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Transactions market in Bitcoin. Empirical analysis of the demand and supply block space curves

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Abstract:	Blockchain transactions market is expected to gain momentum in the coming years, in a context with gradual transition to fee-regime in many cryptocurrencies, the expansion of blockchain technology to different business areas and the requirement for high transaction throughput in new blockchain-based applications. In this context, the economic assessment of the supply and demand curves defining the transactions market is key to recognize its potential weaknesses, but also to minimize risks and to improve operational efficiency when designing or upgrading blockchain-based applications. The research covers a gap by conducting an empirical analysis of these curves in Bitcoin, based on an extensive dataset spanning two time periods in 2021 and 2023 selected as having different levels of Mempool congestion. The empirical findings support the understanding of why Bitcoin transaction fees are subject to high volatility and how the protocol evolutions made to date have shifted the supply curve. The demand curve, although relatively elastic around the equilibrium price, turns out to be extremely dynamic. On the other hand, the inelasticity of the supply curve, described by an exponential distribution, explains the sharp variations in transaction fees observed under demand shocks. The results bring to light the importance of the transactions market layout as an element of control over the intrinsic problems associated with an imperfect competition, whereas additional sustainability and security aspects beyond pure economic considerations are to be taken into account in the design of this market.

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Abstract

Blockchain transactions market is expected to gain momentum in the coming years, in a context with gradual transition to fee-regime in many cryptocurrencies, the expansion of blockchain technology to different business areas and the requirement for high transaction throughput in new blockchain-based applications. In this context, the economic assessment of the supply and demand curves defining the transactions market is key to recognize its potential weaknesses, but also to minimize risks and to improve operational efficiency when designing or upgrading blockchain-based applications. The research covers a gap by conducting an empirical analysis of these curves in Bitcoin, based on an extensive dataset spanning two time periods in 2021 and 2023 selected as having different levels of Mempool congestion.

The empirical findings support the understanding of why Bitcoin transaction fees are subject to high volatility and how the protocol evolutions made to date have shifted the supply curve. The demand curve, although relatively elastic around the equilibrium price, turns out to be extremely dynamic. On the other hand, the inelasticity of the supply curve, described by an exponential distribution, explains the sharp variations in transaction fees observed under demand shocks. The results bring to light the importance of the transactions market layout as an element of control over the intrinsic problems associated with an imperfect competition, whereas additional sustainability and security aspects beyond pure economic considerations are to be taken into account in the design of this market.

Keywords

Blockchain, transaction fees, Bitcoin, supply, demand, transactions market

1 Introduction

Bitcoin, the pioneer blockchain application launched beginning 2009 (Nakamoto, 2008)[1] and still the most traded cryptocurrency ways bigger other appeared in its wake[2], implements an inflationary policy, which has been followed by many other cryptocurrencies[3]. A fundamental aspect of this policy is that maximum supply of bitcoins is capped at 21 million, as shown in Figure 1-a) below, which illustrates this predetermined supply limit vs. the current number of circulated bitcoins, and the geometrically decreasing over time coinbase reward per block.

As a result of this policy, transaction fees are expected to play an increasingly important role in the sustainability and stability of Bitcoin in the long run (Carlsten et al., 2016; Easley et al., 2019; Möser & Böhme, 2015)., taking into account that transaction fees will gradually increase their weight in miner's incomes to the detriment of new minted coins (Lavi et al., 2022). In this way, although Bitcoin transaction fees have remained rather marginal so far (Wang, C. et al., 2023), still representing a small percentage of the miners' incomes[4], they have already experienced a remarkable growth, depicted in Figure 1-b).

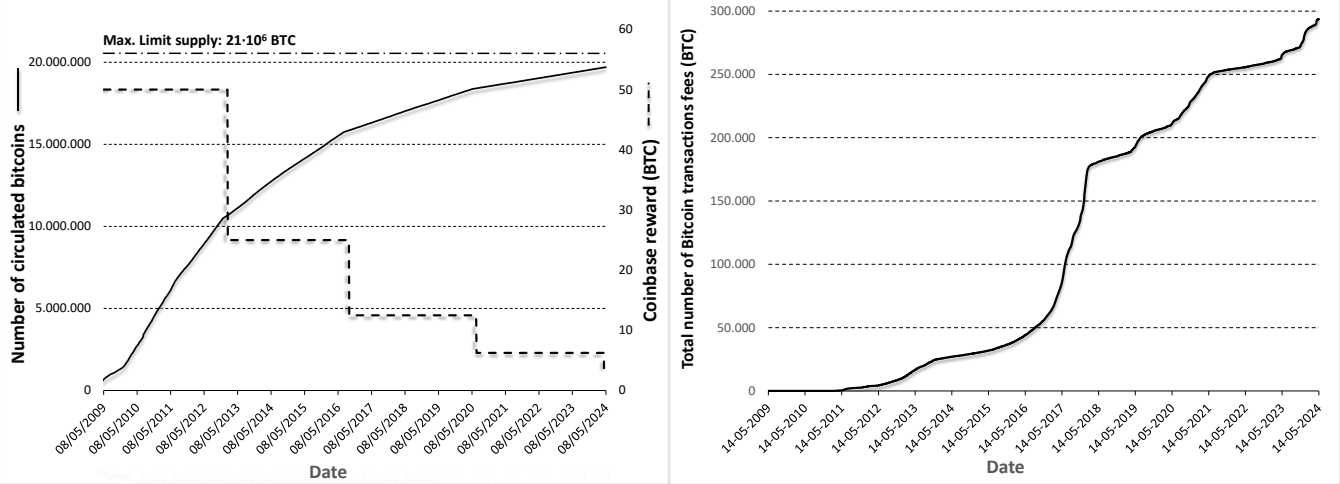

Fig.1 a) (Left) Current number of circulated bitcoins vs. coinbase reward. **b)** (Right) Cumulative transaction fees in Bitcoin

Source: prepared by the authors. Data retrieved from https://www.blockchain.com/charts and https://ycharts.com/indicators/bitcoin_total_transaction_fees_per_day_btc on 14/05/2024. Halving dates: 28/11/2012 (25 BTC), 9/07/2016 (12,5 BTC), 11/05/2020 (6,25 BTC), 19/04/2024 (3,125 BTC).

[1] White paper issued in October 2008, describing the Bitcoin blockchain protocol. The "*Genesis block*" was launched January 3rd, 2009, and the first Open Source client released one week later.

[2] More than three times bigger than the second one, Ethereum, and ten times compared to the third one, Ether. ($1{,}13 \cdot 10^{12}$ $ vs. $352 \cdot 10^{9}$ $ and $111 \cdot 10^{9}$ $ respectively. Source: https://coinmarketcap.com/ accessed 01/05/2024)

[3] 9 out of the top 20 cryptocurrencies in terms of market capitalization (according to https://coinmarketcap.com/all/views/all/, accessed 26/05/2024), establish a maximum supply of minted coins: Bitcoin, XRP, Cardano, Avalanche, Chainlink, BitcoinCash, Polygon, Uniswap, Litecoin.

[4] https://bitinfocharts.com/comparison/bitcoin-fee_to_reward.html#alltime

Transaction fees are distributed according to the specific rules defined by each application. Particularly, in Bitcoin, these fees are subject to supply and demand dynamics, resulting from the block space market generated by the mining activity. On the one hand, the supply of space for transactions is determined by the limited space available in the new blocks regularly generated by the miners, naturally prioritizing transactions according to the proposed fees in order to maximize their revenues. On the other hand, the demand is shaped by the size of the transactions posted by the users (Rizun, 2015), offering fees in a competition for inclusion in the new blocks while optimizing the balance between the proposed fees and the management delay. In this way, users set the amount of fee they are willing to pay to get their transactions included in the blockchain, and miners collect these fees each time a new block is generated.

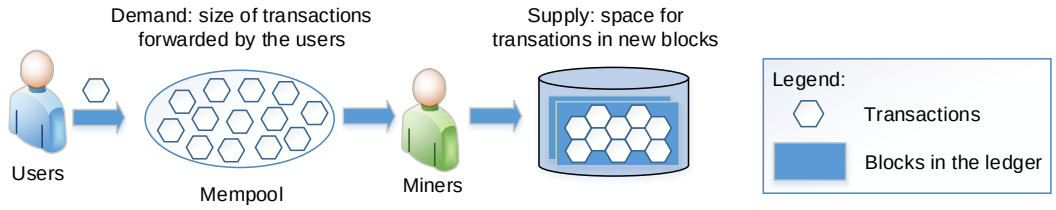

Fig.2. Demand and supply of space for transactions

It should be noted the relevant role played by transaction fees in the sustainability and security of blockchain applications, with various threats and consequences depending on the underlying blockchain typologies (Rico-Peña et al., 2023). They have the ability to straightforward reward the agents[5] for the management of the proposed transactions, encouraging their participation. The number of agents across distributed networks, where the security does not rely on a central authority but on the agreement through the participation of members, is decisive form the sustainability of the system, as a critical mass of them is required to keep the probabilistic consistency of the global system state (Möser & Böhme, 2015). The communal hash power provided by the agents secures the system, making it less vulnerable to attacks (Pass et al., 2017) and discouraging deviations from the expected behaviour (Kiayias et al., 2016). Typically, a high number of agents decreases the likelihood of 51% attacks (Kaşkaloğlu, 2018; Sayeed & Marco-Gisbert, 2019)[6], thus minimizing the risks of one (or a group of them) taking control over the system. These agents naturally join or quit the mining activities in competition with others according to their assessment between costs and incomes.

[5] Economic term for participants or users verifying and validating transactions. Named *miners* in the terminology of cryptocurrencies.

[6] This kind of attacks are also sensitive to other factors, particularly the hash power controlled by the mining pools.

Although numerous studies focus on diverse aspects of the transaction fees, the related market dynamics has been to a large extend overlooked so far, due to a great extent to the still modest weight of the transaction fees as reward mechanism for miners. To the best of the author's knowledge, no previous research to date conducts an economic analysis based on the empirically derived transactions supply and demand curves in Bitcoin, the pioneering blockchain application. This paper covers this gap, extracting data from a Bitcoin node during several months in two separate time periods selected as having different levels of Mempool congestion (October-November 2021, May-June 2023), so that enabling the research questions raised to be answered. Our work has twofold implications for blockchain policy makers and managers. First, in support of the assessment of the impacts on the transactions market as a result of the protocol upgrades in Bitcoin-like applications. Second, in the design of new blockchain-based applications targeting high transaction throughputs.

The remainder of this paper has been organised as follows: section §2 presents de literature review and research motivation. Section §3 introduces the research questions and methodology. Section §4 describes the data sources and process followed to calculate the block space demand and supply. Section §5 details the derived transactions' demand and supply curves in the Bitcoin block space market, and include insight into the characteristics of these curves. Section §6 discusses the results achieved and contributions, describe the limitations of our work and suggest some future research directions. Finally, section §7 summarizes the main conclusions.

2 Literature review and research motivation

2.1 Transaction fees in the scientific literature

Blockchain transaction fees have been analysed from several points of view since the inception of this technology. In terms of contribution to the security and stability of the blockchain applications, both their role to potentially protect the network against spam attacks (Kiayias et al., 2016; Nayak et al., 2016; Pass et al., 2017) or to guarantee their sustainability in the long run (Brown et al., 2019; Carlsten et al., 2016; Easley et al., 2019; Kaşkaloğlu, 2018; Kraner et al., 2022; Lavi et al., 2022; Möser & Böhme, 2015) have been considered. In this respect, recent research propose novel fee reward approaches aiming to improve the sustainability of Bitcoin or PoW (Proof Of Work)-based blockchain in general, under the forthcoming transaction-fee regime (Lin et al., 2018; Sahitya & Borisaniya, 2022; Zhao & Si, 2021; Zhao et al., 2023).

In the same direction, alternative fee setting mechanism have been put forward, looking for a more equitable distribution of fees by allowing to reward specific aspects not currently considered, as the transactions broadcast (Babaioff et al., 2011; Ersoy et al., 2018), the storage cost of transactions (Liu et al., 2020; Liu et al., 2022) or the miners' seignorage (Chiu &

Koeppl, 2022); or seeking for a more efficient allocation of fees to miners by replacing the standard first-price auction process implemented by Bitcoin (Basu et al., 2019; Lavi et al., 2022; Li, J., Yuan, & Wang, 2019b; Roughgarden, 2021; Wu et al., 2024; Yan et al., 2020; Yao, 2020).

Their role to support the prioritization of transactions and determine their latency has also been extensively analysed (Azzolini et al., 2019; Guo et al., 2021; Kasahara & Kawahara, 2019; Kawase & Kasahara, 2020; Li, J., Yuan, & Wang, 2019a; Li, J. et al., 2020; Malakhov et al., 2023; Qi et al., 2020; Ricci et al., 2019; Shang et al., 2023; Tedeschi et al., 2019; Tedeschi et al., 2022). Linked to this prioritization, several research focussed on the strategy followed by miners and mining pools to select transactions based on the offered fees (dos Santos et al., 2019; Hiraide & Kasahara, 2023; Jiang et al., 2021; Li, Z. et al., 2023; Meybodi et al., 2022; Wang, C. et al., 2023; Wei et al., 2023).

Approaching an economic perspective, the transaction-rate bottleneck leading to congestion situations where transactions struggle for block space have been thoroughly analysed (Baqer et al., 2016; Chiu & Koeppl, 2019; Huberman et al., 2021; Jain et al., 2023; Kim, S. T., 2020; Kruminis & Navaie, 2022; Monem et al., 2024; Saad et al., 2018; Sokolov, 2021; Tsang & Yang, 2021). From a similar perspective, other authors have studied how users to set the fees submitted in their transactions (Chung & Shi, 2023; Dimitri, 2019; Ferreira et al., 2021; Kim, D. et al., 2023; Li, J. et al., 2020; Yan et al., 2022).

Specifically focussing on the transactions market and the associated supply and demand curves, some previous research have served as a starting point for our study. This is the case of the original analysis linking transaction fees, block size and system security (Houy, 2014), the introduction of the block space supply curve and the mempool demand curve (Rizun, 2015), the models for calculating the marginal cost of production in Bitcoin (Hayes, 2017), further back-tests of the production cost (Gottschalk, 2022; Hayes, 2019; Kim, T., 2017) and empirical econometric approaches to this market (Huang et al., 2017; Ilk et al., 2021; Jalan et al., 2022; Tsang & Yang, 2021).

Finally, it is worth mentioning that the transaction fees in other blockchain-based applications, such as Ethereum, DAG (Directed Acyclic Graph) or Lightning Network have also been the subject of research (Donmez & Karaivanov, 2022; Erdin et al., 2020; Gangwal et al., 2023; Mercan et al., 2021; Wang, T. et al., 2022; Yin et al., 2018).

2.2 Research motivation

The economic significance of the transaction fees is expected to gain momentum in the upcoming future due to several factors, in addition to the inflationary policy followed by many cryptocurrencies, as introduced above, the following two are worth mentioning:

1) The expansion of blockchain technology to different areas beyond cryptocurrencies like accounting (Dai & Vasarhelyi, 2017; Schmitz & Leoni, 2019), finance (Eyal, 2017; Treleaven et al., 2017), healthcare (Hölbl et al., 2018; Kuo et al., 2017), insurance (Kar & Navin, 2020) or logistics and supply chain (Chod et al., 2020; Gonczol et al., 2020; Pournader et al., 2020; Saberi et al., 2019). This growth has been accompanied by the deployment of a variety of blockchain typologies (Wang, W. et al., 2019; Zheng, Z. et al., 2018), deriving from the pioneer design carried out by Bitcoin.

   Whatever the blockchain application, the participating agents need to be compensated in exchange for providing resources and services. The transaction fees have the ability to reward these agents, which is particularly pertinent for non-cryptocurrency solutions, where it is not possible to offer minted cryptocurrency as an incentive.

2) The need to handle high transaction throughputs, required by more and more blockchain-based applications, as is the case with those related to IoT (Internet of Things). Actually, scalability issues have been identified for different blockchain typologies (Sanka & Cheung, 2021). Thus several alternatives have been proposed and implemented allowing to manage a high number of transactions per second, basically, based on different consensus protocols and non-linear blockchain structures as DAGs architectures (Cao et al., 2019; Ling et al., 2020).

   Certainly, transaction fees become particularly relevant under high throughput regimes. Blockchain applications in this domain need to minimize the transaction fees charged to users, in order to make the service economically affordable and efficient, while guaranteeing adequate remuneration to the agents to foster their participation.

These factors show up the relevance of the transaction fees, and by extension the market determining how they are regulated, as part of the income received by the agents in exchange for the resources allocated (typically processors, memory and network bandwidth consumption) and the electrical power consumption for the management of the submitted transactions. Basically, these agents decide to get involved depending on the incurred variable and fixed costs and the expected incomes (Prat & Walter, 2021).

It is worth noting that these costs may differ significantly depending on the blockchain typology. In particular, the PoW (Proof-Of-Work) consensus protocol used by Bitcoin and most of permissionless blockchain applications (although rare in permissioned ones) requires very powerful and expensive hardware processors[7], enabling realistic chances to occasionally solve the corresponding crypto-puzzle in competition between miners. This hardware consumes a big amount of energy

[7] Currently, the use of expensive ad-hoc ASICs, which assess tens of trillions of hashes per second, is the only way to effectively be able to compete with other miners of major PoW based cryptocurrencies.

(Badea & Mungiu-Pupazan, 2021; Dong et al., 2023; Truby, 2018), which exceeds that of many entire countries (de Vries, 2018). On the other hand, PoW protocols show lower capability in terms of average time to generate new blocks than other consensus algorithms (Cao et al., 2020), therefore presenting higher susceptibility to suffer from bottleneck issues.

In this context, the research aims to provide comprehensive understanding on the way Bitcoin transactions' demand and supply are formed, thus regulating transaction fees, and whether Bitcoin underlying permissionless typology involves restrictions, therefore shaping the corresponding market structure.

3 Methodology and research questions

3.1 Methodology

The process carried out throughout the research sticks to the empirical research methodology, as a basis to yield objective and consisting findings, while allowing to reproduce the scientific study. Accordingly, the following systematic approach has been considered:

1.- Formulate the research questions and boundaries of the research.
2.- Analyse the supporting theories and relevant literature.
3.- Determine data sources and data acquisition process.
4.- Perform systematic data collection and analysis.
5.- Report the results.

The first point is covered in the next subsection, whereas the thorough literature review performed has been summarized in the previous subsection §2.1. Points 3, 4 and 5 are dealt with in the following three sections of the paper. Pursuing transparent practices and making possible the reproducibility of the research, both the source code developed for the purpose of extracting the data of interest, as well as the datasets are made available at an online open access repository (*Figshare*, details in section §4).

3.2 Research questions

Our work follows a modular innovation approach (Voss, 2003), by examining one of the focal constructs of Bitcoin, the transaction fees, through a singular lens. This approach allows to formulate interesting research questions (RQ), as a first step to conducting research with relevant contribution. In this context, the following ones are worth answering, in line with the motivation and the objectives of the research:

RQ1: How are the transactions' demand and supply curves shaped in Bitcoin?

RQ2: What form do these curves take?

RQ3: How these curves determine the transaction fees paid by users?

RQ4: What is the effect of the Bitcoin protocol evolution on these curves, and the resulting transaction fees?

RQ5: How have these curves evolved over time, under different transaction loads?

The formulation of these questions aims to ensure producing valuable, useful and achievable results, by following the FINER criteria (Covvey et al., 2024). To this end, the availability of the resources (F, feasibility), as well as the appeal (I, Interest), novelty (N), ethical implications (E) and possible impact (R, Relevance) of the research have been assessed.

4 Data sources and data acquisition process

4.1 Data sources and rationale for selection of periods under analysis

The primary data to calculate the block space demand and supply are extracted from a local Bitcoin node (v0.21.1) through a software code specifically developed for this purpose[8]. The arrival of new transactions awaiting confirmation and the generation of new blocks are replicated in the *Mempool* and *Chainstate* databases of Bitcoin nodes, which are synchronized over the peer network through the information propagation performed by the controlled flooding protocol implemented by Bitcoin. Next figure depicts the content of these databases:

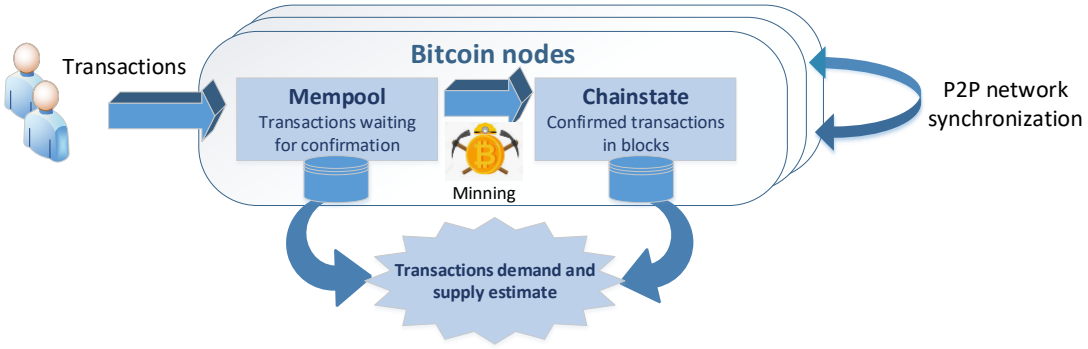

Fig.3 Bitcoin node databases, source to extract transactions block space demand and supply data

These data have been randomly extracted several times a day over two separate time periods, between October and November 2021 the first one and between May and June 2023 the second. The selection of these separate periods makes it

[8] Golang code uploaded in Github. The source code and reference dataset are available in *figshare* data repository through the following links: https://doi.org/10.6084/m9.figshare.24190251.v1 (source code), https://doi.org/10.6084/m9.figshare.24190272 (supply data), https://doi.org/10.6084/m9.figshare.24183288 (demand data).

possible a comparative analysis of the evolution with a broad time perspective and, primarily, under different Mempool load situations. Figure 4 below shows the total number of transactions recorded on Bitcoin and the Mempool size covering these two time periods, illustrating that the size of the Mempool varies irrespective of the growth experienced in the total number of transactions managed.

