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Emergence of a scale-free network topology in a blockchain-based Shared Manufacturing

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***Abstract*—The development of smart manufacturing modes, following the guidelines of the Industry 4.0 paradigm, suggests the use of new technologies to ensure greater agility, individualization and personalization. Blockchain technology, as one of the new technologies, enables decentralization and trustless environment, however, on the other hand, introduces scalability limitations into the system. This paper presents an exploratory network analysis of money flow in blockchain-based Shared Manufacturing. We conduct an experiment in the form of an online game with people in order to obtain real data on network of prosumers in the said concept. We describe a relation between the money flow network, the supply of services in the market and the state of occupancy of the blockchain network in blockchain-based Shared Manufacturing. A greater supply of services in the market and a more occupied blockchain network causes a tendency for money flow network to organize like scale-free networks, however, this claim will be further verified in future work.**

***Index Terms*—Shared Manufacturing; Blockchain; Network analysis**

I. Introduction

Advances in fields of digitalization and servitization in past years have stimulated the development of new modes of smart manufacturing. The requirements collected under the term Industry 4.0 have directed manufacturing systems towards agility, individualization and personalization [1]. One of the new modes is Shared Manufacturing [2] (SharedMfg). The main property of the concept is that it cuts vertically into the structure of production systems, where an individual part of the production system is placed directly on the market in the form of a service. It reaches an individual level and thus increases the sociality of manufacturing, which can benefit the participants (both consumers and providers) with improved capabilities and competitiveness, boosting reciprocal business models.

Blockchain technology has emerged with the arrival of Bitcoin [3] as an alternative to the traditional monetary systems. It is a decentralized banking system organized in the form of a network of nodes that form a distributed database of all transactions that have occurred on the network. Transactions are written in blocks that occur in a certain time interval and the blocks are connected in a chain. The main property of the blockchain technology is that the network forms a consensus on confirmed transactions in a decentralized way, so it is not necessary for users to trust each other [4]. With the evolution of blockchain technology, different implementations of the consensus mechanism have emerged, such as Proof-of-Work (PoW), Proof-of-Stake (PoS), Proof-of-Authority (PoA) and many more. PoW is the consensus mechanism used in Bitcoin blockchain networks, presented by Nakamoto [3]. In PoW nodes compete with each other, trying to solve cryptographic puzzles in order to add new blocks to the blockchain and earn themselves a reward. One of the main disadvantages of the PoW mechanism is power consumption [5], due to the constant need of computing resources in order to generate new blocks. PoS was presented as an answer to the mentioned problem, first introduced by King et al. [6]. In PoS, a block generator is chosen on the basis of its proportional stake in the network that is its wealth in terms of that cryptocurrency. The chosen node uses a digital signature to prove its ownership over the stake instead of solving a complicated hash problem [7].

The new SharedMfg concept proposes an approach in which resource sharing is at all levels of manufacturing systems. Given that this concept allows the integration of smaller production systems and subsystems that are in traditional systems connected more locally [8], new connections in the network will also be formed at the global level. This raises the problem of how to effectively organize such a large number of autonomous production units (APUs) that do not trust each other into a network of prosumers. Solutions have been proposed where the platform that took care of aggregation was implemented using blockchain technology [9], [10]. Blockchain technology with its properties allows transactions between individual entities to be carried out in a decentralized manner without centralized intermediaries. On the other hand, blockchain technology imposes certain restrictions on SharedMfg. The problem with blockchain technology is network scalability [11]. The frequency of transaction validation is limited by the speed at which information is propagated

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across the network [12], and blockchain networks are often congested with transactions awaiting confirmation. Such congestion causes transaction costs to rise as competition between transactions occurs in order to be confirmed as quickly as possible [13].

