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Experimental study of work system networking in production environment

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ABSTRACT

In the context of distributed manufacturing, existing models for the management of orders and work systems assume that the entirety of information about the state of the production environment is known. Instead, this paper studies the implications of networking in an environment in which no element possesses information about the entire state. An experiment in the form of a production simulation game is designed and carried out to explore the emergence and behaviour of such a network. Network structure and dynamics as well as the social aspects of networking are discussed and evaluated.

1. Introduction

Global competition and the increased complexity of the production world are forcing companies to become more flexible and responsive. As a consequence, companies are organising into production networks–cross-company cooperations enabling mutual use of resources and joint planning of the value adding process [1].

While the operation of production networks has been studied extensively, the underlying mechanisms of networking remain relatively poorly understood for three reasons. First, networking is not only a technical but also a social process involving human subjects and is therefore difficult to model. Second, real-world experiments are almost impossible to conduct because they represent risks for the companies involved. And third, real networks often behave as complex adaptive systems [2,3], where the phenomenon of emergence is difficult to describe mathematically.

In this paper, we apply the methods of experimental economics to the study of the networking process in a production environment. Specifically, we design and carry out an experiment in the form of a simulation game to study decision making, coordination, and social preferences involved in the networking process of work systems [4]. We test two hypotheses related to social aspects of networking and network robustness. We show that social preferences significantly influence networking and that network performance is minimally affected by external disturbances. The results highlight the potential of the approach for use in the study of various production phenomena.

2. Work system networking

Production systems can be considered to be networks on various levels, from inter-company production networks [5,6] to supply chains [7] to intra-company networks of work systems [8]. The usual focus of scientific research is the operation of such networks and is less often on their creation and dynamics [9,10]. Hence, the underlying principles and achieved effects of networking are seldom considered in production science.

Production networks behave as complex adaptive systems in which each part of the network impacts every other part, either directly, or indirectly, through the environment. A high level of complexity prevents prediction of future states and actions based solely on technical and economic data because the social aspects are the main source of complexity. Acquaintances, friendships, trust, bounded rationality, opportunism, resentments, selfishness, envy, and so on, dictate how a network will emerge, evolve, and operate. Examples of complex social networks can be observed in biology, e.g., a flock of fish, a lion pride, an ant colony, and so on. These cases demonstrate that such networks are intrinsically robust, express synergistic effects, and allow the emergence of new behaviour based on the simple behaviour of individuals [11,12]. Network structures that for a period of time can be seen as irrational, socially motivated, unbeneficial for some members, and generous to others, can also lead to risk dispersion, redundancy, and robustness in the long run.

We argue that production, although usually seen as a technical endeavour, is actually a highly social one, and we explore the social properties of work system networks through a game-based experiment.

3. Game-based experimentation

For the study of work system networking in a production environment, we use the methods of experimental economics [13–15]. This type of experimentation has been used to study various problems in the field of manufacturing, for example, those related to decision-making [16,17]. Laboratory studies are intended to provide a basic understanding of the observed

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phenomena under different conditions. Their results can serve as a rigorous empirical pre-test of economic theory prior to the use of field data tests [18].

The validity of economic experiments, i.e., the degree to which they measure what they are supposed to measure, is often challenged. The validity must be ensured by proper experiment design and adequate selection of participants. In our case, internal validity is ensured by the abstraction of the production environment, while external validity is provided by expert interpretation and understanding of the modelled production environment by the participants [19]. Additionally, experiment reproducibility is an important part of ensuring the validity. Hence, our experiment design and the game rules are explained in detail in the next chapter.

4. Experiment design

The abstraction of the production environment and the game rules are defined to enable the observation of networking between work systems. Two hypotheses are tested.

Hypothesis 1. The connections in the network are formed more frequently between subjects who are in a social relationship than they would be if the connections were at random.

Hypothesis 2. When work systems are allowed to connect, an external perturbation does not have a long-term impact on the performance of the system as a whole. Alternatively, the behaviour of the network is more robust than the behaviour of disconnected individuals.

The rest of the section provides an overview of the experiment, a detailed explanation of the game's rules, the underlying models, and a comment on the implication of the rules.

4.1. Experiment overview

The experiment takes the form of a game played by human subjects – players. Each player represents a work system that produces custom-made products by solving various tasks. It is presumed that a short time frame of a few months in work systems' operation is observed over the course of the experiment. In this time frame, the work systems' capabilities remain constant. All work systems are subjected to the same rules and, at the outset, have an equal probability for success. The game is entirely computerised and is played over the Internet. Communication between players is assisted by a built-in messenger-like programme, but alternative forms of communication, e.g., audio or video conferencing, are permitted and encouraged.

