ABSTRACT

In this COVID-19 epidemic, due to insufficient awareness of the impact of sudden public health emergencies on agricultural logistics at this stage, agricultural products were left unsold, stocks were backlogged, and losses were severe. In the process of distribution, we should not only ensure a short time cycle and avoid the contamination of agricultural products by foreign bacteria, but also pay attention to the waste of human, material, and financial resources. Therefore, this study mainly adopts the combination of the petrochemical network and blockchain to build an agricultural products emergency logistics model. This paper first shows the operation mechanism of the petri dish network and blockchain coupling in the form of a graph and then uses the culture network modelling and simulation tool PIPE to directly verify the construction model. It is proved that the structure and overall business process of the agricultural products logistics system constructed by combining the Petri net and block chain are reasonable, reliable, and feasible in practical application and development. It is hoped that this study can provide a reference direction for agricultural emergency logistics.

KEYWORDS
Petri net; blockchain; coupling model; agricultural emergency logistics.

1. INTRODUCTION

Agricultural logistics enterprises, logistics distribution centres, and wholesale markets should be organised to strengthen cooperation with production bases, leading enterprises and farmers' cooperatives to improve the efficiency of logistics and distribution. In the absence of data transparency and trust mechanisms, the development of logistics industry has gradually fallen into a trust dilemma [1]. The use of blockchain technology and Petri network coupling mechanism to achieve information sharing and information symmetry has solved the problem of low transparency of logistics information as well as the problem of obstructed transportation, saving transportation time, and reducing losses.

In the field of block chain application: domestic scholars have done a relatively in-depth research on the application of blockchain technology. Blockchain technology is applied to logistics information traceability system, food safety traceability system, etc. effectively solving the traditional agricultural products logistics quality and safety, circulation rate, agricultural products information asymmetry, and other problems. On the other hand, foreign scholars' research on blockchain technology is mainly applied in commercial finance, and their research on logistics is mostly in general commodity logistics. The application of blockchain technology in supply chain and logistics has also achieved good results. In addition, blockchain technology has also been studied in intelligent logistics. Ye et al. [2] designed and developed a supply chain prototype system, which effectively solved such thorny issues as low trust among participants in the supply chain, difficult government regulation, and difficult

2. PETRI NET AND BLOCKCHAIN COUPLING MECHANISM

2.1 Operating mechanism of the Petri net

Petri nets are mathematical representations of discrete parallel systems and are suitable for describing asynchronous and concurrent computer system models. The place in the Petri net is the issuer of all “tasks”, that is, the “causes” of all asynchronous concurrent operations, and the “changes” correspond to the “results” generated by the corresponding asynchronous concurrent operations. In addition, the prototype Petri net introduces a token in use to represent the dynamic state generated after the “change”, that is, the token in the system. The introduction of tokens can well describe the local “dynamic” situation of the system after asynchronous concurrent operations. It is a system model suitable for describing asynchrony and finding phenomena. It has both strict mathematical definitions and intuitive graphical representations. Therefore, it is often used as the main modelling tool for discrete event systems. At present, the Petri net theory has formed an independent branch of discipline and has made certain research results in many other disciplines and technical fields.

The emergency logistics system is different from the ordinary logistics system; it is a typical discrete event system, a dynamic system driven by the event system process. The time interval of the event and the location are uncertain, and it is difficult to determine a timely distribution. There are emergency resource management difficulties, rescue demand information and feedback are difficult to obtain in real-time. These series of problems are challenging for the entire emergency logistics system. Therefore, the Petri net must be expanded and improved according to the emergency logistics system [16].

The Petri net includes four basic elements: repository, transition, directed arc, and token, and two common elements: condition and event. The classical Petri net model is shown in Figure 1. The sufficient conditions of the Petri net are as follows:

\[ P \cap T = \emptyset \]  \hspace{1cm} (1)

\[ P \cup T \neq \emptyset \]  \hspace{1cm} (2)
2.2 Operating mechanism of blockchain

Due to the sudden and uncertain occurrence of agricultural product emergency logistics, the command centre cannot obtain accurate information in time, which seriously affects the decision-makers' judgment and then makes wrong decisions, resulting in a large area of logistics paralysis. The decentralised technology of blockchain can solve this kind of problem effectively. Decentralisation makes the rights of the participants in the logistics system equal, and the information provider and decision-maker are not unique, which makes the information diversified and greatly improves the accuracy and timeliness of information. Decentralisation also makes the generation of transactions, verification transactions, recording transactions, and processing transactions based on the distributed network. The separation processing method can deal with more data problems in a short time and improve the operation efficiency.

The smart contract of blockchain technology is a group of scenarios. The parties who sign the contract agree on the content of the contract and deploy it on the blockchain in the form of smart contract, which can automatically execute the contract on behalf of the signers without relying on any central organisation [19]. In the process of the emergency logistics of agricultural products, we can use smart contract to restrict the contract parties in the intermediate process, ensure the fairness and reliability of the intermediate process in a certain sense, and promote the operation efficiency of the agricultural emergency logistics system.

2.3 Coupling mechanism of the blockchain and Petri net

From the above analysis, it can be seen that there are great similarities between the blockchain and Petri nets in the agricultural logistics process. The Petri net provides a unified graphical representation method graph analysis technology for the agricultural product emergency logistics system to describe the characteristics of the system.
Blockchain and Petri net are in the role of emergency logistics of agricultural products.