The aim of this work is to explore how the properties of blockchain technology affect the prosumer network and how this is reflected in the performance of the SharedMfg concept. The concept of blockchain-based SharedMfg is based primarily on the approach of decentralized organization of individual production units in the global manufacturing network. Therefore, it is important to analyze how the networks will be organized within the concept and whether the principle of decentralization, which is crucial for the operation of such a system, will remain through the operation of the system. The network analyses on existing blockchain applications have shown that the limitations of the technology affect the operation of such applications and may eventually lead to discouraging users from using such system [14]. The main research question is how the concept of blockchain-based SharedMfg affects the money flow network of prosumers that is formed in the system. Analyses have shown that in some existing permissionless blockchain networks, larger groups of transaction validators have emerged over time, acting together as one entity in the competition for transaction confirmation [15], [16]. Such nodes (with larger resources) have a higher payoff in participating in transaction validation [17], [18] and have economic incentives to collude and build stake market with only a small number of participants [19], therefore, we anticipated that when network occupancy increases due to blockchain technology limitations, a scale-free network organization based on the "rich get richer" principle would emerge.

The main contributions of the paper are summarized as follows:

- An experiment was performed with the participation of people in the form of an online game. Game design and implementation was done according to the concept of blockchain-based SharedMfg.
- Relation between the money flow network, the supply of services in the market and the state of occupancy of the blockchain network in blockchain-based SharedMfg is described, where a greater supply of services in the market and a more occupied blockchain network causes a tendency that money flow network would organize like scale-free networks.

II. Methods

A. Online game experiment

In reality there is no system that would implement the concept of blockchain-based SharedMfg and because the implementation of the concept is very complex, experiment was conducted to test the hypothesis in the form of an online game. The game tries to map the concept of blockchain-based SharedMfg into the virtual world. The experiment is based on the approaches similar to those used in the field of experimental economics [20]–[22]. Players in the game need to be incentivized to behave in the game as similarly as they would behave in the real world. Therefore, it is necessary to establish a reward system that ranks players according to their performance in the game. The ranking of players is done using two criteria. The primary criterion is development of their production system (production criterion), and the secondary criterion is the amount of assets they currently own (economic criterion).

The entities in the game are the players representing the Autonomous Production Units (APUs) in the SharedMfg concept and the blockchain network that takes care of the execution of transactions (Figure 1). APUs are manufacturing systems that can implement and offer their service in the market. Players are classified into three groups (service A, B and C) that offer the same type of service for of each group. An individual player offers a service that he performs for a certain time. By purchasing other two types of services, the player upgrades his APU and thus reduces the time to perform the service. Upgrading production is in accordance with a predefined production function, which determines how the time for performing the service changes with the number of upgrades. Medium of exchange is virtual money that all players have equal amount at the beginning of the game. The blockchain network in game implements the PoS consensus mechanism. Individual transactions are confirmed with constant frequency. The transaction, that is highest in the queue (offers the highest transaction fee as a reward to the validator) when confirmation is performed, is selected for confirmation. All confirmed transactions are shown in a table that is publicly available to all players. The blockchain network in game is also maintained by players, meaning they run network nodes and validate transactions. The reward from confirmed transactions is divided according to the share of the stake, as is usual in PoS blockchain networks.

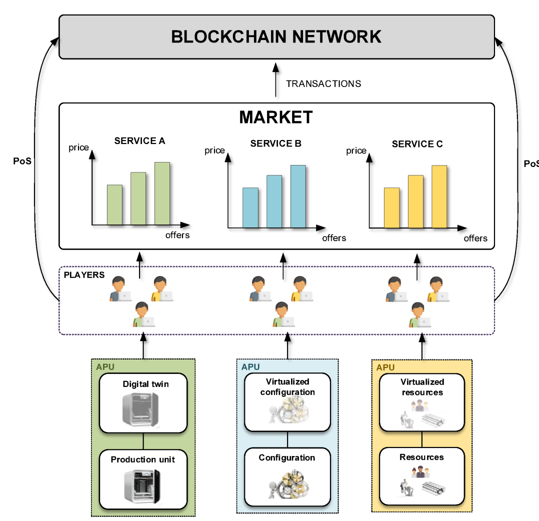

Fig. 1. Online game implementation of blockchain-based SharedMfg.