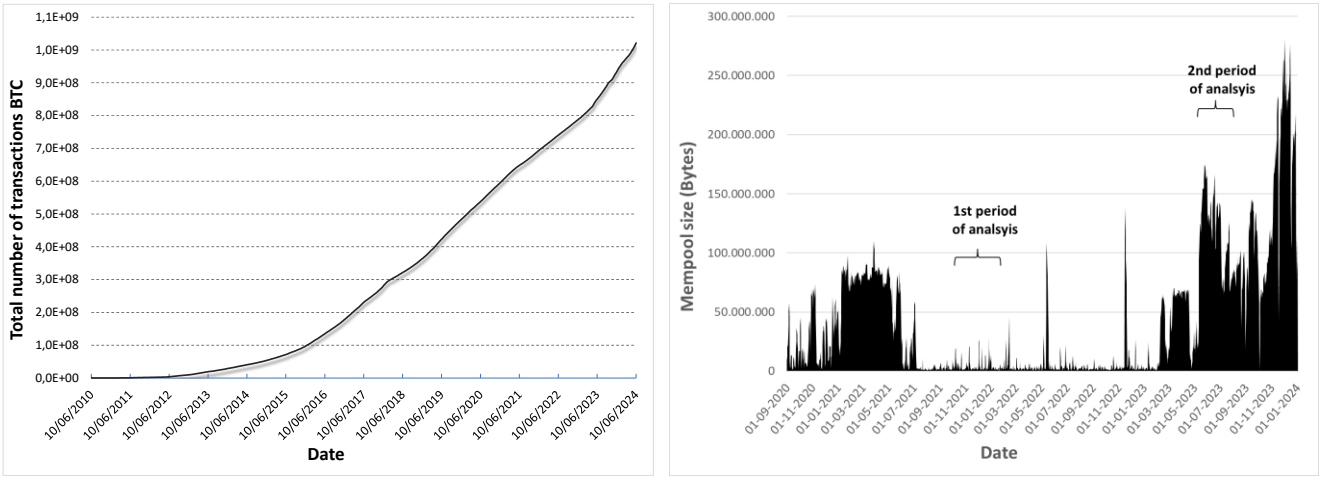

Fig.4 a) (Left) Total number of transactions recorded on Bitcoin. **b)** (Right) Mempool size, covering the periods under analysis

Source: prepared by the authors. Data retrieved from https://www.blockchain.com/charts 11/06/2024

The analysis performed relies on a huge dataset, more than four million transactions and one thousand blocks has been read during these two periods. The following tables summarize, respectively, the most relevant data extracted from the mempool transactions and blocks analysed in the two periods of time under consideration.

Table 1 Summary of mempool transactions analysed[9]

	Number of transactions analysed	**Average transaction fee (satoshis)**	**Average transaction size (Bytes)**	**Average transaction weight (WU)**	**Average fee density (satoshi/vByte)**
2021 period	1.498.491	4.160,3	887,8	2.434,7	11,0
2023 period	2.546.502	8.865,4	1.598,1	3.373,3	12,8

[9] Not calculated as an average of averages (transactions grouped together at mempool readings) but considering all transactions in a single set. This avoids multiple posting of transactions that remain in the mempool for a long time (those with lower fees).

Table 2 Summary of blocks analysed

	Number of blocks analysed	Average fees collected (satoshis)	Average size (Bytes)	Average weight (WU)
2021 period	383	10.748.169	1.229.245	3.264.076
2023 period	600	24.047.216	1.695.857	3.993.797

4.2 Process to calculate the block space demand

Fig.5 below summarizes the process. The Mempool content is recurrently read, so that allowing to have updated sets of transactions representative of the Mempool content. When a new block is generated, the size, fees and weight[10] of all the transactions in the last set are stored into a CSV (Comma-Separated Values) file. The calculation of fees requires to access the total amount of the inputs for each transaction in the chainstate [11].

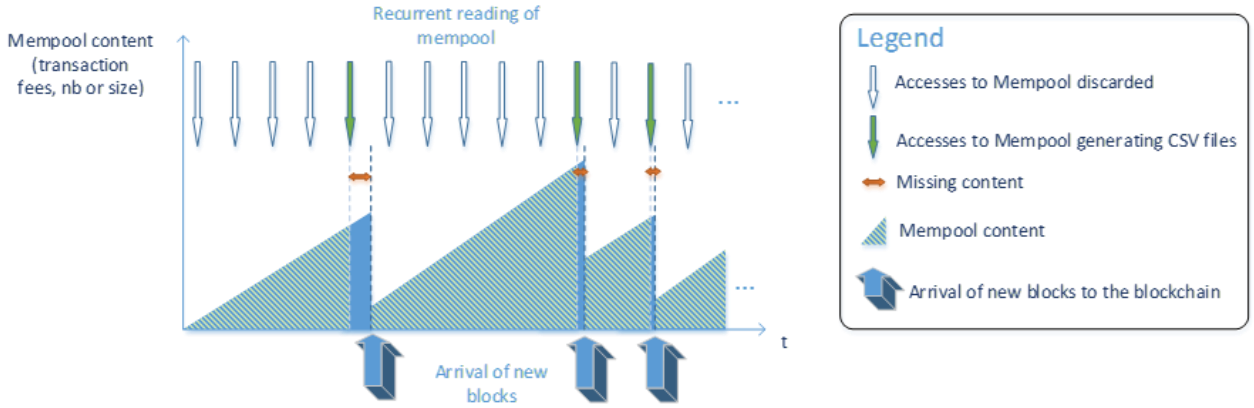

Fig.5 Process to extract the block space demand

It is to be noted that the transactions arriving between the last access to the Mempool and the generation of new blocks are lost in our demand estimate. Although this gap may involve a slight shift down of the curves, it does not harm the results, taking into account that:

- The transaction submission rate and related fees are independent of the Mempool status.

[10] Information recovered: Transaction identifier (hash), fees (satoshis), size (bytes) and weight for each transaction in the Mempool.

[11] The transaction fees are not explicitly declared in Bitcoin transactions. The fee proposed by a transaction is the difference between the total amount of inputs (unspent transaction outputs or UTXO) and outputs, so that it necessary to access the transactions in previous blocks from the *chainstate* database to calculate the fees of the unconfirmed transactions in the *Mempool*.

- There is a time gap between the generation of a new block in a given node and the arrival to the rest of the nodes, as they need some time to be processed and broadcasted through the P2P network. Meaning that there is also an offset between the Mempool content considered by the miners for the generation of a block and its status when the block is known by the nodes.

On other hand, it is possible that two or more valid blocks are generated within the sample period. The probability of this event is very low[12], and again the results are still valid in the event that this happens, considering that the information is retrieved from the Mempool content and not from the new generated blocks.

The resulting CSV files are manually verified, in order to discard invalid transactions arrived to the local Mempool, for instance trying to spend unavailable outputs (double-spending).

4.3 Process to calculate the block space supply

The block space supplied by the miners is determined by the size of the transactions included in the new blocks. These data and the collected fees can be directly extracted from the chainstate. Two different ways of recovering this information into CSV files have been implemented, depending on whether it is obtained from the already existing blocks, or from the upcoming blocks. In this last case the chainstate is recurrently read, waiting for the arrival of new blocks. The processes are respectively illustrated in Fig.6.

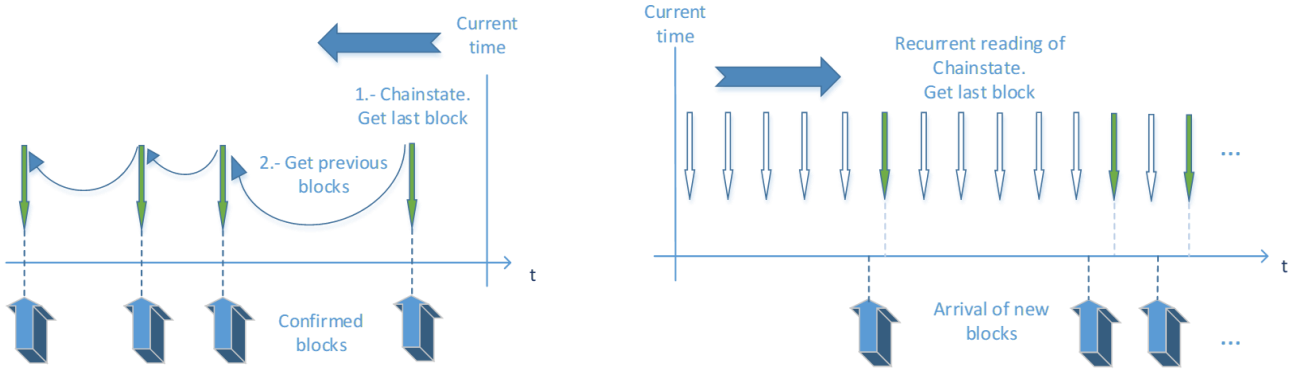

Fig.6 Processes to extract block space supply information

[12] 1,75% for sampling every two minutes. Assuming the time between blocks follows a Poisson distribution, which has a probability function given by $P(k;\lambda) = e^{-\lambda t}\frac{(\lambda t)^k}{k!}$

5 Empirical obtained transactions' demand and supply curves

5.1 Block space demand curve

Fig.7 depicts in linear and logarithmic scale the fees offered by the first 5.000 valid transactions in the Mempool, ordered from highest to lowest, at ten different instances of time randomly selected. The total number of valid transactions in the CSV is shown in the logarithmic scale chart.

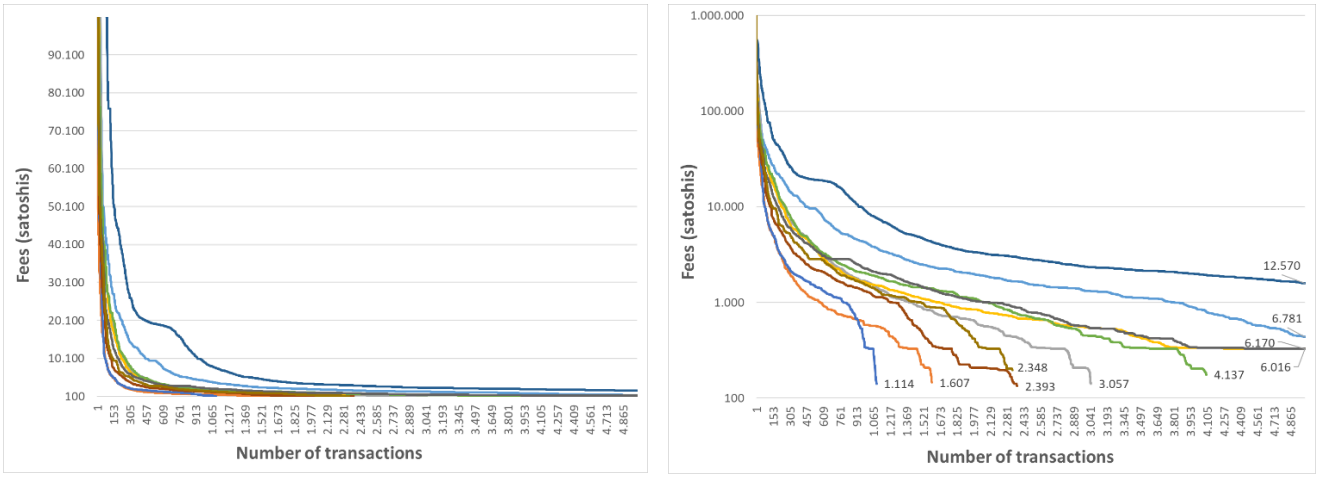

Fig.7 Fees offered at ten different instances of time randomly selected. Linear and logarithmic scale

It can be seen that the level of fees offered varies significantly, and that the higher the number of transactions in the Mempool, the higher the fees for a given number of transactions. Nevertheless, it is also to be noted that plain transaction fees are not the driving factor used by miners to set priorities. Instead, given the limited space available in the new blocks, the most relevant factor to maximize the total fee of selected transactions is the fee density (Fiz et al., 2018), which corresponds to the ratio between fee and virtual size. Basically, the virtual size considers different weight of witness and non-witness data (factor one and four respectively) within a transaction, in line with the current protocol rules particularly atter SegWit (Segregated Witness)[13] softfork was activated, resulting in an effective increase of block raw byte capacity[14] beyond the original limit of 1 megabytes[15].

[13] SegWit was proposed in BIP (Bitcoin Improvement Proposal) 141 and activated on 24 August 2017. It introduces block weight as a new metric vs. raw byte length, considering witness signature data as having less weight than other parts of the transactions. This frees up space, allowing to add more transactions into the blocks, which is equivalent to an increase in the block size.

[14] Biggest block to date (#774628, 01/02/2023) 3,955,272 bytes (https://blockchair.com/bitcoin/block/774628) Close to current Bitcoin's block size limit, stretched to 4MB.

[15] It is worth mentioning the Taproot upgrade on 12th November 2021 (BIP 340, 341 and 342), basically involving key generation and verification improvements, targeted to increase the transaction efficiency, the privacy of the network, and its ability to support smart contract initiatives.

In this way, although each miner on the P2P network is free to make its own decisions, the metric allowing to maximize the fee yield from new blocks consists of ordering the set of transactions in the Mempool in decreasing order of fee density, applying then different algorithms (ie. Greedy) to select them (dos Santos et al., 2019). Fig.8 shows the fee density for the same instances of time considered in previous Fig.7.

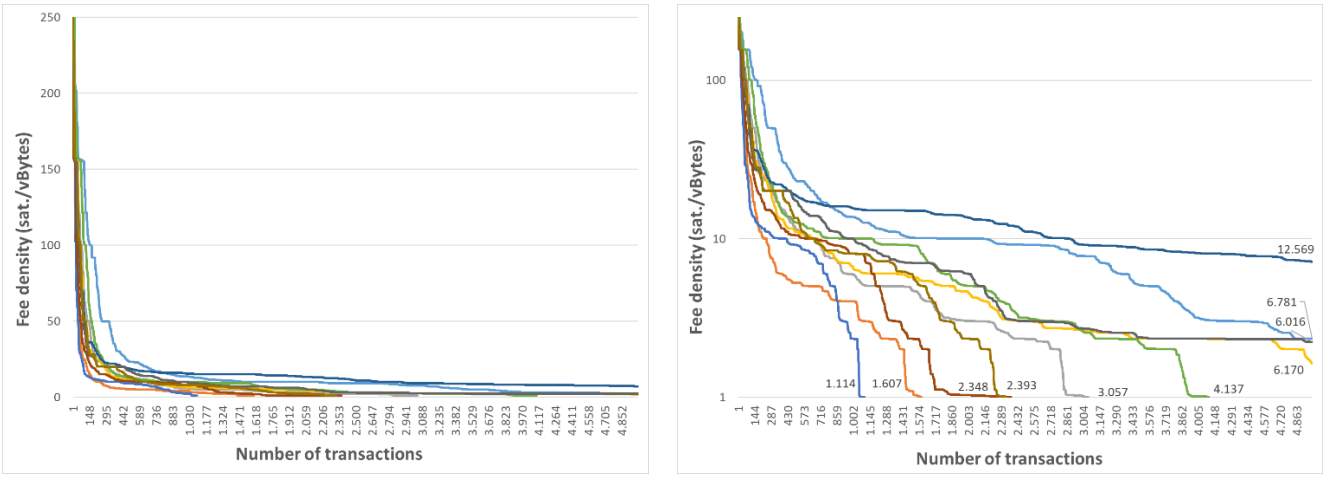

Fig.8 Fee density at ten different instances of time randomly selected. Linear and logarithmic scale

Taking into account that the transactions are gathered together in blocks, the maximum fees a miner can claim by producing a given block space is the cumulative fee of the transactions fitting that block. Fig. **9** illustrates how the resulting overall demand curve is built (Rizun, 2015) and shows an example.

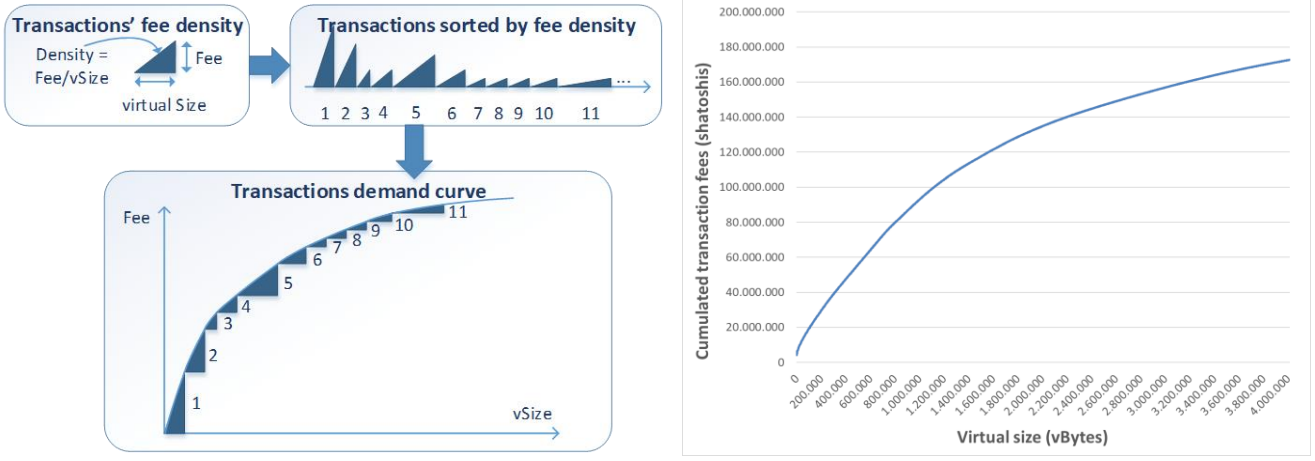

Fig. 9 a) Generation of transactions demand curves, b) empirical example

Source: prepared by the authors. Empirical demand curve from mempool content with 12.589 transactions before generation of block 00000000000000000008f7e5f600a283df009aa5b619d50c58479279a6f7544e on 14/10/2021.

The transactions in the Mempool are constantly updated, increasing with the continuous arrival of new transactions[16] and decreasing at each block generation round, meaning that the curves are extremely dynamic. Following the process introduced in the previous section, Fig.10 and 11 below depict the transactions demand curves obtained at different instants of time, randomly selected from the hundreds of files created in 2021 and 2023 respectively. An extended view up to 10 vMB and a zoom-in graph showing the Bitcoin size limit (currently set to 1 vMB) in the middle of the figure are presented.

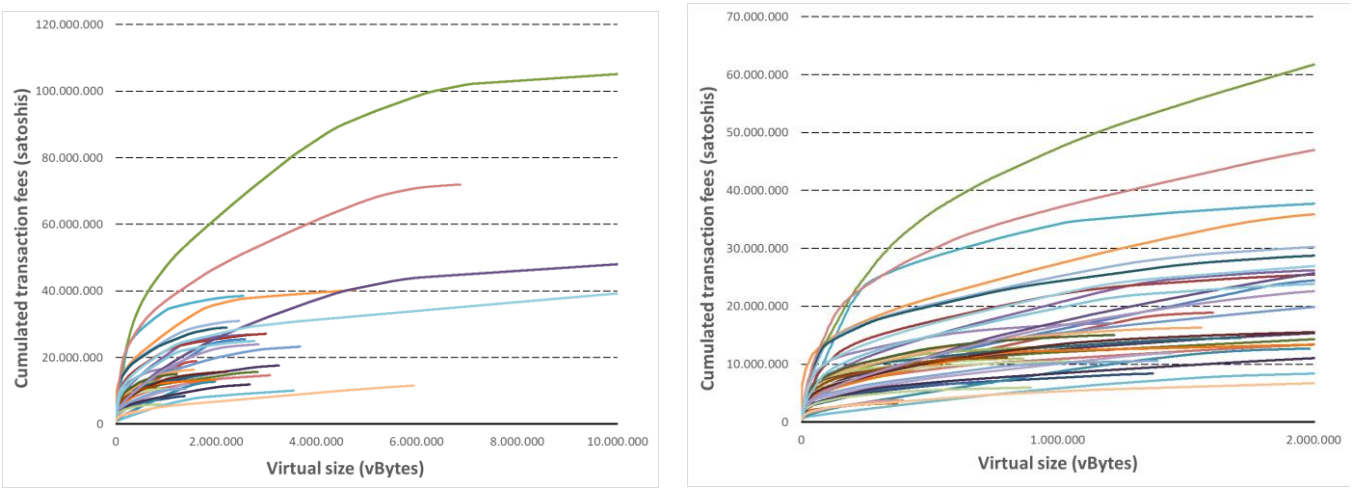

Fig.10 a) Transactions demand curves in 2021, b) Zoom on x-axis up to 2 vMB of the preceding figure

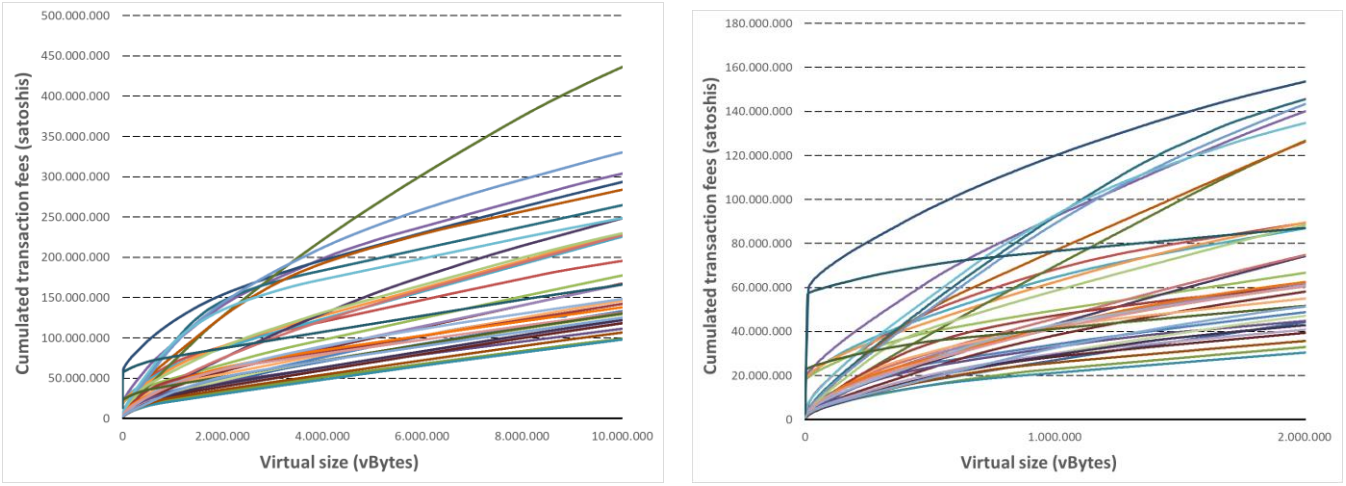

Fig.11 a) Transactions demand curves in 2023, b) Zoom on x-axis up to 2 vMB of the preceding figure

[16] Around two hundred and fifty thousand transactions daily in the last three years (Source: https://www.blockchain.com/charts/n-transactions).

Several preliminary aspects are to be highlighted from these curves. On the one hand, irrespective of the period under consideration:

- There are significant differences in the fee densities offered by the transactions, determining their prioritisation (Kasahara & Kawahara, 2019; Kawase & Kasahara, 2020; Li, J. et al., 2019a; Sokolov, 2021). Nevertheless, abnormally high values are occasionally observed[17], at an order or magnitude above those guarantying their inclusion in new mined blocks with high priority.
- Aggregate demand curves are highly variable in the short term even between consecutive blocks or very close together in time.

On the other hand, considering the evolution in the aggregate demand curves between 2021 and 2023:

- The increase of transactions in the mempool in 2023 wrt. 2021 shifts the demand curve upward, also causing the demand for block space to generally exceed 10 vMB, which was rare in 2021. The mempool size is not necessarily increasing over time, having in fact undergone substantial variations up or down in the past, as can also be seen in previous Figure 4.b).
- The average elasticity of the curve around the point of interest 1vMB is higher in 2021 than in 2023 (4,0 vs. 2,1 respectively), thus more homogeneous prices and close behaviour to perfect competition. This is consistent with a context where there was less competition between transactions, which are selected on the basis of the fees offered.

5.2 Block space supply curve

The block space consumed can be straightforwardly obtained from the size of the transactions included in the blocks. Nevertheless, the cost to generate these blocks is not so easy to evaluate for a variety of reasons, one of the main ones being that the electricity prices available to miners vary significantly from one region to another. Furthermore, beyond the deployment of the computational power wherever high profit could be found, electricity consumption undergoes significant fluctuations, on which transactions exert both a temporary and permanent effect (Zheng, M. et al., 2023).