Two scenarios are devised. In the first, players individually solve tasks provided by the environment. In the second, the only difference is that the players can connect amongst themselves to share tasks. In both scenarios, a perturbation, negatively affecting randomly selected players, is simulated approximately halfway through the experiment.

4.2. Detailed game rules

The game is played simultaneously by N players. Players start with 1920 points, which is equal to the total length of the experiment in seconds, and lose one point per second, which simulates running costs. The goal of the game is to score as many points as possible by solving tasks, using player-specific capabilities.

A player's capability is defined as a set of characters that he (or she) can write with his keyboard, such as "ABDF...". Each capability consists of 14 characters, randomly chosen from the 26 characters of the English alphabet. Each pair of players, therefore, shares at least two characters.

A task is defined as a sequence of characters, such as "ABDBA...". Tasks can be of different lengths, ranging from $L_{\min} = 5$ to $L_{\max} = 15$ characters. A player can solve a task if his capabilities include every character in the task. Players are able to bid on tasks that they receive. When a player solves a task correctly and on time, he receives an award equal to his bid. The maximum bid is chosen randomly and is between $b_{min} = 60$ and $b_{max} = 120$ points. If more than one player bids on a task, which is only possible in networked mode, the task is awarded to the player with the lowest bid. If a player does not solve a task or solves it incorrectly, he receives a penalty equal to his bid. Players can cancel tasks after they are awarded to receive a smaller penalty. Lateness is punished proportionally. The reward-penalty model is presented in Eq. (1), where r is the reward, b is the player's bid, t_{task} is the total time available for solving the task, and t_r is the task's remaining time, positive when solved in time and negative when late.

$$r = \begin{cases} b & \text{if } correct \text{ and } t_r \geq 0 \\ b + (b \cdot t_r)/t_{task} & \text{if } correct \text{ and } 0 > t_r \geq -2 \cdot t_{task} \\ -b/2 & \text{if } canceled \text{ and } t_r \geq 0 \\ -b & otherwise \end{cases} \quad (1)$$

Tasks are generated by a single task generator. The task generator starts with a predefined budget and seeks to spend the entire budget by the end of the game. The starting budget is the product of the total game length t_{total} and the number of players N.

Task arrivals are assumed to be independent. The Poisson arrival model is used, meaning that the time between two received tasks has an exponential distribution. The task rate λ_i is player specific and changes during the experiment as follows.

The experiment lasts for 32 min. For the first 7 min the rate is the same for all players, one task per 60 s on average (Eq. (2)).

$$\lambda_i = \bar{\lambda} = \frac{1}{60\,\text{s}} \quad (2)$$

After 7 min, the average rate changes every minute according to the total success of the players in the last 5 min. The new average rate is modified according to quotient between average budget for 15 min $B_{15\,\text{min}}$ and the sum of average budget for 10 min $B_{10\,\text{min}}$ and total reward awarded to players in the last 5 min $R_{5\,\text{min}}$ (Eq. (3)). This means that the task generator seeks to spend 15 min of budget in the next 10 min, by considering the budget already spent in the last 5 min.

$$\bar{\lambda} = \frac{1}{60\,\text{s}} \cdot \frac{B_{15\,\text{min}}}{B_{10\,\text{min}} + R_{5\,\text{min}}} \quad (3)$$

A specific player's rate then changes with respect to the average rate and relative success of the player in the last 5 min, that is, the number of tasks he solved, n_i, divided by the average number of tasks solved by all players in the last 5 min n/N. The new rate, λ_i', is then the average of the previous rate and the specific player's rate (Eq. (4)).

$$\lambda_i' = \frac{\lambda_i + \bar{\lambda} \cdot ((n_i \cdot N)/n)}{2} \quad (4)$$

After approximately 17 min, a perturbation is simulated. The perturbation affects a randomly chosen 20% of players by lowering their task rate to 20% of the calculated one for 5 min. This simulates a temporary interruption of connections between a work system and its potential customers. After 22 min, the rates of the players directly affected by the perturbation return to those calculated using Eq. (4).

The task contents are generated as follows. Each task is generated for a specific user. In 60% of cases, the user is able to solve the task himself. At least 20% of the players can solve any generated task.

In the second scenario, the players are able to connect amongst themselves. When a player is connected, a task received by him is also forwarded to all the players to whom he is connected. This creates a competitive environment, where multiple bids are possible for each task. To enable educated networking, each player is informed of how many characters he shares with each other player.

4.3. Implications of the game rules

The strategy: While the only difference in rules between the two scenarios is that networking is possible only in the second scenario, the strategic possibilities are very different. In the first scenario, the