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The market operates on the principles of the free market, whereby the prices for services are self-regulated by buyers and sellers [23]. Players can offer their service in the market by placing an offer on the orderbook. The offer is defined by the type of service offered by the prosumer, the set price for the service and the time for performing the service. An individual player can perform only one service at a time, but can purchase several services at the same time. A player cannot purchase services that are of the same type as the service they offer themselves. The request to purchase the service is made by the player by specifying the transaction cost that he is willing to pay as a reward to the transaction validators. The generated transaction is queued for confirmation according to the specified transaction fee. The service is purchased when the transaction is confirmed. The service starts automatically when the transaction is confirmed and cannot be canceled. Multiple players can compete for the same service, the player whose transaction is first confirmed buys the service. For all others whose transactions are still in the queue, the transactions are deleted and refunded. The same happens if the service provider withdraws the service from the market before any transaction has been confirmed. Blockchain network maintenance is performed automatically and the player does not need to perform any actions. The increase or decrease of the share of stake is carried out in the form of transactions, which are treated in the same way as transactions for the purchase of services. The distribution of the transaction fee among the players for each individual confirmed transaction is also performed by the application itself. The decision process of an individual player is shown in the flowchart (Figure 2).

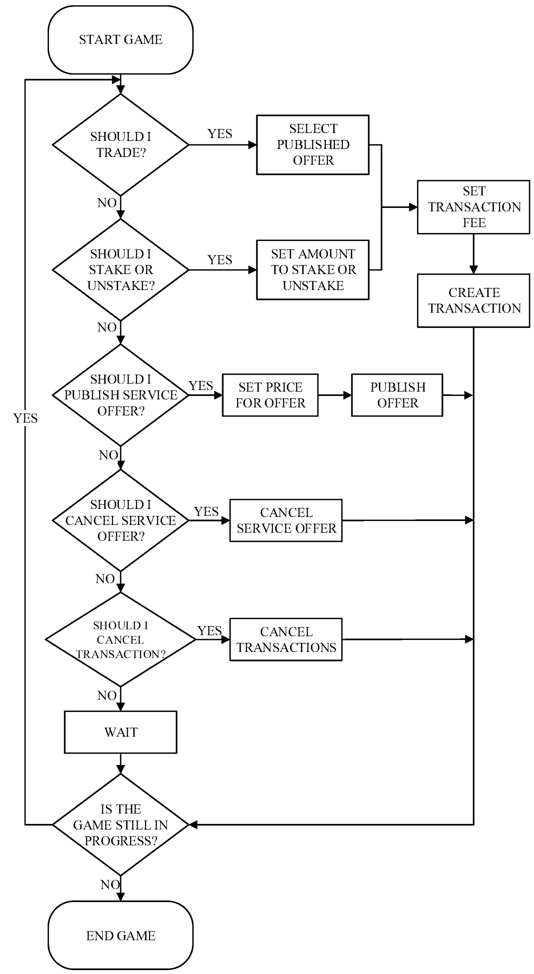

Fig. 2. Flowchart of player decision process.

The dynamics of the game is determined by three parameters, namely the number of players (n), the frequency of transaction confirmation on the blockchain network (f_{BC}) and the initial time for service (t_{inital}). The total initial production frequency ($f_{initial}$) is defined by Equation 1 and is lower than the the frequency of transaction confirmation (f_{BC}).

$$f_{initial} = \frac{n}{t_{inital}} \tag{1}$$

The production function, which defines how the time for service ($t_{service}$) changes with an APU upgrade, is defined by Equation 2. The time for service after the upgrade is defined by the current time for service. The exponent e defines by what proportion the time for service will decrease with each upgrade and n_u represents number of upgrades of the APU. The time limit (t_{limit}) represents the limit of the production function.

$$t_{service}(n_u + 1) = e * (t_{service}(n_u) - t_{limit}) + t_{limit} \tag{2}$$

Network analysis

Systems of interacting objects or individuals in natural and social sciences can be modeled with complex graphs whose nodes represent the dynamical units, and whose links stand for the interactions between them [24], [25]. Objects positioned in vertices of such graphs interact along edges with their neighbors. The structure of neighborhoods may have a quite complex topology resulting from various processes which describe mechanisms of growing graphs [26]. For most large networks the vertex connectivity significantly deviates from a Poisson distribution and it rather follows a scale-free power-law distribution. This feature was found to be a consequence of two generic mechanisms: (i) networks expand continuously by the addition of new vertices, and (ii) new vertices attach preferentially to vertices that are already well connected [27].