Following Hayes (2017), the (marginal) cost of production (in US dollars, $) per unit of mining power and per day can be expressed as follows:

$$E_{day} = (\rho/1000)\left(\$/kWh \cdot WperGH/s \cdot hr_{day}\right) \quad (1)$$

[17] Some examples, transactions: 830867b9ecbe43be34f3374aeb78f5bfe8347e940358ef0c634bd6122f5b99d8, 0cfc0b33f0eee930a024d1dba1fdbff198f3d16b54ae02597ab2a3c217844d80, efed683d2a4853f7cd063c3fb3e83746cb8a7170b88bf8b4aaeb7cedb4ab4f62, bf2845791c5cf1352ba2dbb1bc4bcc4b7cd3bf97dd691d658927f36ac8af0711, 1226f509a5890649ab76b791c6da280519822171c4c08e3fbd46d9cd7161213e

Where ρ is the hash power employed by a miner (in Giga Hash/s), *$/kWh* is the price per kilowatt hour, *W per GH/s* is the energy efficiency of the mining hardware, and hr_{day} is the number of hours in a day. The daily cost of production for the whole network, and the cost for a single block, considering that one block of bitcoin is found on average every ten minutes, can be estimated from (1)[18]:

ρ = 375,60 ExaHash/s[19] (375,60 · 10^{18} Hash/s)

$ / kWh = 0,06[20]

W per GH/s = 0,0395[21]

hr_{day} = 24

$\Rightarrow$ E_{day} = 21.370.060 *$/day*

Average Cost$_{Block}$ = 148.403 *$ / Block*

A similar result is given by the *Cambridge Bitcoin Electricity Consumption Index*[22] (142.591 $/block). It should be noted that miners look for cheaper and sustainable energy sources to protect their profitability (Krause & Tolaymat, 2018; Stoll et al., 2019; Zade et al., 2019), which makes it difficult to think about a clear reference for the electricity price, so that any of these values should be considered as an approximation. In any case, the average cost per block is not suitable for the assessment of the supply curve, as it is necessary to take into account the specific mining time for each block, so that we will just make use further below of the calculated E_{day} value as a reference, without loss of generality.

Bitcoin block arrivals can be assumed to occur according to a homogeneous Poisson process, as suggested in the original Bitcoin paper (Nakamoto, 2008). The Probability Mass Function for a discrete random variable *X* having a Poisson distribution with $\mu > 0$ is given by:

$$P_X(k) = \begin{cases} \dfrac{e^{-\mu}\,\mu^k}{k!} \; for\; k \in \Re_X \\ 0 \quad otherwise \end{cases} \tag{2}$$

Where $E(X) = \mu$ and $Var(X) = \mu$

[18] This cost includes the electricity consumed in the mining process, which is the primary ongoing cost for Bitcoin production, while fixed costs such as hardware, network access, facilities or labour are excluded.

[19] Source: https://www.blockchain.com/charts/hash-rate (accessed 29/07/2023). Similar values (although not identical) from other sources: https://bitinfocharts.com/comparison/bitcoin-hashrate.html#3y, or https://ycharts.com/indicators/bitcoin_network_hash_rate

[20] Source, U.S. Department of Energy, Energy Information Administration https://www.eia.gov/electricity/monthly/ (US price for electricity to industrial customers May 2023, West South Central region has been considered, minimum value).

[21] Average energy efficiency for the top five Bitcoin mining Hardware (source https://www.softwaretestinghelp.com/bitcoin-mining-hardware/, updated 18/07/2023): AvalonMiner A1166 Pro, WhatsMiner M30S++, AvalonMiner 1246, Antminer S19 Pro and WhatsMiner M32-62T.

[22] Source: https://ccaf.io/cbnsi/cbeci. Accessed 30/07/2023. Values 14,24 Bitcoin Network Power Demand, 124,91 annualised consumption, with average electricity cost at 0,06 *$ / kWh*. Both E_{day} values are consistent with the reward per block at 6,25 BTC + fees, and the corresponding $/BTC exchange rate.

Considering the average rate *r* at which events (block arrivals) occur in Bitcoin, the previous equation (1) can be adapted as follows for $k \in \mathfrak{N}_X$

$$P_X(k) = \frac{e^{-rt}(rt)^k}{k!} \tag{3}$$

Where $\mu = rt$, being *k* the number of events within a time interval *t*

From equation (3), next figure depicts the probability of block arrivals in Bitcoin[23] within a given period of time.

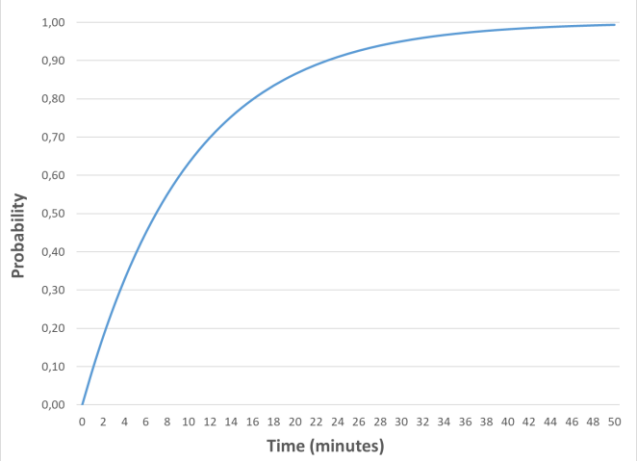

Fig.12 Probability of mining block in Bitcoin

It is to be noted that, while the cost to generate a block is random, following a Poisson distribution, its size is independent of the time needed to generate it. Indeed, the block size can be set to the maximum allowed (1 vMB) as long as there are transactions enough in the mempool[24], meaning that the theoretical supply curve is vertical, perfectly inelastic, with a marginal cost proportional to the time taken to mine blocks. More precisely, (Saito & Iwamura, 2019) exposes that the supply of Bitcoin, thus of blocks pace, is slightly positively sloped, considering that the adjustment of the target mining difficulty (hash computation) is performed automatically; when the demand rises, there will be slightly more supply before the adjustment and vice versa.

[23] At least one block (1-P(0)), with *r* = 10 minutes, taking into account that Bitcoin's hard-coded algorithm into its source code constantly readjusts the difficulty of the mining process to ensure that blocks are discovered at a steady pace of 10 minutes.

[24] Many blocks with a timestamp of just a few seconds later than the previous block present a vSize close to 1 vMb (weight above 3.990.000), ie. blocks #796.385 (8 seconds), #796.344 (3 seconds), #796.292 (9 seconds) or #796.119 (6 seconds).

This cost distribution on the quasi-vertical axis follows the Probability Mass Function shown in Figure 13 a) (probability of a given number of blocks arriving within a time period), whereas Figure 13 b) illustrates the waiting time between arrival of blocks, which are exponentially distributed with a Probability Density Function given by:

$$F(t) = \mu\, e^{-\mu t} \tag{4}$$

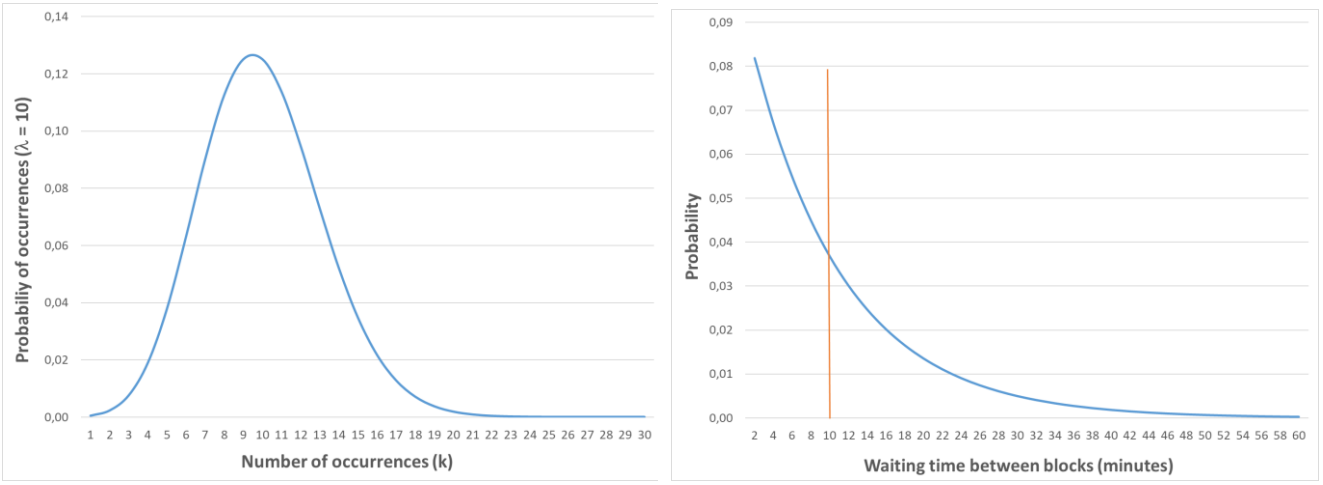

Fig.13 a) Probability Mass Function of Bitcoin block generation. b) Bitcoin block arrival waiting time [25]

The block generation time is known to be approximated with this exponential distribution (Decker & Wattenhofert, 2013; Kawase & Kasahara, 2018). The blocks analysed in our research fit this distribution, with a small deviation due to the relatively low number of samples, as shown in Fig.14.

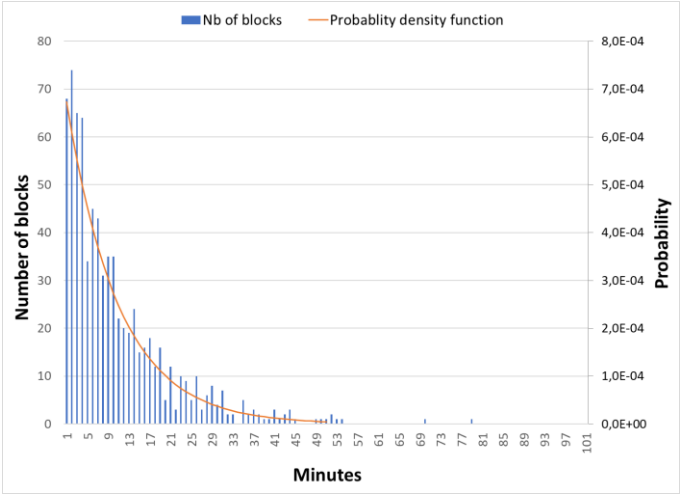

Fig.14 Waiting time of blocks computed

[25] The orange line represents the mean waiting time, 10 minutes.

The data extracted from the Bitcoin node, shown in Fig.15 below, reveal an inelastic behaviour of the supply curve. The cost is estimated by multiplying the time in seconds consumed for the generation of each block (difference between timestamps of consecutive blocks), by the average daily cost of mining (value of E_{day} calculated above / number of seconds in a day).

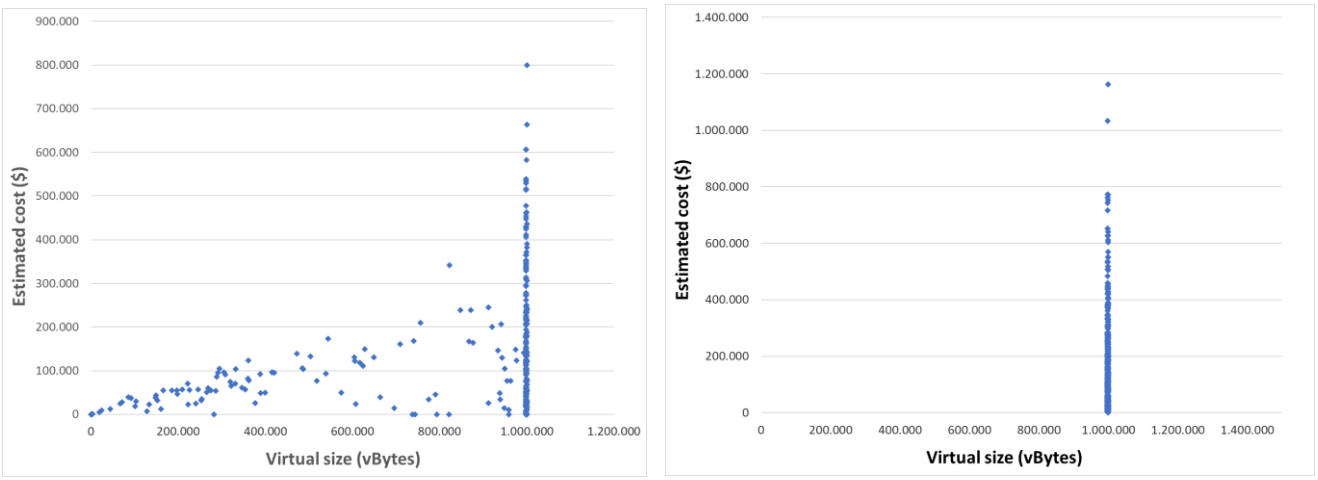

Fig.15 Effective supply curves a) 2021 b) 2023

The following points are worth noting:

- The empirical curve becomes vertical when the demand for block space is sufficient to fill the available space in the mined blocks (2023), approaching the inelastic theoretical curve. Otherwise, it presents a spread upward-sloping profile (2021)[26]. Inelasticity of the theoretical curve remains valid whatever the costs of mining, with the distribution on the Y-axis varying according to these costs.
- Upfront fixed costs impose entry barriers for miners, and represent a sunk cost once incurred and a barrier to exit. Therefore, miners' activity can be justified even if the marginal costs are not covered, waiting for a recovery to achieve their return-on-capital targets in the medium or long-term. As stated above, fixed costs are excluded from the analysis.
- The cost is denominated in USD fiat currency, whereas the fees in the previous demand curves are denominated in BTC cryptocurrency. Furthermore, this marginal cost is to be compared with the total miner's income, consisting of fees (representing a small percentage)[27] and coinbase block reward.

[26] It has been verified that in periods with low demand before 2021, the graph also shows a high degree of dispersion before reaching the limit size at 1 vMB.
[27] 1,7% in 2021, 3,7% in 2023 for the blocks evaluated.

In other words, to compare pears with pears, the coinbase block reward should be deducted, and the currencies homogenised according to the exchange rate on the spot.

5.3 Market equilibrium demand - supply

The demand and supply data match rather well, as shown in Fig.16 below, although not always exactly. The delta can be explained by three main factors (other factors are of lesser relevance[28]): First, the mempool content is not the same on all Bitcoin nodes, typically due to the delay of information dissemination in the bitcoin network (Decker & Wattenhofert, 2013; Donet-Donet et al., 2014; Moustapha, 2020), or even the decision not to broadcast information (Babaioff et al., 2011). Second, some transactions are missing due to the process followed (introduced in subsection §4.2**Error! Reference source not found.**), so that involving a downward shift of the demand curve. Lastly, miners do no (yet) have a strong incentive to perform an optimal selection of transactions, considering the low percentage coming from fees compared to the coinbase reward (% detailed in previous subsection §5.2**Error! Reference source not found.**).

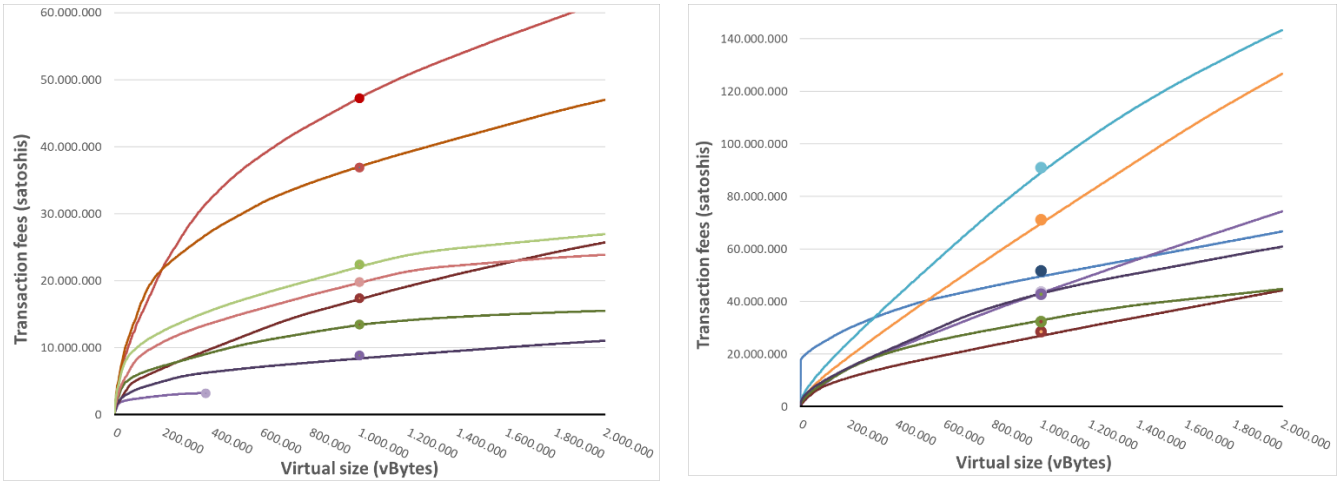

Fig.16 Equilibrium demand – supply

A few aspects of this figure deserve to be highlighted:

- Miners tend to draw on all the space available in the new blocks (1 vMB). When the number of transactions in the mempool is not enough, the fees reward is maximized by collecting all of them.

[28] For instance, the size of the block header has not added to the aggregate demand. The effect is negligeable, when comparing the size of the header (88 bytes), with the total block size.

- There is not an apparent relation between the collected fees and the production costs. However, these variables are linked through the profitability of mining activities (Derks et al., 2018; Islam et al., 2023), making miners to join in or drop out of the circuit.

6 Findings and discussions

6.1 Analysis of results

A priori, there are some significant elements of the Bitcoin transaction market that may suggest it is a perfect competition, such as the homogenous service provided (transaction inserted in the database) or the large number of vendors with no differences between them (even users can not choose to whom they are "buying"). However, the results obtained show that this market is far from being a perfect competition[29], which was certainly not one of the objectives when the protocol behind Bitcoin was designed[30].

From the demand side perspective, the curve present a quite elastic profile (>1) showing users' willingness to pay in order to get their transaction included in the blockchain faster (Kasahara & Kawahara, 2019; Kawase & Kasahara, 2020; Li, J. et al., 2019a; Sokolov, 2021). Most of the users seem to act rationally, tuning the fees proposed in their transactions according to the context, with values in a range that allows a quick incorporation to the blockchain without spending beyond the necessary. Nevertheless, abnormally high fee values (in terms of density) are often posted (some examples are provided in subsection §5.1), which does not seem wise. On the other hand, quite a number of users propose very low fees, not caring about the delay their transactions could take. A consequence of the different propensity to pay for the service is the outstanding variance in the aggregate demand curves, resulting in high fluctuations of the fees collected by miners in the regular auctions carried-out every ten minutes on average. Finally, it cannot be ignored that transaction fees are of relative importance for the time being, as the coinbase reward is still the main source of income for miners.

An important aspect stemming from the elasticity shown by the demand curve is the limited capability for miner pools to become price makers. They compete with different reward schemes to conform its market power, making mining activities

[29] Perfect competition is characterized by a perfectly elastic demand curve (price taker), whereas it presents a downward sloping profile in the rest of market structures. This curve is relatively elastic for monopolistic competition, price-elastic in the oligopoly, where it is affected by competition, and more inelastic in the case of pure monopoly, where agents have the most control over price.

[30] The authors do not intend to prejudge the most appropriate transactions market system.

more stable (Jia & Li, 2023; Tovanich et al., 2022), but the extent to which an agent is a price maker is rather determined by the price elasticity of demand in the relevant price range.

On the supply side, the curve shows an inelastic profile, which helps to explain Bitcoin transactions volatility and the sharp variation in the price of transactions (in cryptocurrency terms) produced by demand shocks. For instance, Denial of Service (DoS) attacks[31] have led to an increase of average transaction fees and delays in processing (Baqer et al., 2016). Another example can be found in late 2017[32], when the number of transactions submitted by users spiked in parallel with the Bitcoin price, creating sudden growth in the mempool size and thus steep increase of the operative transaction fees. These effects are not exclusive to Bitcoin, similar situations can be seen in Ethereum, where the number of pending transactions has a relevant influence on the transaction fees (Pierro & Rocha, 2019).

Certain Bitcoin's algorithm upgrades (ie. SegWit or Taproot, referenced above) shifted the supply curve to the right by improving the system's capacity and streamlining the processing of transactions; this shift entailed a relevant reduction in the transaction fees (Brown et al., 2019) in periods of high congestion. Nevertheless, the supply curve has remained inelastic, so that not allowing to absorb demand shocks and therefore automatically stabilize market prices.

Finally, the results are complementary to previous econometric research (Huang et al., 2017; Ilk et al., 2021; Tsang & Yang, 2021), which include exogeneous variables in the analysis of the curves; typically an association between transaction fees and bitcoin prices (exchange rate to US dollar) is shown, with mutual feedback loops.

6.2 Contributions

The findings of this research have twofold readings. On the one hand, the empirical findings provide an insight into the theoretical characteristics of the transactions market of Bitcoin. In this regard, the paper covers a gap by conducting an economic analysis of the empirical transactions supply and demand curves, based on a huge dataset. This analysis is performed over two separate time periods, thus allowing to identify their actual behaviour in different situations of congestion and recognise patterns independently from short-term situations. The research provides valuable information on the features of these curves, helping to explain why transaction fees are subject to high price volatility (as with commodities, inelastic supply boosts the volatility), and why demand shocks drive up the transaction fees as result of the competition between users to

[31] Attack performed by flooding the system with superfluous transactions coming from different sources, in an attempt to overload it and preventing legitimate ones from being fulfilled.

[32] Bitcoin block rate crunch 11th-12th November 2017; similar situation on 22nd-26th August 2017.

purchase scarce block space. Besides, it has been exposed that, although the protocol evolutions pursuing efficiency gains have historically shifted the supply curve to the right, its inelasticity has been preserved.

On the other hand, our research has implications for practice. First, in the potential future protocol evolutions of Bitcoin and other analogous blockchain-based applications[33]. In a gradual transition towards a transaction-fee regime, the economic risks of any update able to reshape or shift the supply or demand curves need to be carefully assessed before implementation. Typically, it may be worthwhile to evaluate the implementation of an upward-sloping supply curve, allowing to reduce the volatility of the transaction fees. Anyhow, the assessment should be coupled with the resilience of the proposed solution to deliberate attacks or accidental stressful situations, while taking into account security and sustainability issues linked to the target implementation. Second, in the design of new applications, particularly those intended to reach high levels of transactions throughput or where the transaction fees play a key role for rewarding miners. In this regard, it is to be noted that the consequences of the performance and vulnerability issues have already been significant (Alkhalifah et al., 2019; Baqer et al., 2016; Pierro & Rocha, 2019; Shanaev et al., 2020; Sokolov, 2021; Vasek et al., 2014), and are expected to go hand by hand with the increasing use of blockchain technology in different areas beyond cryptocurrencies.

