along $\mathbb{N}$? Because, as $t \in \mathbb{N}$, if the (spending for) land G_t in the denominator of ρ_t does not essentially grow, whilst the spending for R_t in the numerator of ρ_t keeps growing, then[4], spending more and more for R_t ($\Rightarrow \rho_t$), thus, for construction activity D_t ($\Rightarrow d_t$), when the supply of (hence, the spending to) the available building land is minute and practically frozen, means that buildings are growing taller and taller upon to roughly the same always existing land. The more the construction activity keeps going on, the less the buildings are able to spread out horizontally as all the scarce land gets eventually occupied, so, exclusively, the more the buildings are allowed to (indefinitely) expand perpendicularly.

By following the lead of Brakman et al. (2019, Chapter 4, section 4.9)[5], one may insert the construction industry (thus, the construction market and the real estate market) into a dynamic stochastic general equilibrium set up and convey the usual results of this literature, but by having added a novel urban (spatial or geographical)

[3]Both to facilitate the presentation and because this turns out to be preferred (if not required).

[4]And even when allowing for some substantial error concerning the fact that some of the associated economic activity is oriented to the re-construction (or refurbishment) of the existing buildings, or perhaps to the downwards vertical extension of either new or old buildings.

[5]This simple but inspiring, static and deterministic, urban-spatial analysis bears some notional resemblance and has some economic proximity with the general context of the setting of this paper.

dimension into them. This, however, is not the objective or the concern of this paper. This entry does not serve neoclassicism *per se*, but follows another approach and is targeted to different upshots.

In particular, assuming that the whole world is acting as a unit and that people around the globe are enriched with acumen, let $(\Omega, \mathcal{F}, P)$ be a probability space. The (uncountably infinite) set Ω contains all the possible (and not necessarily equiprobable) primitive outcomes, scenarios or prospects, or simply all the alternative states of nature of the world, concerning the instantaneous realisation of some random variable of interest. This random variable represents some economic phenomenon under consideration by the whole population of the earth, is continuous and instantaneously defined, and evolves and gets realised in time as a discrete stochastic process, where a discrete stochastic process is, as usual, a random time-sequence of random variables. The σ-algebra $\mathcal{F}$ contains all the events (subsets of primitive outcomes) of Ω and $P : \mathcal{F} \to [0, 1]$ is a unanimous probability measure that people safely rely up-onto and use in order to evaluate the likelihood of the events in $\mathcal{F}$. Let then the continuous random variable (measurable function) $\rho_t : \Omega \to (1, +\infty)$, $t \in \mathbb{N}$[6], defined onto the previous probability (measure) space $(\Omega, \mathcal{F}, P)$. The *observation* of interest here is *the average height of the average building in the average urban area of the world*. Suppose that the stochastic process $\{\rho_t\}_{t\in\mathbb{N}}$ follows an observable law of motion for its time path and, namely, it is a discrete-time martingale with respect to the probability measure P. This simply means that:

$$\forall t \in \mathbb{N},\ E(\rho_t) < \infty \text{ (integrability) and } E(\rho_{t+1}|\rho_1, \rho_2, ..., \rho_t) = \rho_t \text{ (unbiasedness)},$$

which can be translated as: the conditional expected value of our next *observation* (which is always finite and exists), given the values of all the prior *observations*, is equal to the value of the most recent *observation*. Extend now the (time-independent) probability space $(\Omega, \mathcal{F}, P)$ into the (time-adjusted) filtered probability space $(\Omega, \mathcal{F}, \{\mathcal{F}_t\}_{t\in\mathbb{N}}, P)$, where the time-sequence $\{\mathcal{F}_t\}_{t\in N}$ is an informational filtration of $\mathcal{F}$, that is to say, each $\mathcal{F}_t$ is a sub sigma field of $\mathcal{F}$ and $\mathcal{F}_t \subseteq \mathcal{F}_s$, for every $t \leq s$, $t, s \in \mathbb{N}$. It is natural to assume then that the martingale $\{\rho_t\}_{t\in\mathbb{N}}$ defined on the filtered probability space $(\Omega, \mathcal{F}, \{\mathcal{F}_t\}_{t\in\mathbb{N}}, P)$ is adapted to the filtration $\{\mathcal{F}_t\}_{t\in N}$. Thereupon, we just have to extend the previous definition, which characterises or denominates $\{\rho_t\}_{t\in\mathbb{N}}$ a martingale, which martingale shall be now defined with respect to the filtration $\{\mathcal{F}_t\}_{t\in N}$as well, so as to include one more condition[7]:

[6]With $\rho_t \to \infty$ as $G_t \to 0$, as $t \to \infty$.