A unique property that scale-free systems possess is their invariance to changes in scale. Power-laws are the only functional form $f(x)$ that remains unchanged, apart from a multiplicative factor, under a rescaling of the independent variable x, being the only solution to the equation $f(\alpha x) = \beta f(x)$ [28]. Other mathematical laws that might describe similar qualitative properties of the network degree distribution will not satisfy an important condition of the scale invariance [29]. Unlike exponential networks, scale-free networks are extremely heterogeneous, their topology being dominated by a

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few highly connected nodes (hubs), which link the rest of the less connected nodes to the system. Any part of the scale-free network is stochastically similar to the whole network, and parameters are assumed to be independent of the system size [30]. Exploring several large databases describing the topology of large networks, Barabasi et al. [27] have shown that, independent of the system and the identity of its constituents, the probability $P(k)$ that a vertex in the network interacts with k other vertices decays as a power law, following Equation 3.

$$P(k) \sim k^{-\gamma} \tag{3}$$

The exponent γ is typically scattered in the range between 2 and 3. In this regime, the first moment of the degree distribution is finite but the second and higher moments diverge as $n \to \infty$. Consequently, scale-free networks in this regime are ultra-small world. For $\gamma > 3$, both the first and the second moments are finite. For all practical purposes the properties of a scale-free network in this regime are difficult to distinguish from the properties a random network of similar size [31].

Power-law distribution: In order to critically evaluate power-law distribution in empirical data, Clauset et al. [32] have defined a principled statistical framework for discerning and quantifying power-law behavior. The evaluation process is defined in three steps, namely estimation of parameters x_{min} in γ by fitting the power-law to the data using the maximum-likelihood method, calculation of the goodness-of-fit between the data and the power law, and comparison of the power law with alternative hypotheses.

A discrete power-law distribution is one described by a probability density $p(x)$ in Equation 4, where x_{min} is minimum degree cutoff ($x_{min} > 0$) and $\zeta(\gamma, x_{min})$ is the Hurwitz zeta function.

$$p(x) = \frac{x^{-\gamma}}{\zeta(\gamma, x_{min})} \tag{4}$$

Estimating γ correctly requires a value for the lower bound x_{min} of power-law behavior in the data. With the method of maximum likelihood we can derive maximum likelihood estimators of the scaling parameter for the discrete case. The likelihood function is defined with Equation 5.

$$L(\gamma) = -n \ln \zeta(\gamma, x_{min}) - \gamma \sum_{i=1}^{n} \ln x_i \tag{5}$$

Expression for $\hat{\gamma}$ (in Equation 6) in discrete case can be derived using approximation, where x_i, $i = 1, ..., n$, are the observed values of x such that $x_i \geq x_{min}$.

$$\hat{\gamma} \simeq 1 + n \left[\sum_{i=1}^{n} ln \frac{x_i}{x_{min} - \frac{1}{2}} \right]^{-1} \tag{6}$$

If we wish our estimate of γ to be accurate, we also need an accurate method for estimating x_{min}. If we choose too low a value for x_{min}, we will get a biased estimate of the scaling parameter, since we will be attempting to fit a power-law model to non-power-law data. On the other hand, if we choose too high a value for x_{min}, we are effectively throwing away legitimate data points $x_i < x_{min}$, which increases both the statistical error on the scaling parameter and the bias from finite size effects. There are different methods of choosing x_{min} that are structured and work relatively well [33], [34].