6.3 Limitations

Several limitations are acknowledged in this study, some of them briefly introduced throughout the text. These limitations are classified according to the different topics covered in the present article as follows:

Regarding the data extraction process:

- Once the transactions incorporated into the blockchain, they are removed from the mempool, meaning that the results are reproducible for future accesses to the mempool, but not exactly in the same time periods considered in our analysis. Nevertheless, all the files used in this analysis as well as the source code developed for this purpose have been made available (see previous section §4), and the data validity can be checked in different websites[34].

[33] It is common for blockchain–based applications to evolve in order to circumvent identified problems. Some relevant examples:

- Already mentioned SegWit (24th August 2017) and Taproot (12th November 2021) upgrades.
- Bitcoin core 0.22, issued in September 2021, includes various bug fixes and performance improvements (source: https://bitcoincore.org/en/releases/22.0/).
- Creation of Ethereum Classic (hard fork) 20th July 2016, following a successful cyberattack that stole nearly $50 million worth of Ethereum.

[34] ie. https://www.blockchain.com/explorer, https://blockstream.info/, ….

- Data extraction from the mempool requires high computational power, the process carried out on a home computer can take hours for a single access with tens of thousands of transactions (which is usually the case nowadays), limiting in practice the number of demand curves retrieved in a short period of time.

Regarding the demand curve estimation:

- Bitcoin price has not been included as a parameter of analysis. Several studies (Dyhrberg et al., 2018; Koutmos, 2018; Sebastiao & Godinho, 2021; Tripathi & Sharma, 2023) suggest a correlation between the Bitcoin's price and the number of transactions managed or the mempool transaction count, with mutual feedback loops.
- The transactions arriving between the last reading of the Mempool and the generation of a new block are missing, which does not have a significant effect on the results (random shift down of the curve), and the conclusions drawn from the data.

Regarding the block space supply curve estimation:

- Bitcoin block arrivals have been assumed to follow a homogeneous Poisson process, whereas (Bowden et al., 2020) postulate that this process is non-homogeneous. This circumstance does not essentially change the results of the research.
- Several limitations are related to the mining costs. First, the difficulties to assess the overall mining cost (Hayes, 2019; Kufeoglu & Ozkuran, 2019; Zade et al., 2019). Second, the fixed costs are not included in the analysis; although they play a relevant role as entry barrier for mining activities (Prat & Walter, 2021), do not influence the marginal costs of bitcoin production. Finally, without loss of generality, the cost of the whole network has been taken into account, excluding specific evaluation for single miners or pools according to their relative computing capacity (Taghizadeh et al., 2020).

Notwithstanding the identified limitations, the study presents an innovative framework for guiding both research and practice in the development of blockchain solutions, summarized in the following section.

7 Conclusions and research propositions

7.1 Conclusions

In a context where the transactions market is expected to become increasingly important, an economic assessment of the supply and demand curves defining this market is key to recognize its potential weaknesses, but also to minimize risks and to

improve the operational efficiency when designing or upgrading blockchain-based applications. Based on an extensive dataset (circa four million transactions and one thousand blocks) collected from a Bitcoin node through a specifically developed software, our research provides an economic insight into the characteristics of these curves in the pioneering blockchain application.

The empirical findings support the understanding of why Bitcoin transaction fees, regulated in this market, are subject to high volatility and how the protocol evolutions made to date have shifted the supply curve, thus tuning in due time the supply and demand equilibrium. The demand curve, although relatively elastic around the equilibrium price, turns out to be extremely dynamic, with users regularly offering above-market fees to guarantee the access to the sought scarce resource (block space for their transactions) thus boosting the volatility of the transaction fees. On the other hand, the inelastic supply curve is described by the exponential distribution followed by the marginal costs incurred by miners to find consecutive blocks, which explains the sharp variations in transaction fees observed under demand shocks.

The results bring to light the importance of the transactions market layout as an element of control over the intrinsic problems associated with an imperfect competition, involving inefficient allocation of resources. This layout and its ability to meet one market structure or another may be limited by specific operational elements (number and size of sellers, entry and exit barriers, nature of the service provided, price transparency, information flow …). Finally, as Bitcoin has shown, different side aspects beyond pure economic considerations are to be taken into account in the design of this market, particularly the system's sustainability and security typically encouraging some level of congestion.

The research findings have twofold implications for practice for blockchain policy makers and managers. First, in Bitcoin-like applications (in terms of typology, and consensus and reward mechanisms), in which any protocol evolution will require thorough assessment before implementation in a context of gradual transition towards transaction-fee regimes. Second, in new blockchain-based applications intended to use the transaction fees as the main mechanism for rewarding miners or targeting very high transaction throughput by design.

7.2 Future research directions

We encourage future research in two main directions. Firstly, more generally, identify what are the key rules for a transparent and fair market for buyers and sellers, allowing to guarantee their respective private property rights, free and voluntary activity, and restricted control of distribution. In this respect, it is to be analysed whether and to what extent the blockchain typology and market structure may be a constraint for these rules; and if any, what are the advantages and

drawbacks of the different typologies in regard to the transaction fees market and the limitations for the policies adopted. The outcomes would allow to further verify the extent to which a given blockchain-based application fulfils these rules.

Second, in relation to the modelling and empirical approaches of the transaction fees market in tree-structured blockchain typologies, typically based on DAG consensus mechanism. These solutions move away from the traditional linear blockchain structure and have been identified as a promising technology for Internet of Things (IoT) applications (Cao et al., 2019; Li, Y. et al., 2020), achieving very fast transactions settlement. Given the massive throughput of transactions these applications are required to handle (Wang, X. et al., 2019), the research is, in our view, highly relevant. In this context, the risks associated with an inefficient transaction fees market become particularly important; the lack of stability can manifest as severe swings in transaction fees with extreme user dissatisfaction.

Some side issues are to be taken into account in these research, in particular the ability to withstand attacks and operational resilience, which have occasionally shaken the transactions market as seen along the present manuscript.

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Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose directly or indirectly related to this work submitted for publication.

Author Contributions

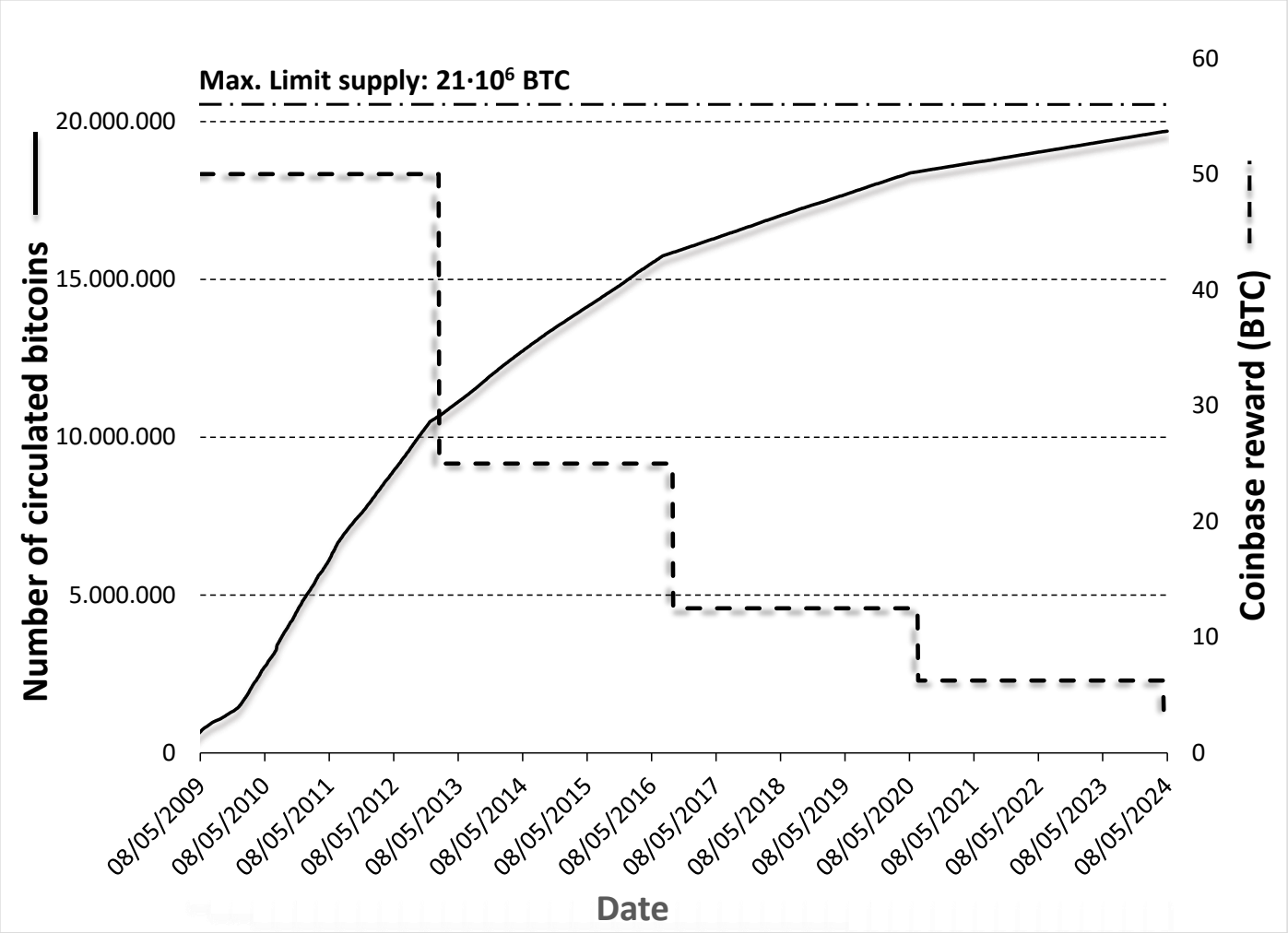
All authors have contributed equally to this work. All authors read and approved the final manuscript.

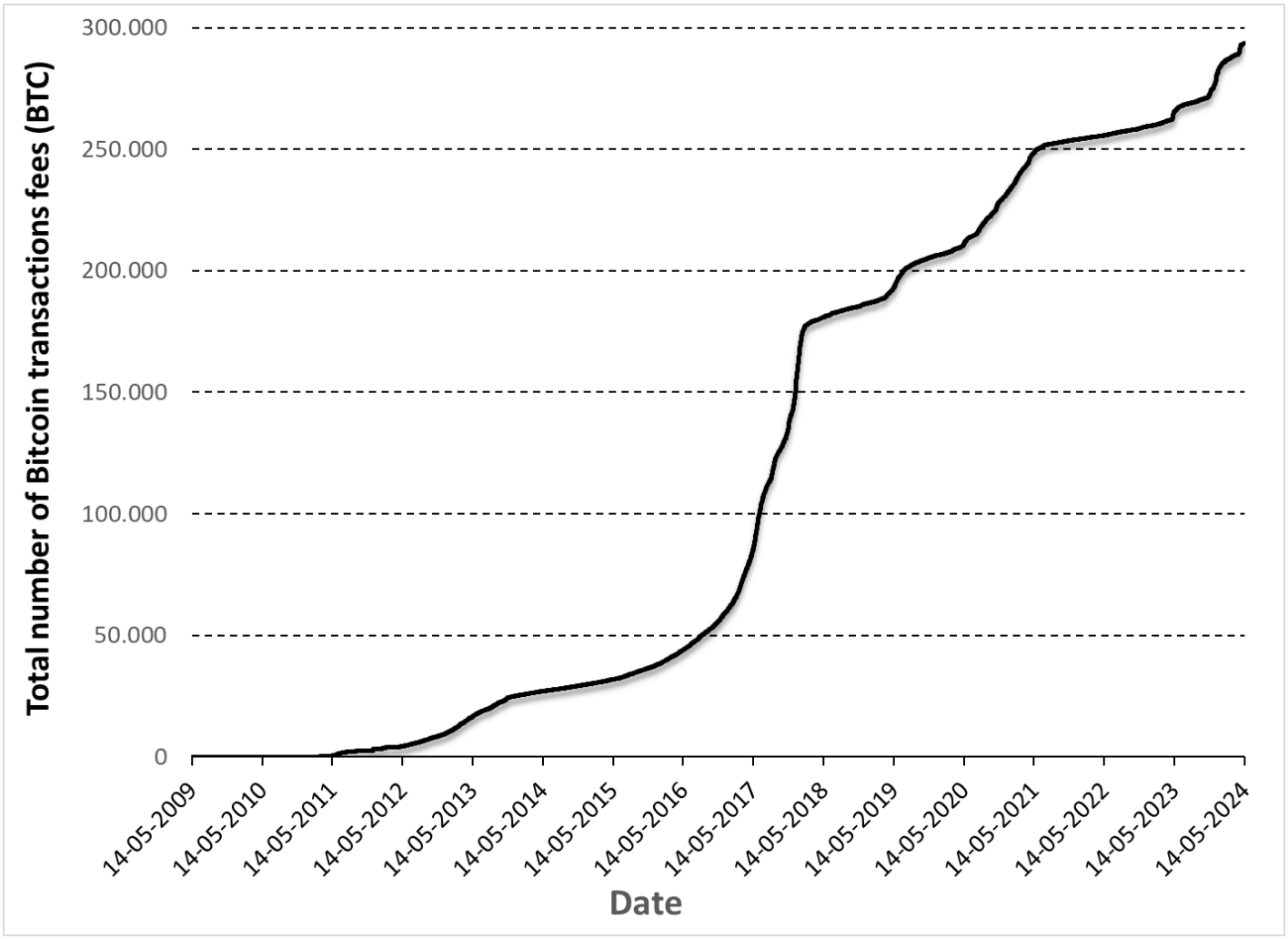
Availability of data and materials

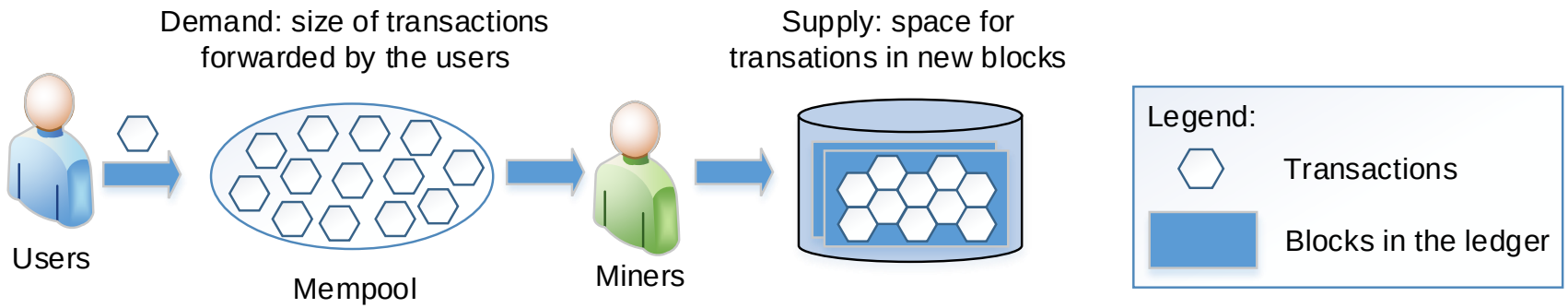
The datasets supporting the conclusions of this article are available in the figshare repository:

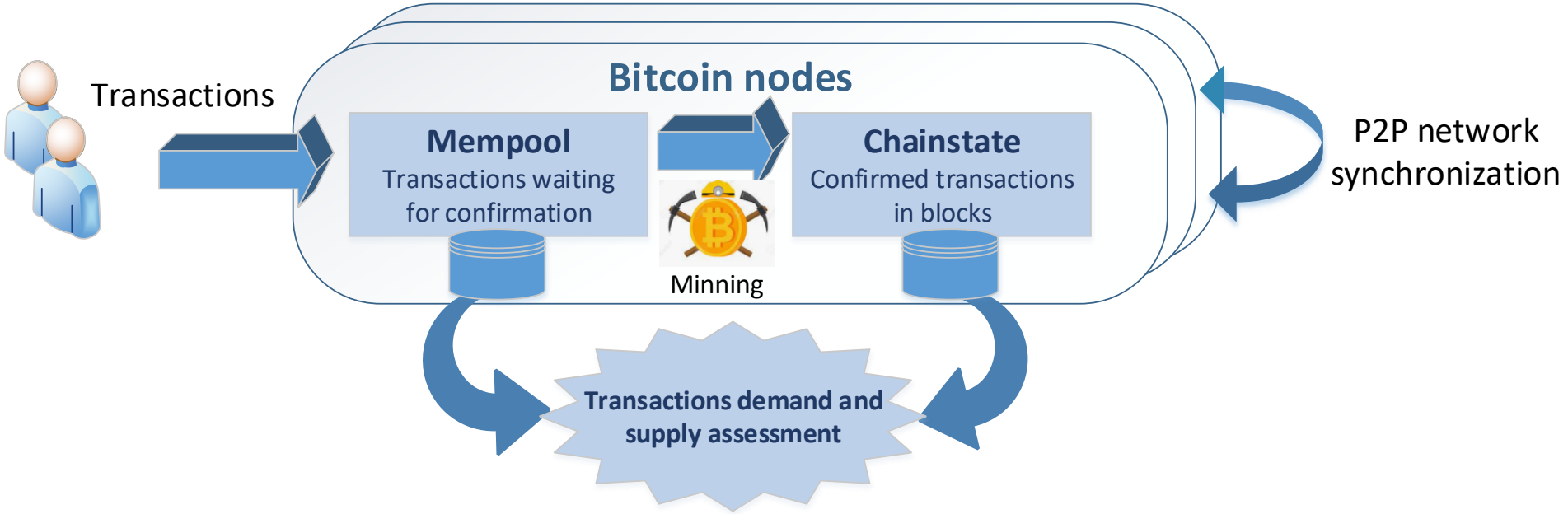
- Source code: https://doi.org/10.6084/m9.figshare.24190251.v1
- Demand data: https://doi.org/10.6084/m9.figshare.24183288
- Supply data: https://doi.org/10.6084/m9.figshare.24190272