[7]The unbiasedness condition can be equivalently restated as $E(\rho_{t+1}|\mathcal{F}_t) = \rho_t$.

$$\forall t \in \mathbb{N},\ \sigma(\rho_t) \subseteq \mathcal{F}_t \text{ (adaptability)}.$$

It is then a widely known result in the theory of martingales (see for example in Bose et al., 2024) that

$$E(\rho_t) = E(\rho_1), \text{ as } t \in \mathbb{N}, \text{ or as } t \to \infty.$$

People, in the neoclassical world that they dwell into by default, are assumed to make no expectation errors because they efficaciously exploit all the (complete and public) information that is available to them. Given their perfect foresight, therefore, the expected value of any random variable world-widely is the actually realisable value of this variable, at every single time instant of the time horizon. This last acknowledgement provides a neoclassical economic translation to the expression supra, when it finally becomes:

$$\rho_t = \rho_1 (= \rho_0), \text{ as } t \in \mathbb{N}, \text{ or as } t \to \infty.$$

As it stands so far, the argumentative path has an exuberant neoclassical feel to it. Yet, the truth is that neoclassical economics are (in the broader literature of Economics) seriously countered, especially when the dimensions of time (or dynamism) and space (or geography) transverse them and, thereby, their weaknesses get exposed and underscored. The neoclassical growth model[8] cannot escape from this spirit or reality, and is definitely, as a result, far from being compelling. Notwithstanding, it is a judicious model without doubt, while it certainly cannot be dismissed out of hand. For what it is worth, it is for sure less enigmatic than what other (extra neoclassical) growth models are, given that it is built upon solid mathematical foundation, which makes up for any of its notional inconsistencies and/or camouflaged analytical impediments. So, given that it is an adequately robust model at the end of the day, let us assume that the neoclassical growth model is veracious.

That being the case, all this over-optimistic model is about is to guarantee that globally:

1. if, along time and given some potential aggregate income, the economic units both (i) consume so as to receive contemporaneous pleasure and (ii) save-invest so as to accumulate capital and create stocked wealth,

and

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[8]Which made its debut without utilitarian welfare via the Solow(1956)-Swan(1956) model, while with the neoclassical tradition of utilitarian welfare was eventually established as the Ramsey (1928) - Cass (1965) - Koopman (1965) model.

2. if both the population (thus, the labour force) and the (depreciated) capital-accumulated of the world are mobile in time with pre-specified rules,
then the growth of the world's production can be sustained or preserved (i.e., will be resilient and uninterrupted) in time, until it eventually stalls out in a desirable steady state, i.e., converges to a limit, in the long-run.

Evidently, as $t \in \mathbb{N}$, when Y_t strictly positively increases, the same is in theory allowed to be happening for R_t ($\Rightarrow \rho_t$)[9], hence, for D_t ($\Rightarrow d_t$), as well. And apparently, within this growth process, all the inter-dependent economic parameters that are involved in this model reach naturally and at some point their own steady states. In fact, since the neoclassical growth model is here stochastic, all the (convergent) discrete time-sequences of the model are essentially stochastic processes. This model, though, abstains in principle from attaching specific properties to these stochastic time series, and allows for the majority of them to be arbitrarily evolving in time.

As the world's output is produced with quantities of labour and with quantities of capital-accumulated, of some quality, two noteworthy elements of this harmonic model are the following. The first is that technical (for instance technological) improvements play a crucial role to the realisation of this balance-signalling long-run growth path of any (stochastic) time-sequence in this model. The second is that, since we do not want to witness a dramatic reduction in the earth's life expectancy, ecology, energy, natural resources, and the environment in general, become critical ingredients in this model, transforming the world's strictly positively growing production from sustained to sustainable.

The ultimate point to be made here is that if it is actually believed that the people of the neoclassical world behave according to the neoclassical growth model, then, given again their perfect foresight, it should be true that

$$E(Y_t) = Y_t < E(Y_{t+1}) = Y_{t+1} < \ldots.. \leq E(\lim_t Y_t = \bar{Y}) = \bar{Y}, \text{ as } t \in \mathbb{N}, \text{ or as } t \to \infty,$$

or else the earth's inhabitants would not have an incentive to act and decide according to this model, and the neoclassical growth model would not be correct.

3. Conclusive Result

To summarise, let us re-state concisely the ensuing result of this paper.

As $t \to \infty$: forever sustained in time strictly positive (expected) growth of Y_t (where 'forever' means up to its long-run steady state) is not compatible with forever sustained strictly positive (expected) growth of ρ_t.

[9] Which is a part of Y_t.

In common parlance: strictly growing our wealth and turning it into prosperity does not necessarily mean strictly growing our buildings and turning them into giants.

Put it differently: in economies, tall buildings are (or shall) not always (be) an indication of success and progress.

According to this paper's storyline: the average building's altitude stops growing in time iff the expenditure to non-geographical recourses for construction activity stops growing in time. The following question then arses: what happens when the *construction industry bubble* deflates and no more (upward-vertically heightened) buildings are constructed?

There are two (not necessarily mutually exclusive) realistic possibilities.

Option 1: People re-locate to rural ares, and reside and work in more makeshift accommodation and plants, respectively, which provide less amenities.

Option 2: People continue to get squeezed and stacked into urban areas, and into sophisticated condos, apartments and working stations, but with the living or activity space inside buildings for the average person becoming tiny, because the same residential or working space will have to shared by more and more individuals.

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For more information:

https://www.dept.aueb.gr/en/econ/

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