In order to calculate the goodness of fit between the data and the power law, we have to use some kind of measure. Such measures or tests describes how well statistical model fits a set of observations. They are based on measurement of the discrepancy (distance) between the distribution of the empirical data and the hypothesized model. This distance is compared with distance measurements for comparable synthetic data sets drawn from the same model, and the p-value is defined to be the fraction of the synthetic distances that are larger than the empirical distance. If p is large (close to 1), then the difference between the empirical data and the model can be attributed to statistical fluctuations alone; if it is small (e.g. $p \leq 0.1$), the model is not a plausible fit to the data. There are a variety of measures for quantifying the distance between two probability distributions, but for nonnormal data the commonest is the Kolmogorov–Smirnov (KS) statistic [35]. The procedure for performing the KS test is as follows:

- fit the power-law to the data using the maximum-likelihood method and calculate KS statistics for the fit,
- generate a large number of power-law distributed synthetic data sets with scaling parameter γ and lower bound x_{min} equal to those of the distribution that best fits the observed data,
- fit each synthetic data set individually to its own power-law model and calculate the KS statistic for each one relative to its own model,
- count the fraction of the time that the resulting statistic is larger than the value for the empirical data.

Money flow network in blockchain-based SharedMfg: The money flow network in blockchain-based SharedMfg concept is a complex network, in which nodes can be seen as APUs (players) and edges corresponding to the amount of money that was transferred between two nodes. In addition, money can be transferred both ways, therefore network is weighted and directed (Figure 3a). In some cases, some money can be transferred from node to itself, thus constructing the loops in the network (edge Z). The connection between the nodes is established for two reasons, namely the payment for the service (edge $price$) and the transaction fee (edge $txFee$), which is distributed during the transaction validation process (Figure 3b).

RESULTS

The experiment involved 27 players, students at the University of Ljubljana, Faculty of Mechanical Engineering, who during their studies were introduced to smart modes of manufacturing systems such as the SharedMfg concept. The game lasted 90 minutes, players were in remote locations, but they were allowed to communicate. The web application was

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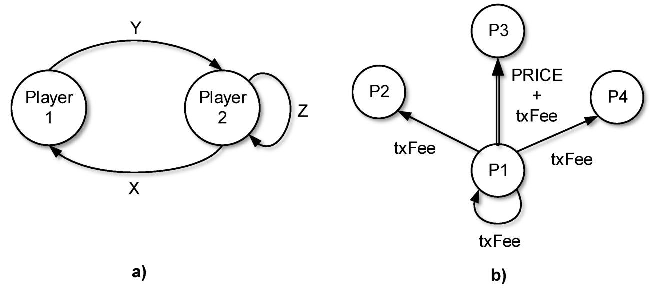

Fig. 3. Money flow network in blockchain-based SharedMfg.

implemented using the MERN stack (MongoDb, ExpressJS, ReactJS and NodeJS). WebSocket API technology was used to provide real time asynchronous communication. No problems with the application were detected during the experiment, and all players participated and played throughout the game. The game parameters that define the game dynamics were set as follows: $f_{BC} = 10$ s, $e = 0.87$, $t_{inital} = 300$ s, $t_{limit} = 20$ s.

Figure 4 represents the value of transaction fee of confirmed transactions in game time. It shows that after the players get used to the game, the value stabilizes somewhere after the first third of the playing time. After half of the playing time (t_1), however, the amount of transaction fee starts to rise sharply. An increase in transaction fees in blockchain networks indicates higher network occupancy, as users compete with each other for their transactions to be accepted earlier by increasing the reward for block validator [36]. Towards the end of the game, we can see that the rise has stopped. We believe that this happened because players knew the approximate time of the game and were expecting the end of the game.

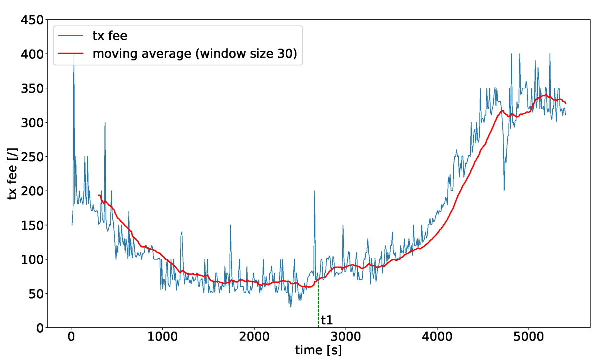

Fig. 4. Transaction fee of confirmed transactions in time.