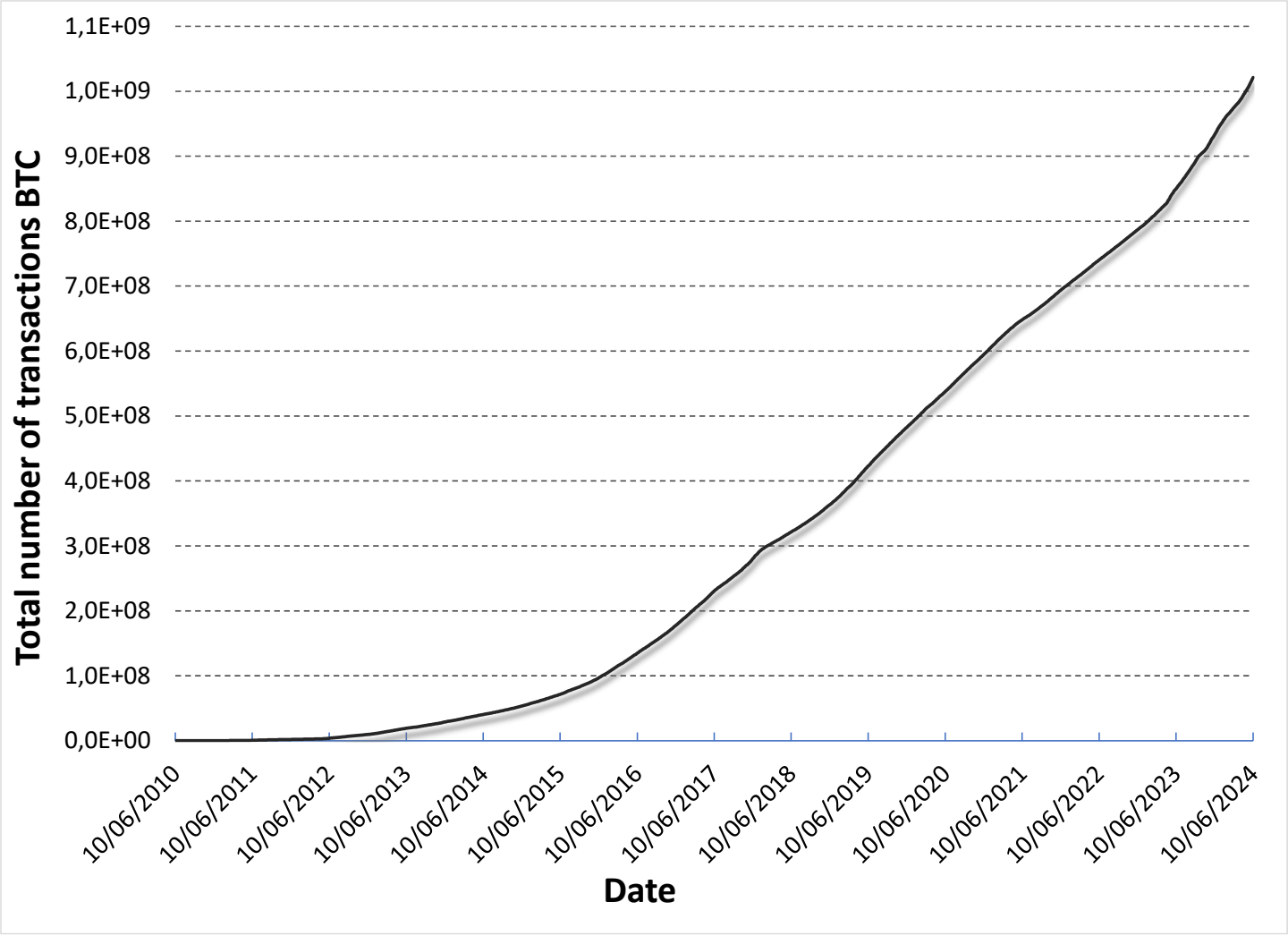
Figures

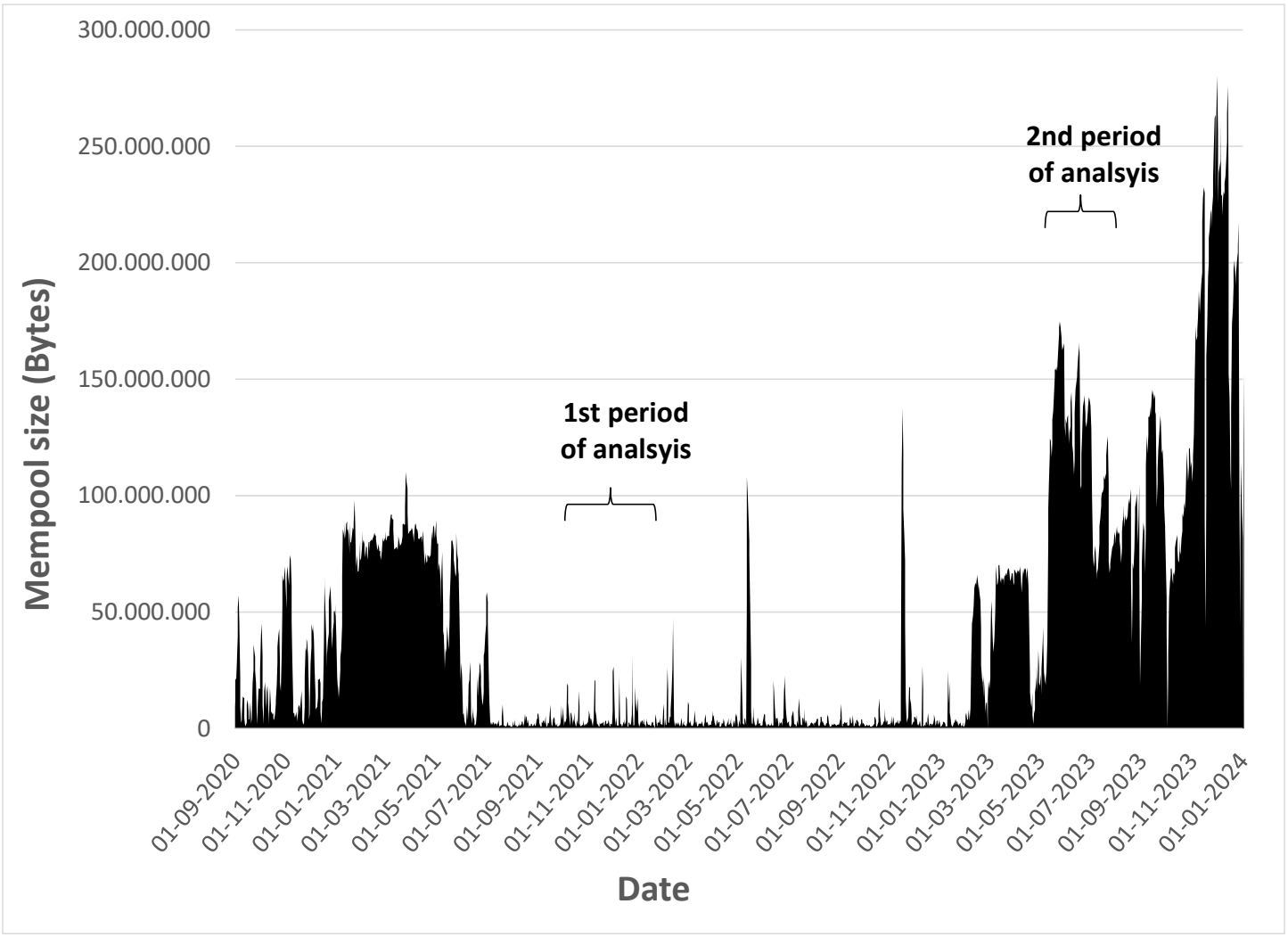


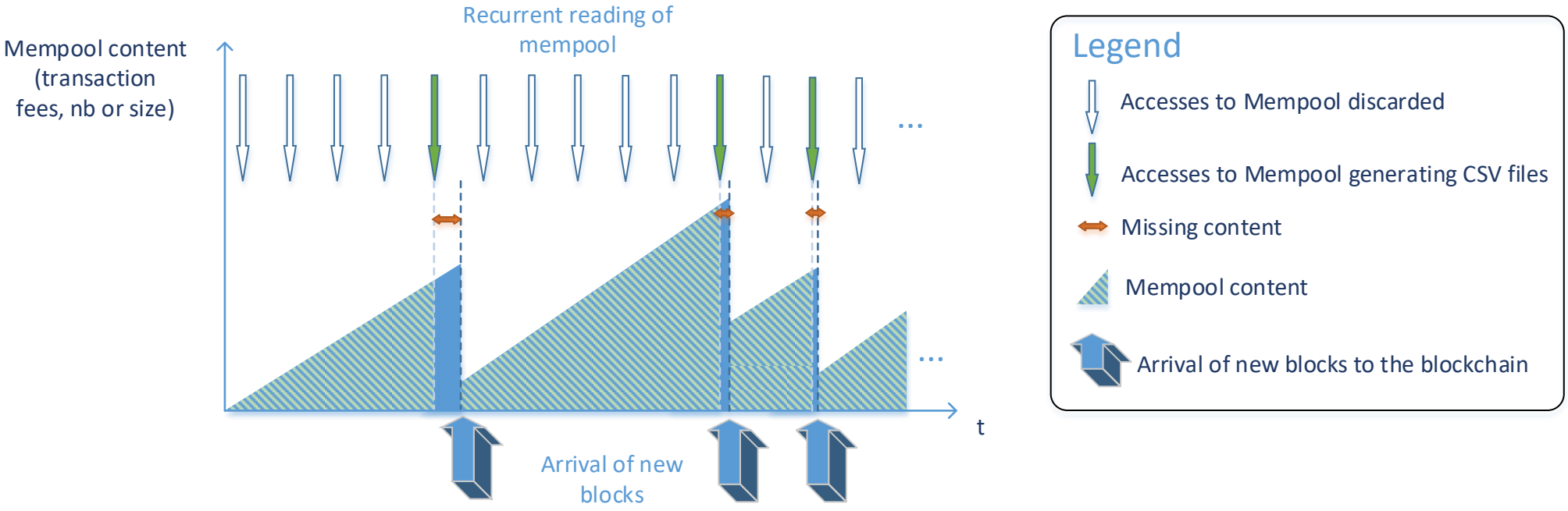

Total number of Bitcoin transactions fees (BTC)
300.000
250.000
200.000
150.000
100.000
50.000
0
14-05-2009
14-05-2010
14-05-2011
14-05-2012
14-05-2013
14-05-2014
14-05-2015
14-05-2016
14-05-2017
14-05-2018
14-05-2019
14-05-2020
14-05-2021
14-05-2022
14-05-2023
14-05-2024
Date

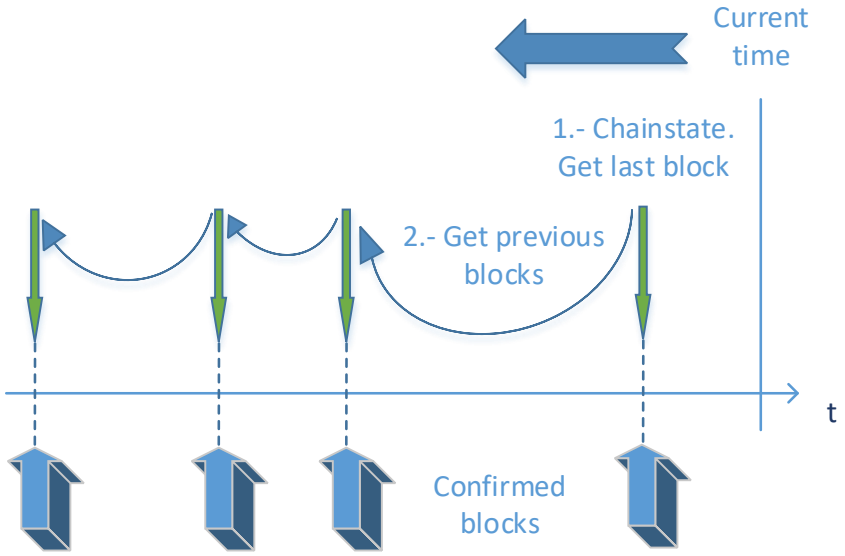

Demand: size of transactions forwarded by the users
Supply: space for transations in new blocks
Users
Mempool
Miners
Legend:
Transactions
Blocks in the ledger

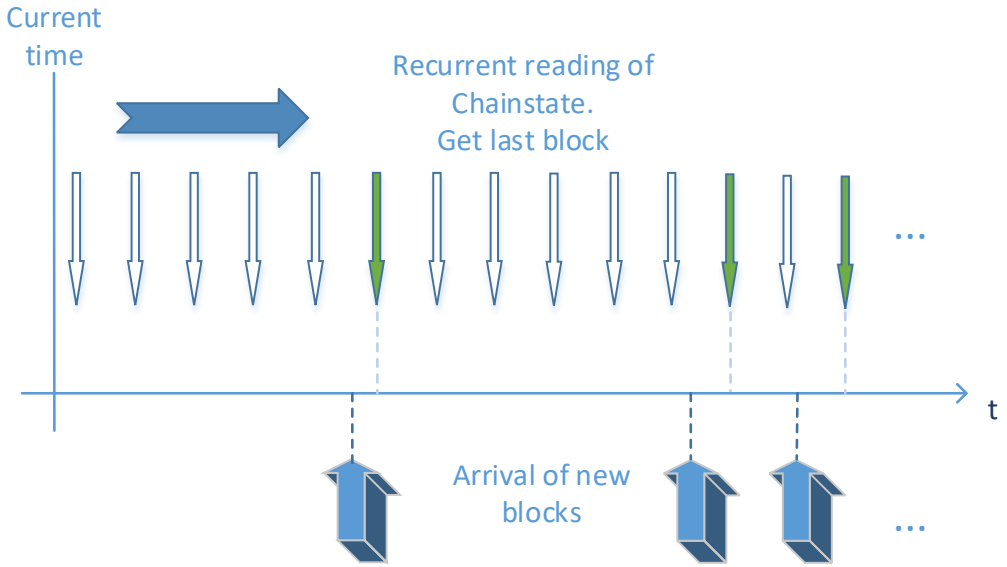

Transactions
Bitcoin nodes
Mempool
Transactions waiting for confirmation
Chainstate
Confirmed transactions in blocks
Minning
P2P network synchronization
Transactions demand and supply assessment

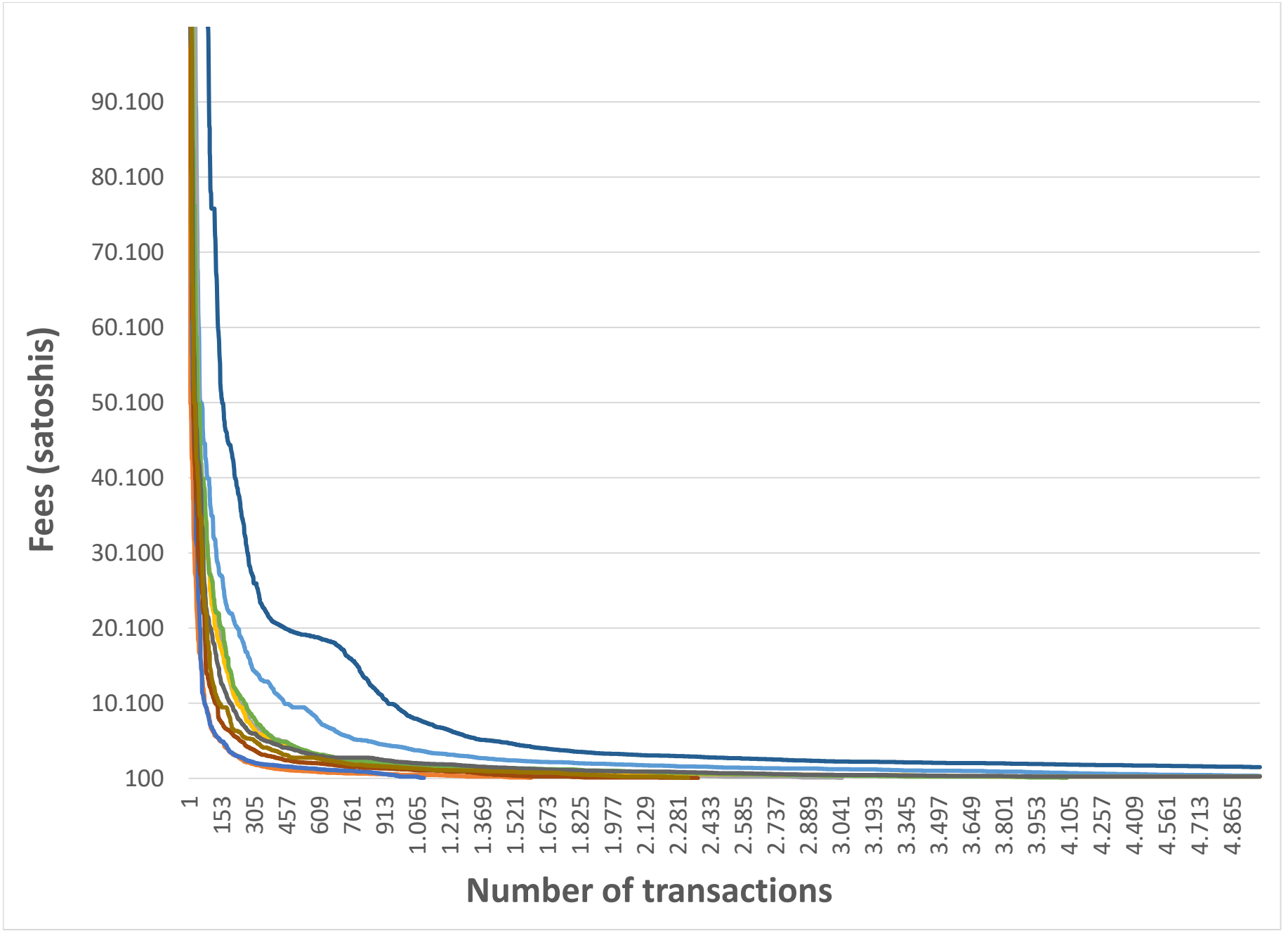

1,1E+09
1,0E+09
9,0E+08
8,0E+08
7,0E+08
6,0E+08
5,0E+08
4,0E+08
3,0E+08
2,0E+08
1,0E+08
0,0E+00
Total number of transactions BTC
10/06/2010
10/06/2011
10/06/2012
10/06/2013
10/06/2014
10/06/2015
10/06/2016
10/06/2017
10/06/2018
10/06/2019
10/06/2020
10/06/2021
10/06/2022
10/06/2023
10/06/2024
Date

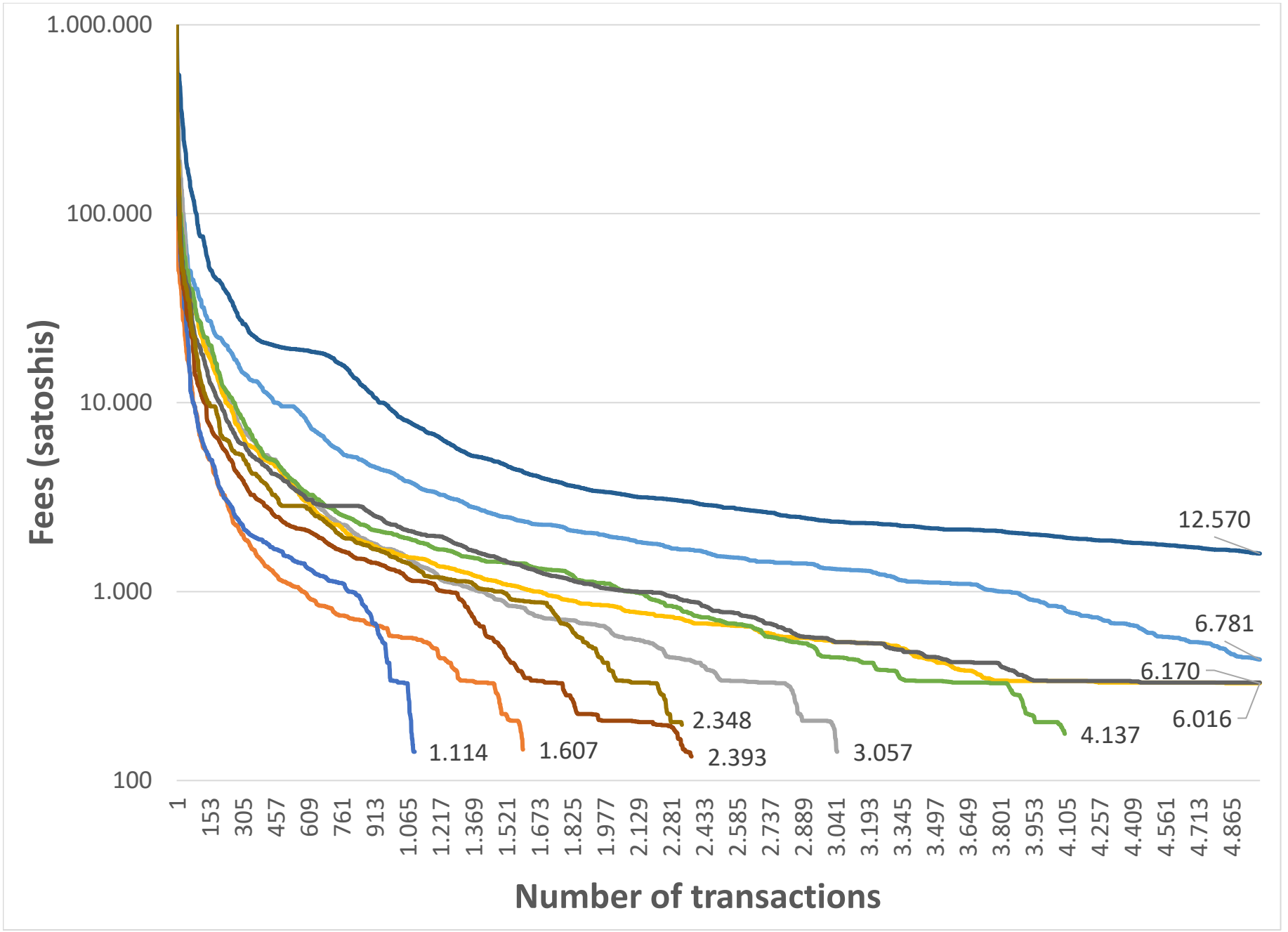

300.000.000
250.000.000
200.000.000
150.000.000
100.000.000
50.000.000
0
Mempool size (Bytes)
1st period of analsyis
2nd period of analsyis
01-09-2020
01-11-2020
01-01-2021
01-03-2021
01-05-2021
01-07-2021
01-09-2021
01-11-2021
01-01-2022
01-03-2022
01-05-2022
01-07-2022
01-09-2022
01-11-2022
01-01-2023
01-03-2023
01-05-2023
01-07-2023
01-09-2023
01-11-2023
01-01-2024
Date

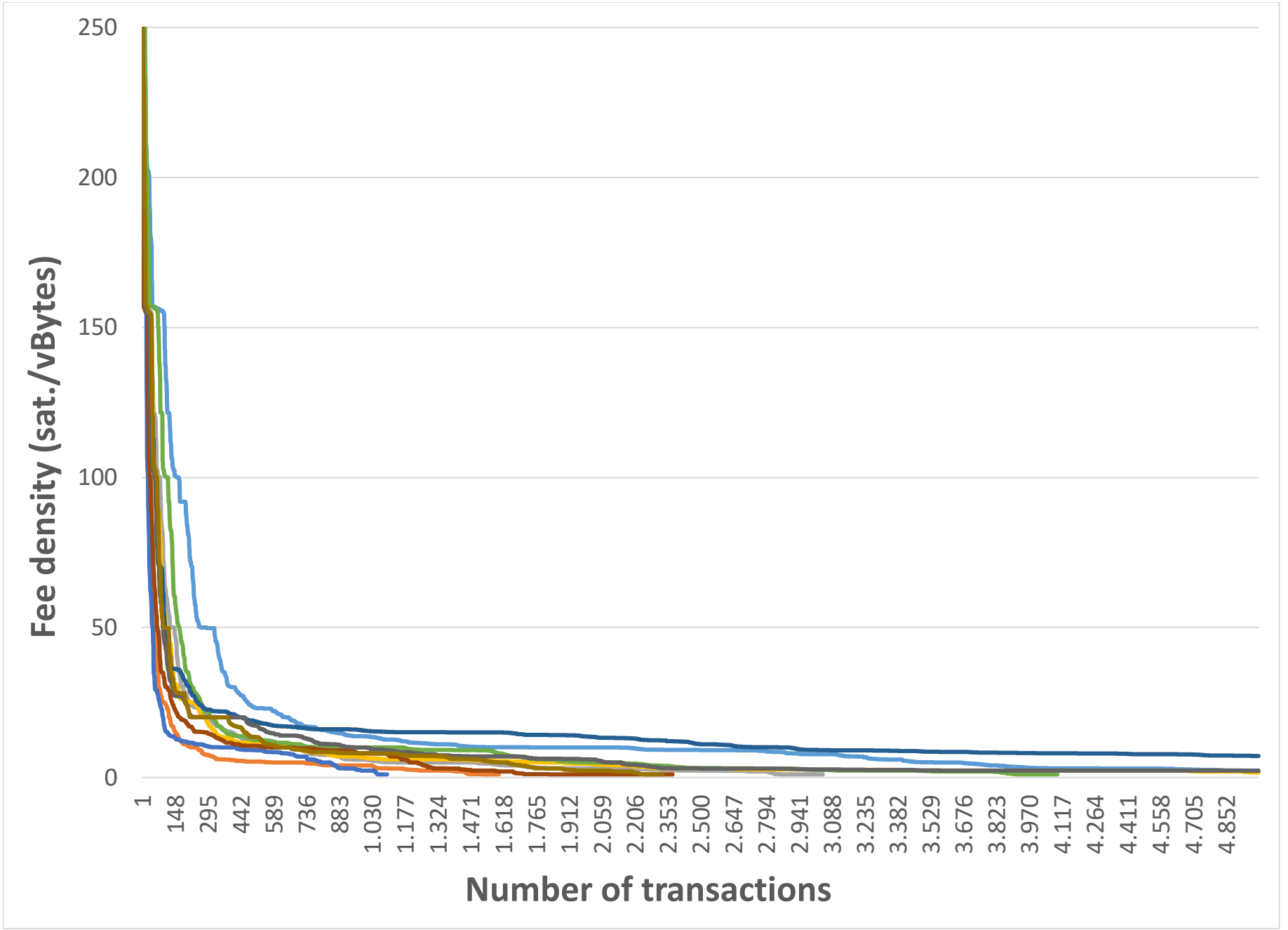

Recurrent reading of mempool
Mempool content (transaction fees, nb or size)
...
...
t
Arrival of new blocks
Legend
Accesses to Mempool discarded
Accesses to Mempool generating CSV files
Missing content
Mempool content
Arrival of new blocks to the blockchain

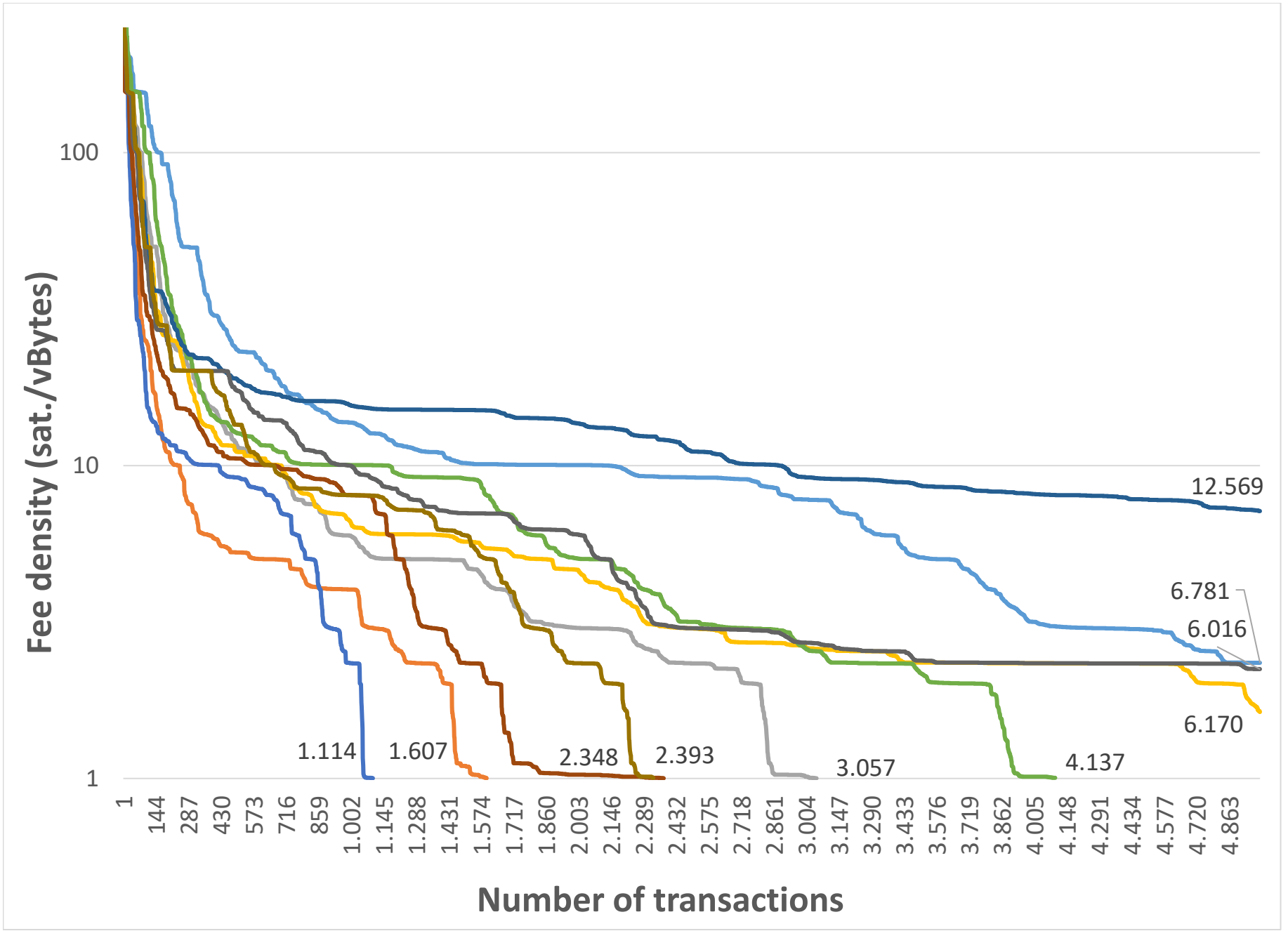

Current
time
1.- Chainstate.
Get last block
2.- Get previous
blocks
t
Confirmed
blocks

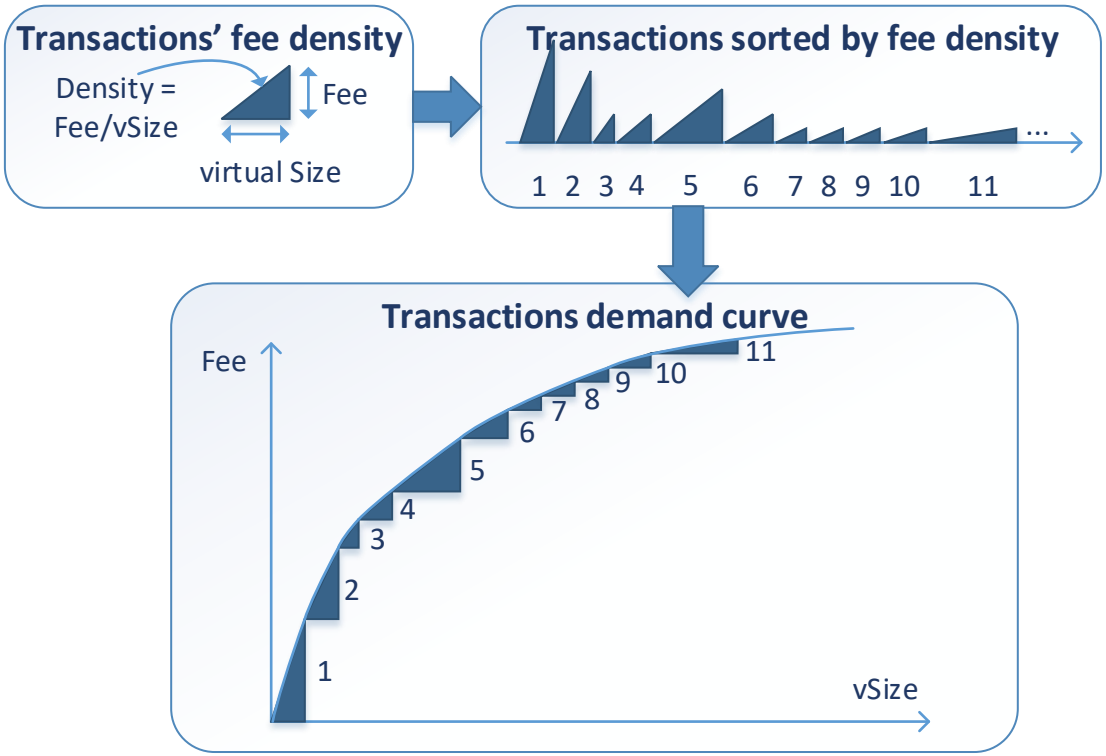

Current
time
Recurrent reading of
Chainstate.
Get last block
...
t
Arrival of new
blocks
...

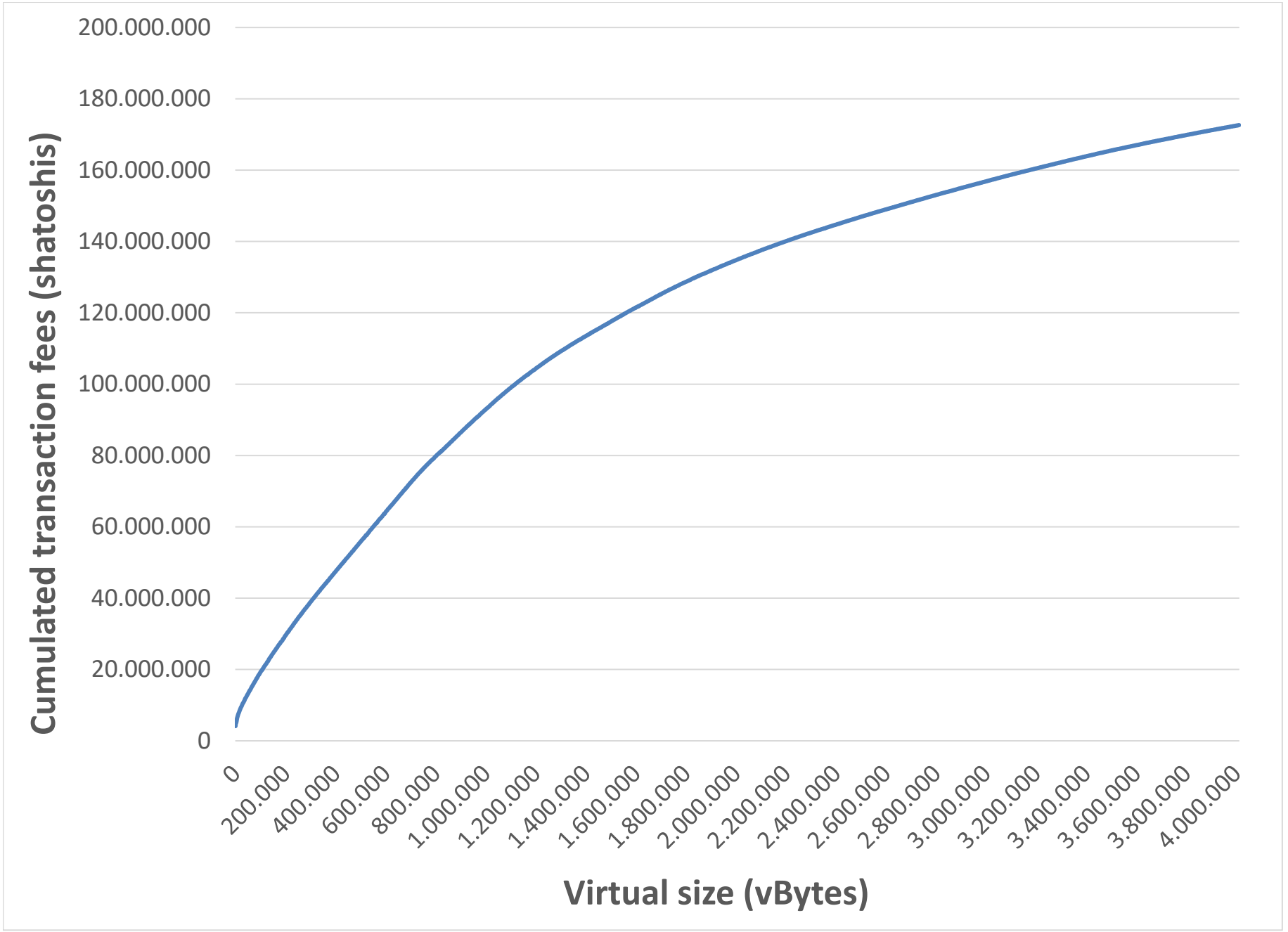

Fees (satoshis)
90.100
80.100
70.100
60.100
50.100
40.100
30.100
20.100
10.100
100
1
153
305
457
609
761
913
1.065
1.217
1.369
1.521
1.673
1.825
1.977
2.129
2.281
2.433
2.585
2.737
2.889
3.041
3.193
3.345
3.497
3.649
3.801
3.953
4.105
4.257
4.409
4.561
4.713
4.865
Number of transactions

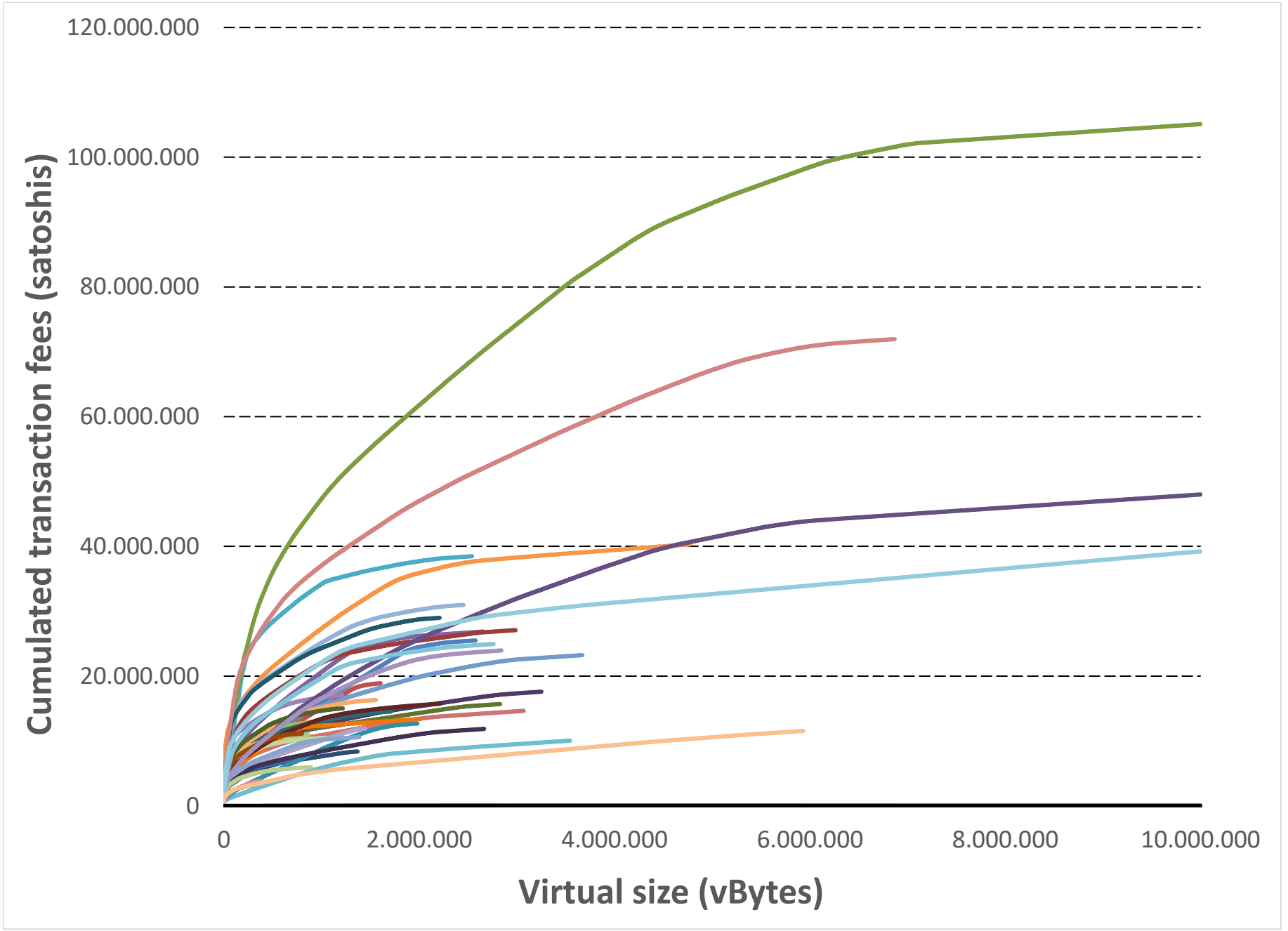

1.000.000
100.000
10.000
1.000
100
Fees (satoshis)
1
153
305
457
609
761
913
1.065
1.217
1.369
1.521
1.673
1.825
1.977
2.129
2.281
2.433
2.585
2.737
2.889
3.041
3.193
3.345
3.497
3.649
3.801
3.953
4.105
4.257
4.409
4.561
4.713
4.865
Number of transactions
12.570
6.781
6.170
6.016
4.137
3.057
2.348
2.393
1.607
1.114

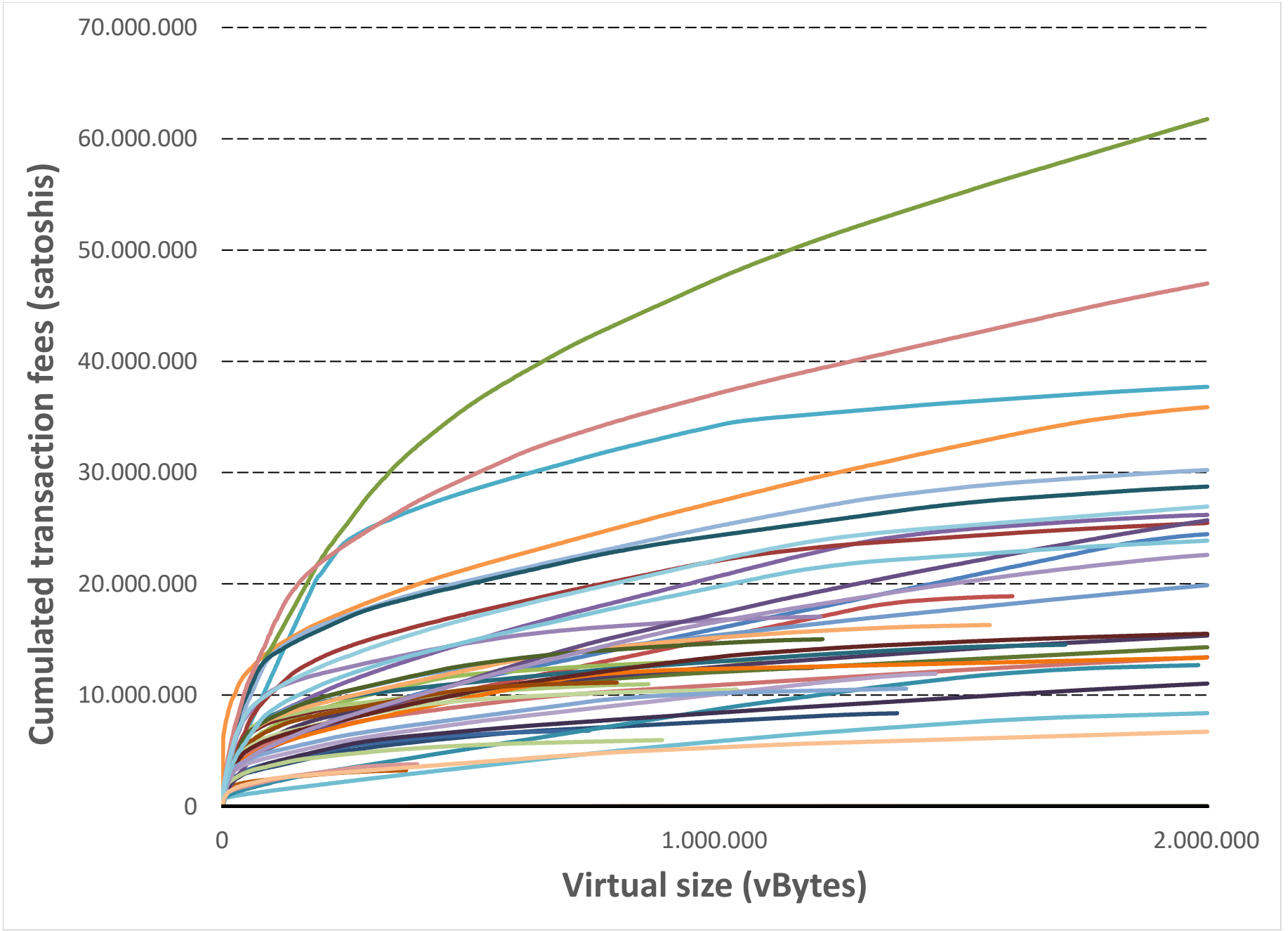

250
200
150
100
50
0
Fee density (sat./vBytes)
1
148
295
442
589
736
883
1.030
1.177
1.324
1.471
1.618
1.765
1.912
2.059
2.206
2.353
2.500
2.647
2.794
2.941
3.088
3.235
3.382
3.529
3.676
3.823
3.970
4.117
4.264
4.411
4.558
4.705
4.852
Number of transactions

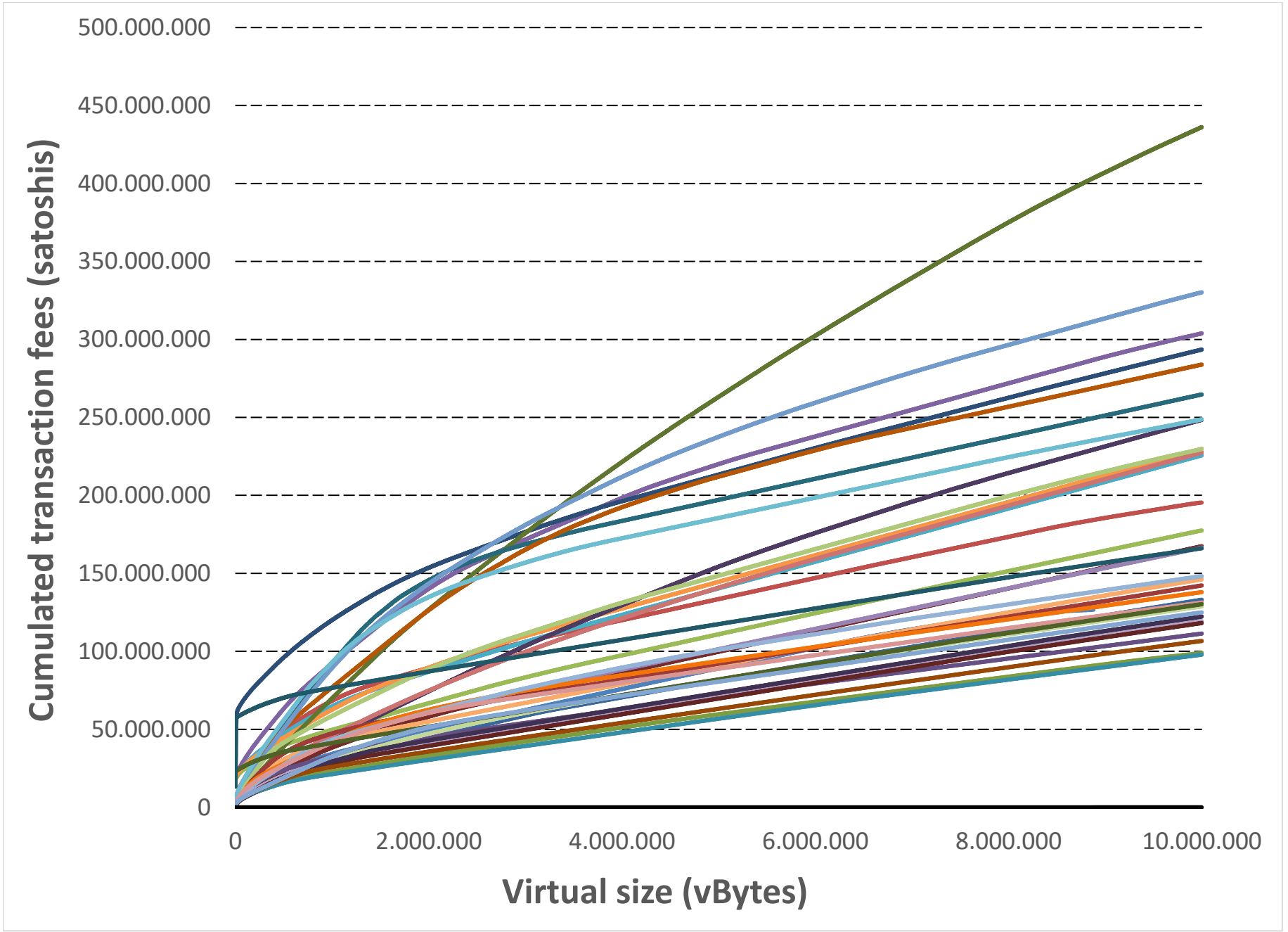

Fee density (sat./vBytes)
100
10
1
12.569
6.781
6.016
6.170
4.137
3.057
2.393
2.348
1.607
1.114
1
144
287
430
573
716
859
1.002
1.145
1.288
1.431
1.574
1.717
1.860
2.003
2.146
2.289
2.432
2.575
2.718
2.861
3.004
3.147
3.290
3.433
3.576
3.719
3.862
4.005
4.148
4.291
4.434
4.577
4.720
4.863
Number of transactions