Figure 5 shows the moving average (window size 20) of the price for service that was provided for each type of service. Price for service rises in the first half of the game and then (after t_1) the trend reverses and starts to fall beneath values that were set at the beginning of the game. At the time t_2 the price for service was equal to the transaction fee and after that time the price for service was lower than the cost for transaction confirmation by the blockchain network. The price of supply in free market systems is affected by the supply demand ratio [37], and we can conclude that at the middle of the game supply began to increase sharply. In connection with the dynamics of the transaction fee, this confirms that there has been a congestion of the blockchain network and the frequency of service provision has outpaced the frequency of transaction confirmation.

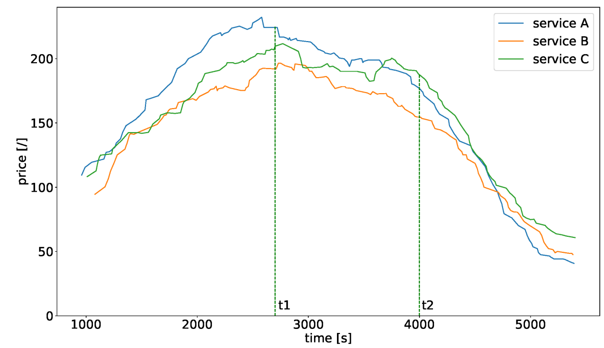

Fig. 5. Price for service in time.

Figure 6 confirms the previous finding, as it shows how the number of services offered on the market first declined, but after the frequency of service provision outpaced the frequency of transaction validation, it began to rise. Figure 6 also shows that the supply on the market fluctuated in waves in the first half of the game. This is due to the fact that the players started the game on equal terms and at the same time. In the second half of the game, this fluctuation is no longer so obvious.

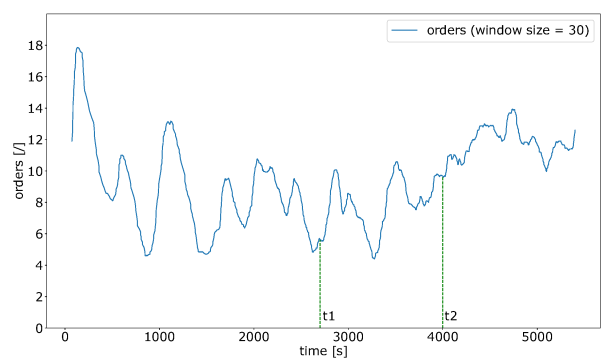

Fig. 6. Number of orders in time.

The histograms in Figure 7 show the money distribution among the players at six time points. At the beginning of the game, the funds were fairly evenly distributed among the players. Over time, however, we can see that a small number of players owned a large amount and many players owned a small amount of assets, suggesting that a scale-free network structure may emerge in the money flow network.

Figure 8 shows the value of the gamma coefficient from the power-law fit on the weighted in-degree distribution of the

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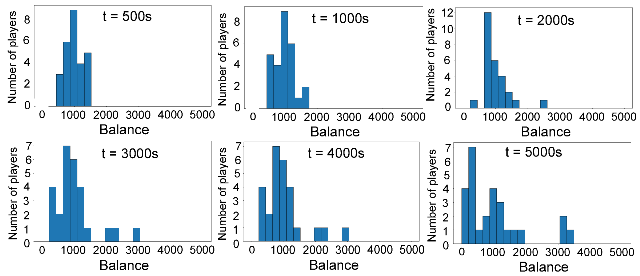

Fig. 7. Asset distribution in six time points.

money flow network during the game. To determine the best fit of power law function by the maximum-likelihood method, we used the Python package *powerlaw* [38]. In the calculation, we use a time window of 700 s, the number of time samples is 700 and a moving average window 30. The gamma coefficient decreases during the game and approaches the values of scale-free networks towards the end of the game (between 2 and 3).

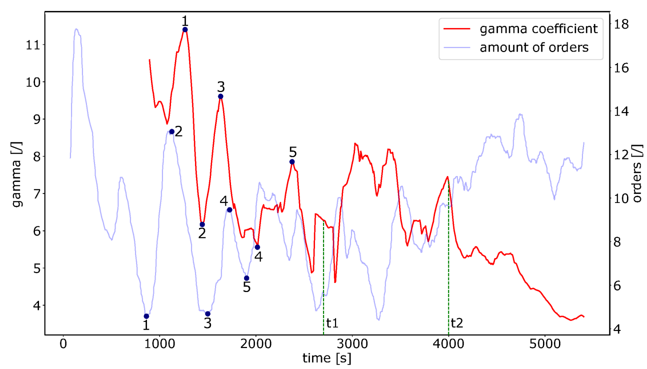

Fig. 8. Gamma coefficient in time.

In Figure 8 there are three modes of network formation. In the first part of the game, when the blockchain network is not yet clogged, market supply defines the shape of the money flow network. The network, with a time delay, follows the fluctuation of the supply of services in the market. With a larger amount of supply on the market, the network starts to form in more scale-free way (points 2 and 4) and with a smaller supply on the market the randomness of network structure increases (points 1, 3 and 5). This phenomenon is due to the fact that with a small supply, many players compete for few services and decide to buy regardless of price and cost. When the offer is larger, the decision-making process is more complex and is influenced by the price and time for the service. In the second part (from t_1 to t_2), when the transaction fee starts to rise and the price for service starts to fall, we have a mixed regime where the effects of the supply on the market are still visible, but following the fluctuation of supply on the market is less obvious. In the third regime (from t_2), when the transaction fee exceeds the price for the service (the network is clogged), a strong tendency for a scale-free network appears. Towards the end of the game, the value of the gamma coefficient is firmly reducing towards the value of 3 and would most likely fall below this limit if the game had continued.

Goodness of fit test (KS test) showed that on average 73.9% of the data set, respectively, passed the null hypothesis with p-values higher than 0.1. For each time window, we compared the resulting power-law fit with a fit of 2500 synthetic data sets. Based on the presented results, we conclude that a larger supply of services on the market and a more occupied blockchain network results in a more scale-free structure of money flow network and blockchain-based SharedMfg.

Discussion

The described experiment is an exploratory study where the above findings only suggest the possibility of the existence of certain properties of the money flow network in the concept of blockchain-based SharedMfg. The experiment was conducted with a small number of players and in a relatively short time. Also, the online game or virtualization of the blockchain-based SharedMfg concept is simplified due to the user experience and in some respects deviates from potential real systems based on the said concept. The findings are the basis for future work and serve as guidelines for how the online game and experiment can be improved so that in the future we can give a more detailed analysis of the money flow network in the concept of blockchain-based SharedMfg.

For better network analysis, the experiment would need to be optimized. First, the online game would need to be adapted to allow more players to participate in the experiment, thus increasing the amount of data captured. It also seems, given the obtained graph of the gamma coefficient (Figure 8), that as the game continues, the value of gamma coefficient would probably go towards the values that defines the scale-free network ($2 < \gamma < 3$). Therefore, this should be verified by a longer experiment. It would be necessary to perform the experiment several times on different groups of players in order to draw a reliable conclusion.

Conclusion

In this work, we present an exploratory analysis of money flow network in blockchain-based SharedMfg. In order to obtain real data, we conduct an experiment in the form of an online game played by people. The analysis showed that the market supply and the state of occupancy of the blockchain network affect the structure of the prosumer network. A greater supply of services in the market and a more occupied blockchain network causes a tendency for money flow network to organize like scale-free networks. The results suggest that a more centralized network structure is emerging in a system, which is based on the principle of decentralization. This, in turn, results in doubts that such a platform, although built on the principles of decentralization, also offers properties of a decentralized manufacturing system. In the described experiment, blockchain technology was the cause that normal operation of the prosumers in the system was obstructed. Players with a smaller share in stake could no longer participate

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as consumers but could, at the end of the game, only offer their service on the market. This type of system operation does not offer an incentive to include new APUs in such a system and excludes existing smaller players from the system. Questions arise how can we integrate blockchain technology in SharedMfg and at the same time ensure the property of a decentralized platform and thus enable normal operation of the system for all users. In future work findings presented in this paper will be verified by an optimized experiment and also solutions for better integration of blockchain technology in SharedMfg will be explored.

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