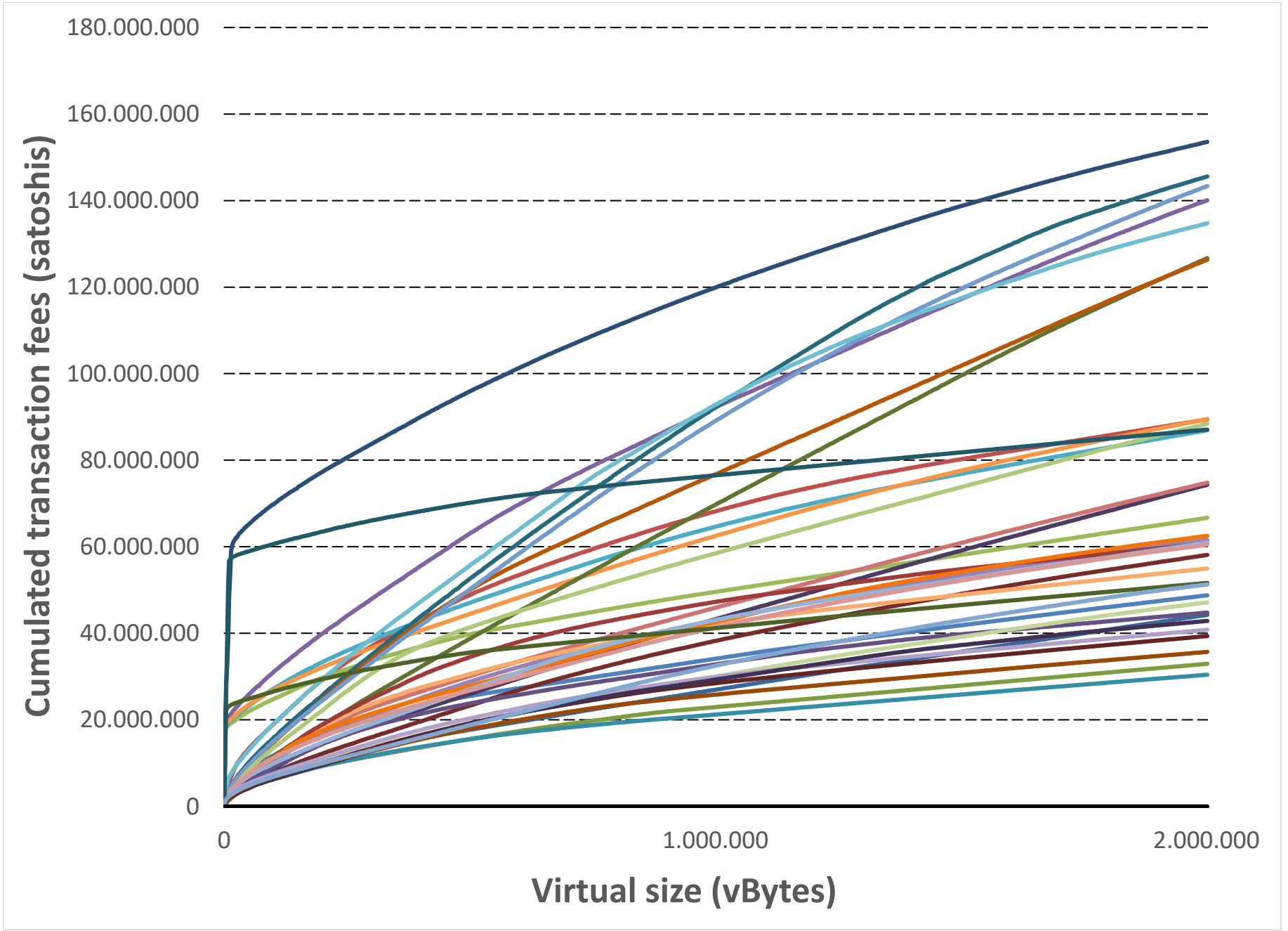

Transactions' fee density
Density =
Fee/vSize
Fee
virtual Size
Transactions sorted by fee density
1 2 3 4 5 6 7 8 9 10 11
...
Transactions demand curve
Fee
vSize
1
2
3
4
5
6
7
8
9
10
11

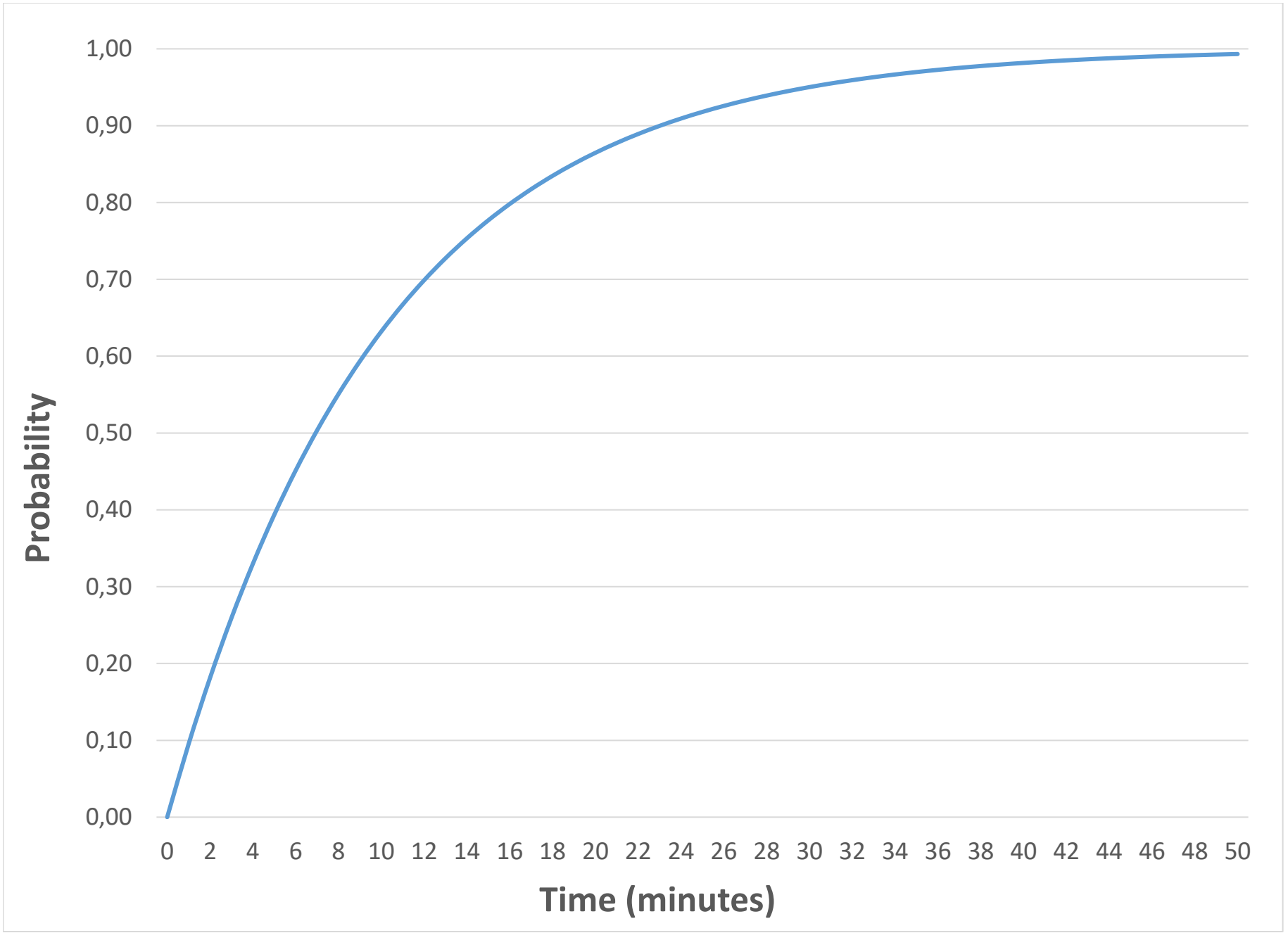

Cumulated transaction fees (shatoshis)
200.000.000
180.000.000
160.000.000
140.000.000
120.000.000
100.000.000
80.000.000
60.000.000
40.000.000
20.000.000
0
0
200.000
400.000
600.000
800.000
1.000.000
1.200.000
1.400.000
1.600.000
1.800.000
2.000.000
2.200.000
2.400.000
2.600.000
2.800.000
3.000.000
3.200.000
3.400.000
3.600.000
3.800.000
4.000.000
Virtual size (vBytes)

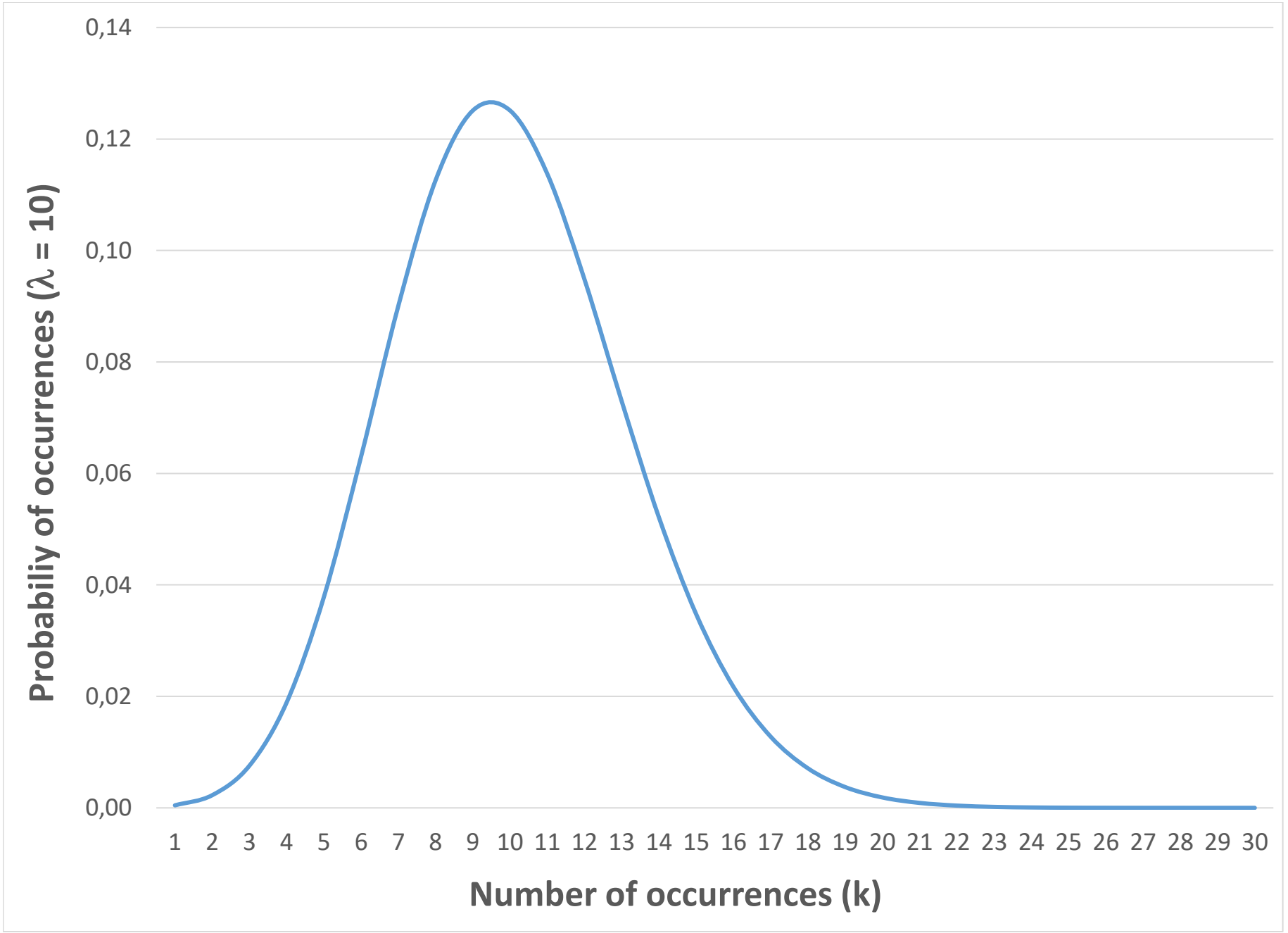

120.000.000
100.000.000
80.000.000
60.000.000
40.000.000
20.000.000
0
Cumulated transaction fees (satoshis)
0
2.000.000
4.000.000
6.000.000
8.000.000
10.000.000
Virtual size (vBytes)

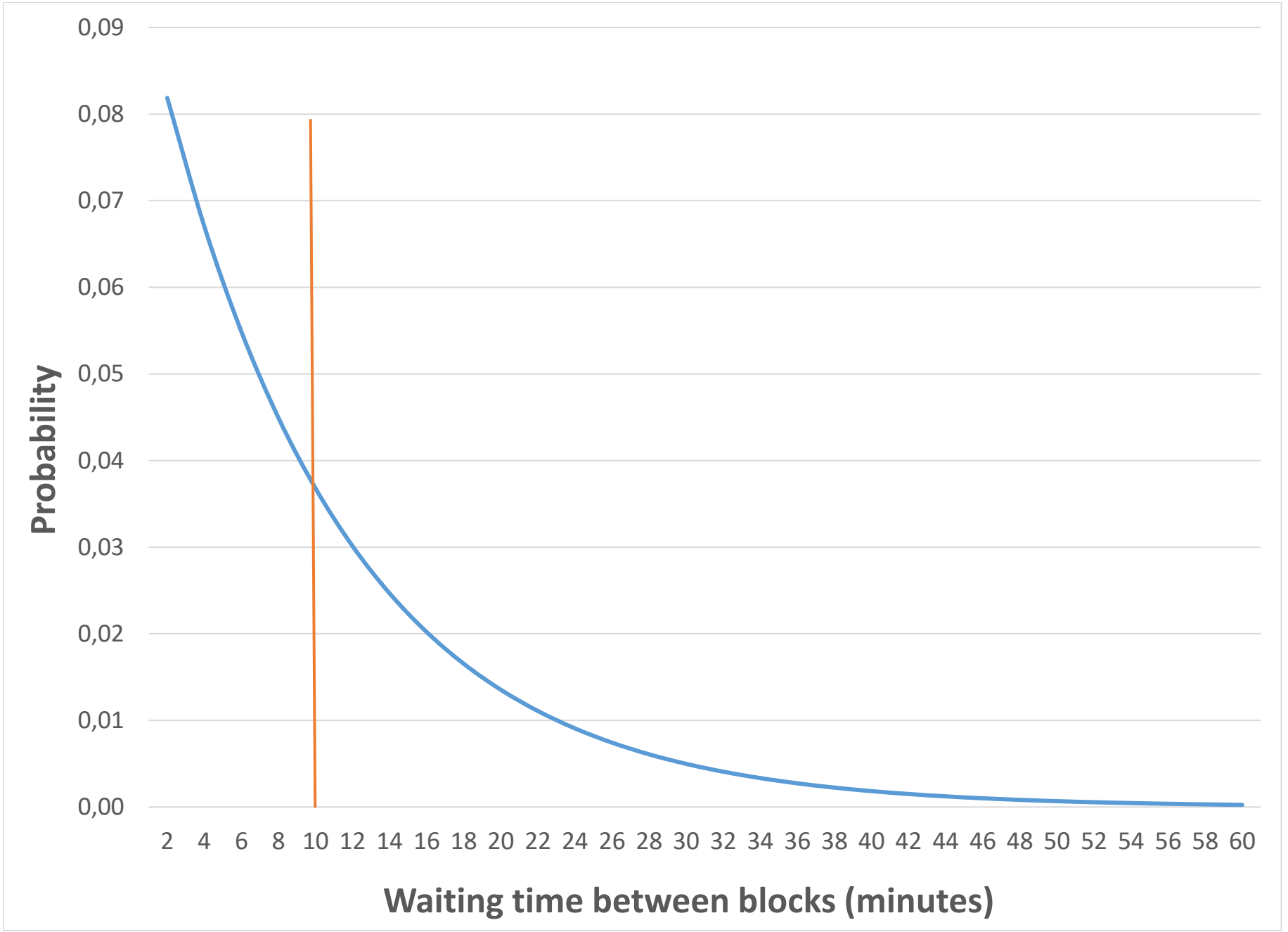

70.000.000
60.000.000
50.000.000
40.000.000
30.000.000
20.000.000
10.000.000
0
Cumulated transaction fees (satoshis)
0
1.000.000
2.000.000
Virtual size (vBytes)

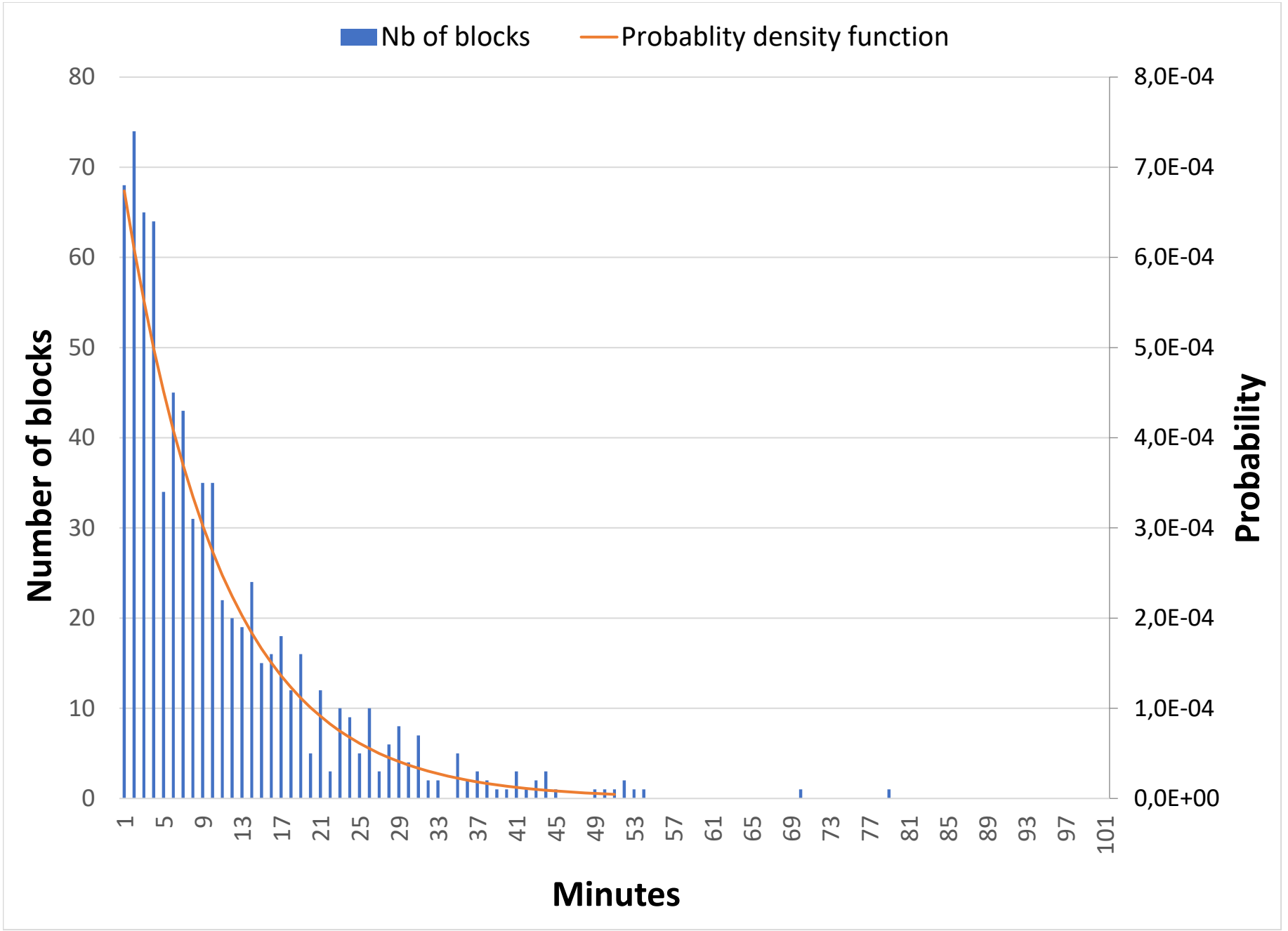

500.000.000
450.000.000
400.000.000
350.000.000
300.000.000
250.000.000
200.000.000
150.000.000
100.000.000
50.000.000
0
Cumulated transaction fees (satoshis)
0
2.000.000
4.000.000
6.000.000
8.000.000
10.000.000
Virtual size (vBytes)

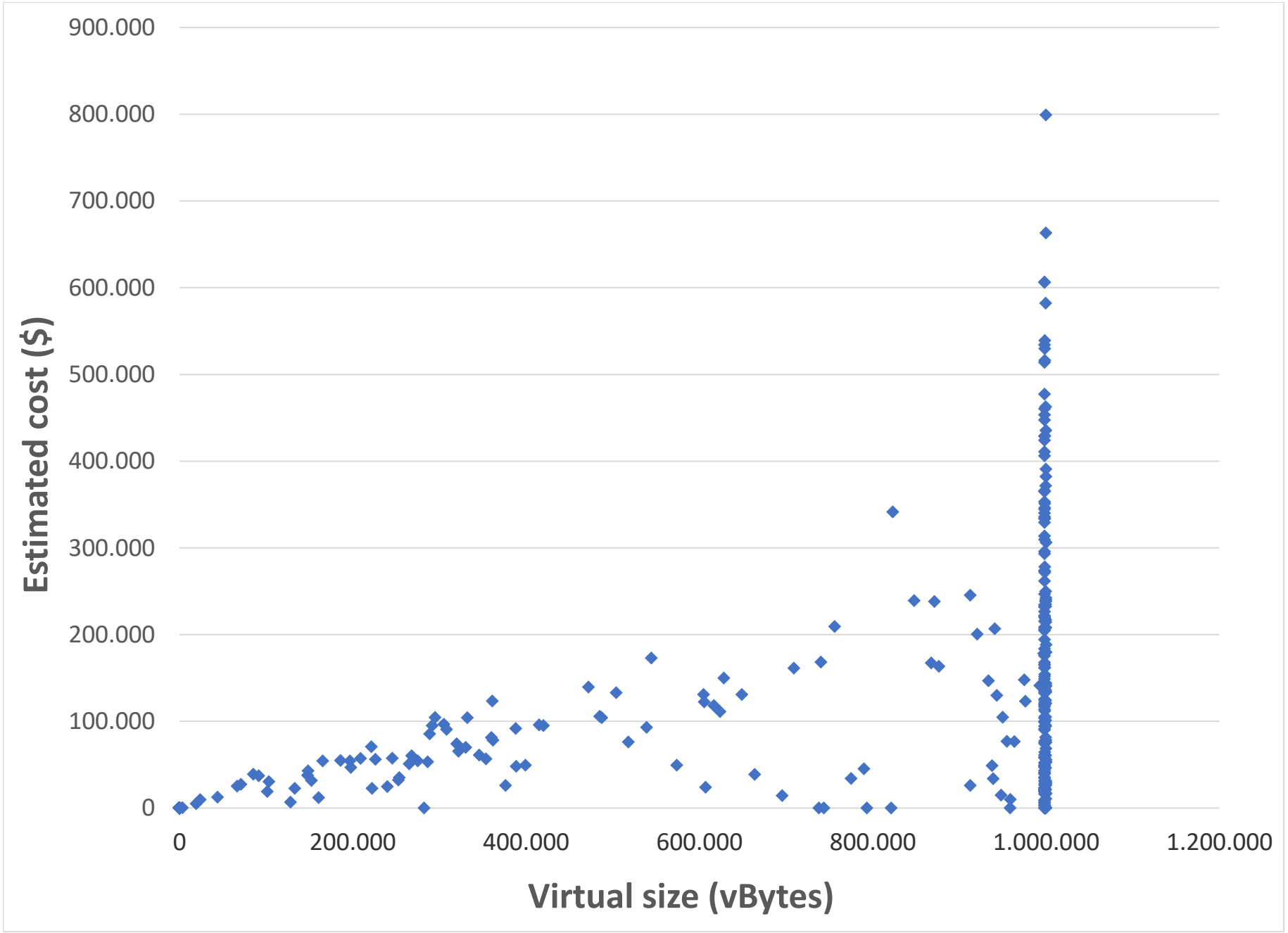

180.000.000
160.000.000
140.000.000
120.000.000
100.000.000
80.000.000
60.000.000
40.000.000
20.000.000
0
Cumulated transaction fees (satoshis)
0
1.000.000
2.000.000
Virtual size (vBytes)

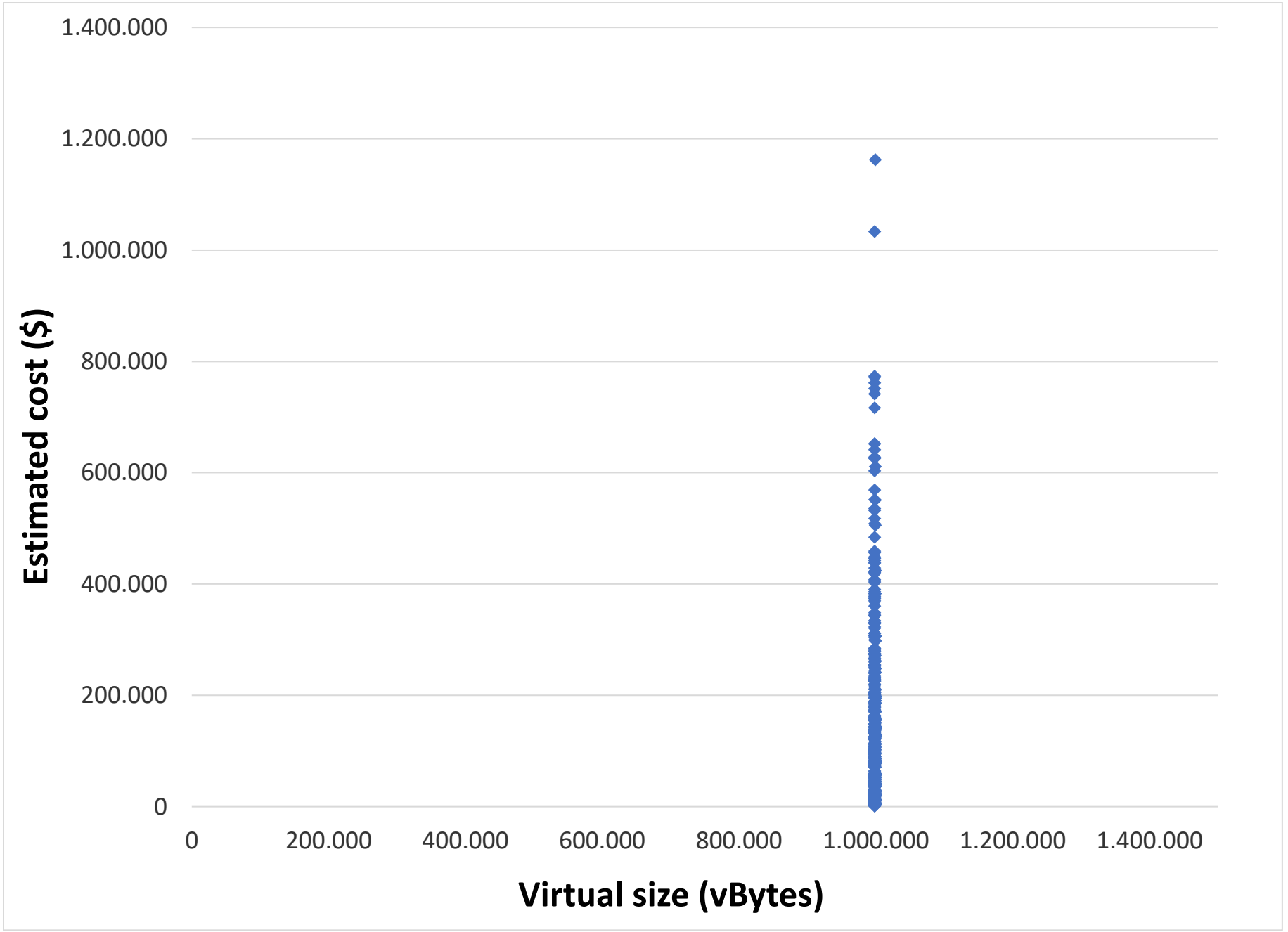

1,00
0,90
0,80
0,70
0,60
0,50
0,40
0,30
0,20
0,10
0,00
Probability
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
Time (minutes)

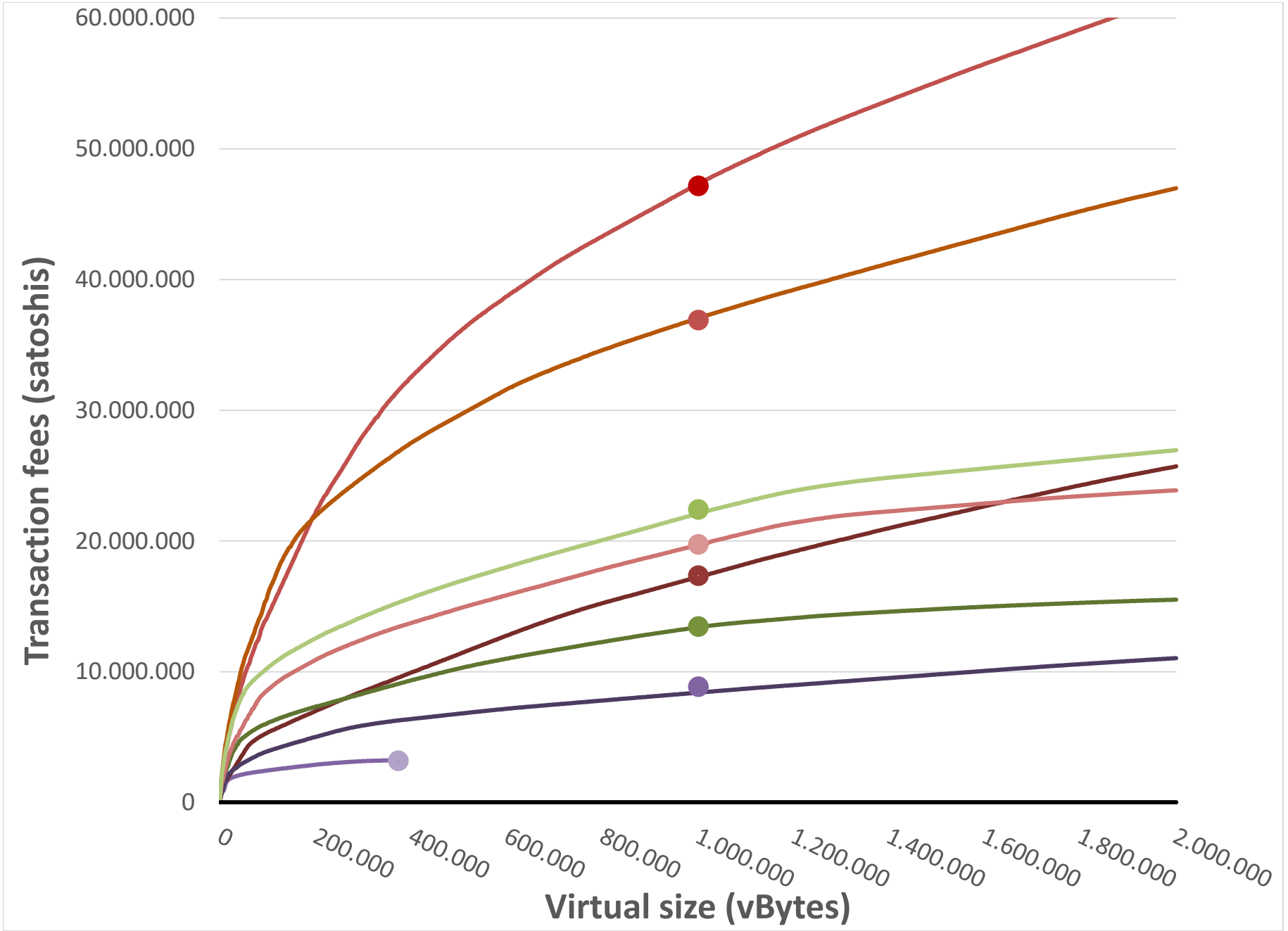

0,14
0,12
0,10
0,08
0,06
0,04
0,02
0,00
Probabiliy of occurrences (λ = 10)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Number of occurrences (k)

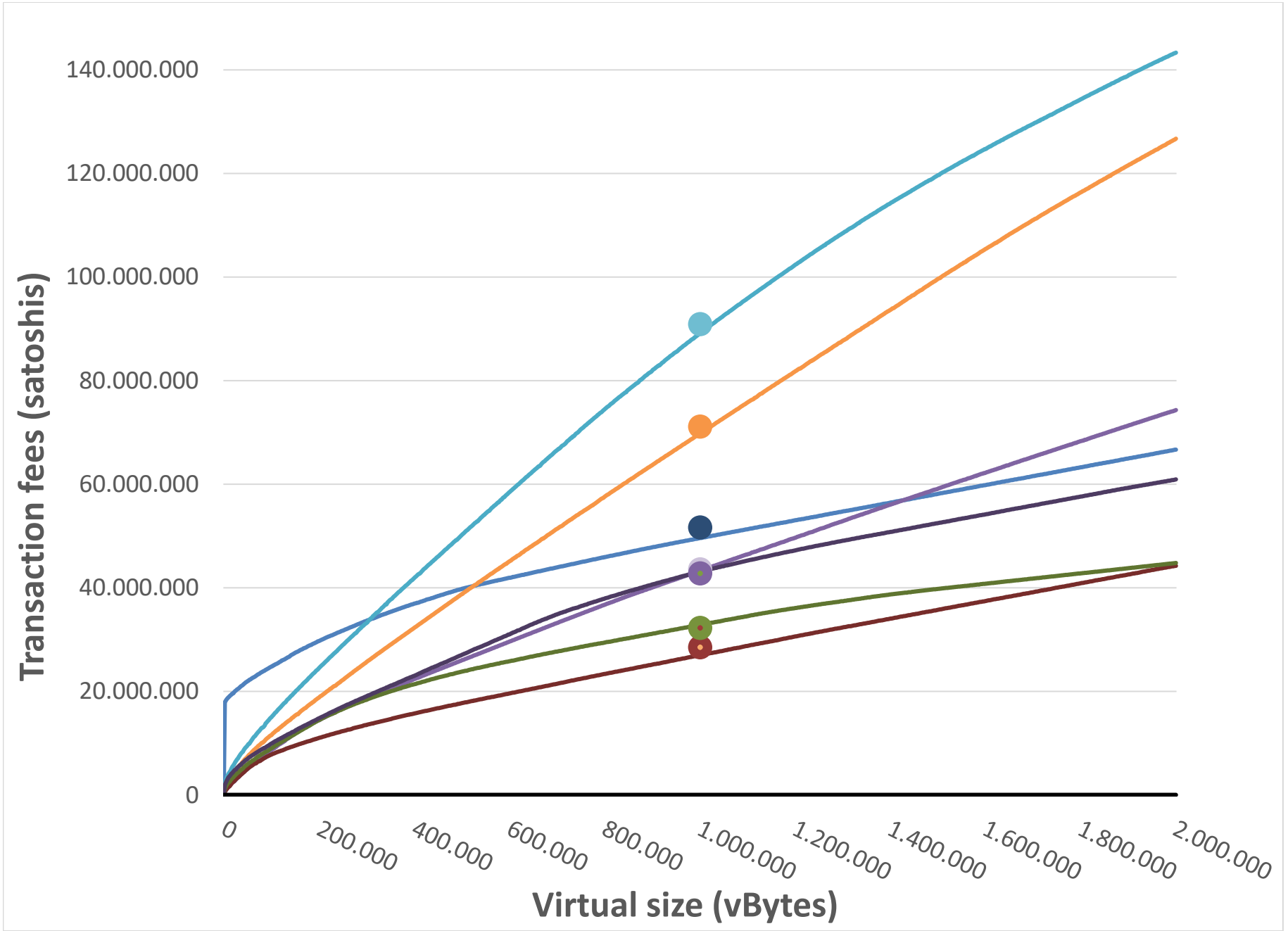

0,09
0,08
0,07
0,06
0,05
0,04
0,03
0,02
0,01
0,00
Probability
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60
Waiting time between blocks (minutes)


Nb of blocks
Probablity density function
Number of blocks
Probability
Minutes
80
70
60
50
40
30
20
10
0
8,0E-04
7,0E-04
6,0E-04
5,0E-04
4,0E-04
3,0E-04
2,0E-04
1,0E-04
0,0E+00
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
61
65
69
73
77
81
85
89
93
97
101


900.000
800.000
700.000
600.000
500.000
400.000
300.000
200.000
100.000
0
Estimated cost ($)
0
200.000
400.000
600.000
800.000
1.000.000
1.200.000
Virtual size (vBytes)


1.400.000
1.200.000
1.000.000
800.000
600.000
400.000
200.000
0
Estimated cost ($)
0
200.000
400.000
600.000
800.000
1.000.000
1.200.000
1.400.000
Virtual size (vBytes)


60.000.000
50.000.000
40.000.000
30.000.000
20.000.000
10.000.000
0
Transaction fees (satoshis)
0
200.000
400.000
600.000
800.000
1.000.000
1.200.000
1.400.000
1.600.000
1.800.000
2.000.000
Virtual size (vBytes)


140.000.000
120.000.000
100.000.000
80.000.000
60.000.000
40.000.000
20.000.000
0
Transaction fees (satoshis)
0
200.000
400.000
600.000
800.000
1.000.000
1.200.000
1.400.000
1.600.000
1.800.000
2.000.000
Virtual size (vBytes)

Transactions market in Bitcoin. Empirical analysis of the demand and supply block space curves

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General comments from authors

We thank the editor and reviewers for the valuable comments, which have led to relevant improvements in the paper. We have carefully reviewed the paper according to the suggestions, and made significant changes before resubmitting this updated version.

The answer/comments to the different reviewers' recommendations are summarized in the paragraphs below.

In this version, the introduction has been shortened, and much of the previous section §2 has been removed, getting to the point. This section §2 has been replaced by a new one, including an up-to-date literature review, and research motivation. The previously missing methodology and research questions have been introduced in a new section (§3). On the other hand, the data sources and data acquisition process are described in a specific section (§4), separately from the presentation of results and findings, which are detailed in a (hopefully) clearer way in sections §5 and §6.

Additionally, we amended the footnotes and some figures in order to present updated information.

Is should be noted that the length of the document has been reduced (from 28 to 26 pages, excluding references and final statements & declarations), while strengthening the information provided.

After having addressed the different comments, we hope the manuscript will now be suitable for publication.

Comments to reviewers

Dear Sirs,

Following your kind invitation, we have carefully revised the manuscript, addressing the issues raised in the reviewers' comments. In this reviewers' file, we have outlined each change made to improve the article, as suggested by the reviewers. We are very grateful for the opportunity to resend a new version. All the comments have been carefully considered.

Reviewer #1

Dear Authors

The research covers a gap by conducting an empirical analysis of these curves in Bitcoin, based on an extensive dataset spanning two time periods in 2021 and 2023. Why?

The analysis is intentionally performed in these two specific time periods, due to the different mempool size during these periods, reflecting a lower/higher level of demand for space (respectively in 2021/2023) resulting from the transactions submitted to the network. This situation is shown in figure 4.b), reproduced below.

In this regard, the results show that an increase in the number of transactions in the mempool, shifts the demand curve upward (subsection §5.1), with an impact on the related transaction fees (which is consistent from an economic point of view).

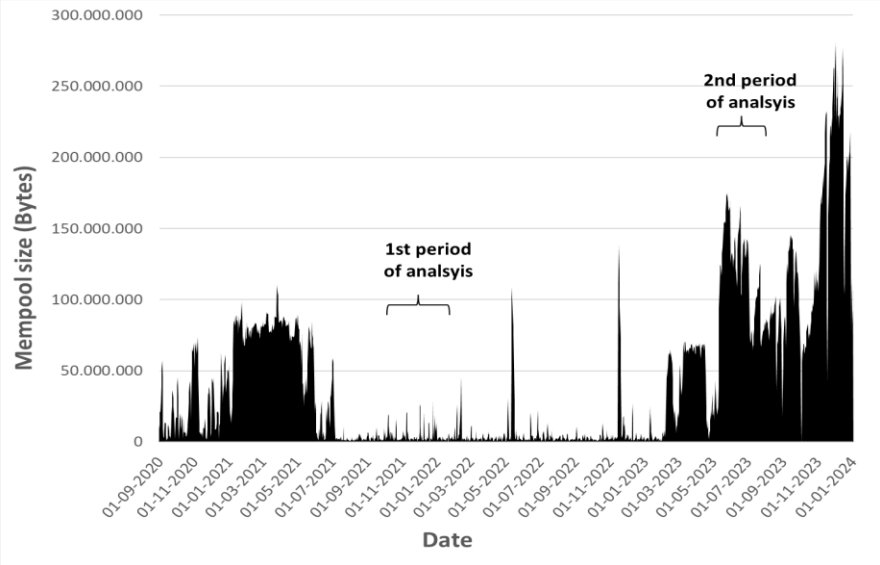

Figure 4.b)

Look at the below paper, I am surprised you didn't mentioned recent work in the manuscript. E.g.,

Mokni, K., El Montasser, G., Ajmi, A. N., & Bouri, E. (2024). On the efficiency and its drivers in the cryptocurrency market: the case of Bitcoin and Ethereum. Financial Innovation, 10(1), 39.

We appreciate the suggestion. A new subsection (§2.1) "*Transaction fees in the scientific literature*" has been included, allowing to better understand the background of the research. This subsection references recent work on the topic, for instance (non-extensive list):

- Hiraide, T., & Kasahara, S. (2023). Analysis of interaction between miner decision making and user action for incentive mechanism of bitcoin blockchain. *Frontiers in Blockchain*, *6*, 1067628. https://doi.org/10.3389/fbloc.2023.1067628
- Islam, N., Marinakis, Y., Olson, S., White, R., & Walsh, S. (2023). Is BlockChain Mining Profitable in the Long Run?. *IEEE Transactions on Engineering Management*, *40*(2), 386-399. https://doi.org/10.1109/TEM.2020.3045774
- Jain, A., Jain, C., & Krystyniak, K. (2023). Blockchain transaction fee and Ethereum Merge. *Finance Research Letters*, *58*, 104507. https://doi.org/10.1016/j.frl.2023.104507
- Jia, D., & Li, Y. (2023). Bounded pool mining and the bounded Bitcoin price. *Finance Research Letters*, *52*, 103529. https://doi.org/10.1016/j.frl.2022.103529
- Kim, D., Ryu, D., & Webb, R. I. (2023). Determination of equilibrium transaction fees in the Bitcoin network: A rank-order contest. *International Review of Financial Analysis*, *86*, 102487. https://doi.org/10.1016/j.irfa.2023.102487
- Li, Z., Li, J., & Zhou, K. (2023). Bitcoin transaction fees and the decentralization of Bitcoin mining pools. *Finance Research Letters*, *58*, 104347. https://doi.org/10.1016/j.frl.2023.104347
- Monem, M., Hossain, M. T., Alam, M. G. R., Munir, M. S., Rahman, M. M., AlQahtani, S. A., Almutlaq, S., & Hassan, M. M. (2024). A sustainable Bitcoin blockchain network through introducing dynamic block size adjustment using predictive analytics. *Future Generation Computer Systems*, *153*, 12-26. https://doi.org/10.1016/j.future.2023.11.005
- Shang, G., Ilk, N., & Fan, S. (2023). *Need for speed*, but how much does it cost? Unpacking the fee-speed relationship in Bitcoin transactions. *Journal of Operations Management*, *69*(1), 102-126. https://doi.org/10.1002/joom.1202
- Wu, K., Shi, E., & Chung, H. (2024). Maximizing Miner Revenue in Transaction Fee Mechanism Design. 15th Innovations in Theoretical Computer Science Conference (ITCS 2024), 287, Schloss Dagstuhl- Leibniz-Zentrum fur Informatik GmbH, Dagstuhl Publishing. https://doi.org/10.4230/LIPIcs.ITCS.2024.98

In the introduction, the authors crafted the figures; however, it is advisable to relocate these visual representations to the Methodology section for greater clarity and coherence.

Previous figure 1 has been duly updated, including current data, and reallocated to subsection §4.1 "*Data sources and rationale for selection of periods under analysis*", which explains why two time periods have been selected.

Additionally, a new section (§3) has been also added, to present the methodology and research questions. Indeed, it (hopefully) brings more clarity and coherence to the manuscript.

Finally, the proposed title has been slightly modified, more precisely expressing the subject of the manuscript.

Reviewer #2

This article performs an empirical analysis for the data spanning two time periods in 2021 and 2023 for Bitcoin to support the understanding of why Bitcoin transaction fees are subject to high volatility and how the protocol evolutions made to date have shifted the supply curve. On the other hand, demand curve turns out to be extremely dynamic. The inelasticity of the supply curve, described by an exponential distribution, explains the sharp variations in transaction fees observed under demand shocks.

I have read the paper carefully and find:

1) The introduction section is not up to mark and is unable to highlight the clear contribution in it's current form.

Following the wise recommendation of the reviewer, the introductory section has been shortened and reviewed, whereas the contents of the previous section §2 have been largely removed (and replaced by a new one), getting to the point. Moreover, the general structure of the manuscript has been rebuilt for greater clarity; we are confident that this new structure allows for a better understanding of the background, motivation and research methodology.

2) The introduction section lacks the motivation to carry out this study where it was too general from the start. The paper introduces figure and discusses in the first few lines that makes it further weak where it was generally better to focus on the motivation behind the essay.

We agree it is appropriate to stress the motivation behind the work, certainly presented in a very generic form in the first version of the manuscript.

The new subsection §2.2 included in the updated version ("*Research motivation*") hopefully offers a better view on the motivation. Certain generalities have been removed (figures, text, paragraphs), trying to focus on the description of the objectives, the research means and process, and the results obtained.

3) There was no research objectives and research questions.

In addition to the new subsection §2.2 ("*Research motivation*"), a new section §3 ("*Methodology and research questions*") has been considered to this purpose.

In order not to mix up different information, the data sources and data acquisition process are also presented in a specific section (§4), which provides details on how to access the datasets and source code (through an open access repository), pursuing transparent practices and making possible the reproducibility of the research. This information was previously integrated in a common section (§4) together with the obtained transactions' demand and supply curves.

4) The paper requires proper literature review section to highlight the progress of existing literature and how the existing literature left the research gap that this study is going to fill in.

Following this relevant reviewer´s opinion, the literature review has been included in the new subsection §2.1, where the most relevant references on the topic have been gathered. It is to be noted that it has been complemented with recent references, better exposing the research gap and justifying the gap-spotting approach followed.

5) The heading 4.2 requires better adjustment.

Previous section §4 (including §4.2 "*Contributions*"), together with §5 have also been reviewed and rearranged, to provide a more logical structure.

6) There was no discussion on the findings. This section is entirely missing.

Updated section §6 ("*Findings and discussions*") integrates the analysis of results, contributions and limitations, as a preamble to the conclusions and future research propositions.

7) It was better to have a clear policy message in the form of theoretical and practical policy headings. however, its missing in its current form.

The implications for practice and insight on theoretical characteristics of the transactions market in Bitcoin are briefly presented in section (§7 "*Conclusions and research propositions*"). We are open to incorporate other changes allowing to improve the manuscript, as with the integration of the other comments.

Overall, paper requires drastic adjustment to be considered among the candidate articles.

Significant readjustment of the initial version of the paper has been performed, hopefully allowing to improve the understanding of the objectives and introducing the methodology and research questions in an appropriate way, while presenting the results in a clearer manner. Some of these information was previously poor or directly missing. In our view, the manuscript quality has improved, thanks to the implementation of the suggestions and comments.

Finally, it should be noted that the title has been slightly modified, aiming to more precisely match the subject of the manuscript.