In terms of information processing, it is conducive to obtaining real information, sharing it in time, and ensuring information security.

In terms of operational efficiency, rapid and effective information transmission ensures the efficient operation of the emergency logistics system for agricultural products.

In terms of intelligent development, it effectively promotes the automation, self-monitoring and correction of the transportation system.

Features and advantages of blockchain technology

- Decentralisation
- Information transparency/Transparent and reliable
- Anti-counterfeiting and tamper-proof
- Highly reliable system
- Permanent data storage/traceable
- Automated performance

Features and advantages of Petri net

- Reflect dynamic behavior
- Multi-dimensional monitoring and correcting system characteristics
- Collect and pass information
- Describe the network system structure in the form of an incidence matrix
- Boundedness
- Active
- Persistent
- Algebraic analysis

Petri net technology and analysis method

- Reachable tree
- Markov chain
- Mesh information flow
- Algebraic analysis

Figure 2 – Coupling mechanism between blockchain and Petri nets
constructed for each step by refining the Petri net modelling elements for each major event at each step.

2) After the model is established, the discrete nature of the blockchain speeds up the transfer of information between subjects and improves efficiency; information is made open and transparent through sharing mechanisms and smart contract technology.

3) Coupling the blockchain consensus mechanism, smart contract, and other technologies with the Petri net's Markov chain, reachability tree, and other analysis methods, sharing information in time, ensuring information security, effectively promoting the automation of the transportation system, and ensuring the emergency logistics system of agricultural products operate efficiently.

The specific manifestation is shown in Figure 2.

3. EMERGENCY LOGISTICS MODEL

After analysing each initial triggerable event in the production, processing, sales, and other processes of agricultural products, the distribution of the number of tokens in the initial state is determined and the emergency logistics model of agricultural products coupled with the blockchain and Petri net is established, as shown in Figure 3.

The meaning of each element in the Petri net is as follows:

- \( p = (p_1, p_2, p_3, \ldots, p_m) \) represents the set of all the places in the Petri net. It is a non-empty finite set, which can be represented as input signals such as resources, conditions, status, and input data.

- \( t = t_1 \cup t_i \) \((t_i \cap t_i = \emptyset)\) is expressed as a Petri net as a collection of changes; \( t_i = (t_1, t_2, t_3, \ldots, t_k) \) is represented as a set of time transitions; \( t_i = (t_{k+1}, t_{k+2}, t_{k+3}, \ldots, t_p) \) represents a set of instantaneous changes, which can represent jobs, events, services, calculation steps, and information processing, etc.

- \( F \subseteq a' \cup a^* \), the set of directed arcs representing the changes of Petri nets, among them \( a' \subseteq p \times t \) is the set of input arcs for Petri net transition, \( a^* \subseteq t \times p \) is the set of output arcs for the Petri net transition; \( a = a' - a^* \) is the incidence matrix of the Petri net.

- \( V \subseteq p \times t \) is denoted as the forbidden arc of Petri net transition \( t \).

- \( W: F \rightarrow N \) is expressed as the weight function of the directed arc of the Petri net, \( N = (1, 2, 3, \ldots) \) represents the mapping of the directed arc set to the weight coefficient space, that is, the Petri net weight coefficient space.

- \( M_0: P \rightarrow N_{\text{Token}} \) is expressed as the initial identification of the Petri net system, \( N_{\text{Token}} = (1, 2, 3, \ldots) \) is expressed as the token quantity of Petri net place, \( M_j(p_j) \) is expressed as the token quantity of place \( p_j \) under the \( j \)th \( M \) mark of Petri net. It is the weight function (weight) of the directed arc on \( N \). If there is no value on the arc, the weight is 1 by default.
\[ \lambda = \lambda_0 \cup \lambda_1 \]
is expressed as a set of Petri net transition balance rates, \( \lambda_i = (\lambda_{i,1}, \lambda_{i,2}, \ldots, \lambda_{i,j}) \) is expressed as a collection of the average rate of time transition of the Petri net, and the average rate of time transition obeys the exponential distribution. \( \lambda_0 \) is expressed as the Petri net's instantaneous transition rate and the implementation delay of the instantaneous transition rate is zero [12].

Table 1 shows the element definition description of the condition set \( P \) and the event set \( T \) in the system of Figure 3.

From the definition [20], we can know that \( \Sigma = (P, T, F, W, M_0) \) is a Petri net system, \( \Sigma = \{P_0, P_1, \ldots, P_m\} \), \( m = |P| \), \( T = \{t_0, t_1, \ldots, t_n\} \), \( n = |T| \), then the incidence matrix of \( \Sigma \) can be represented by a matrix \( A \) of \( m \) rows and \( n \) columns:

\[
A = [a_{ij}]_{m \times n}
\]  

In the formula:

\[
a_{ij} = W(t_i, p_j) - W(p_j, t_i)
\]

\( i \in \{0, 1, 2, 3, \ldots, m\} \), \( j \in \{0, 1, 2, 3, \ldots, n\} \)

For analysis needs, \( A^+ = W(t_i, p_j) \), \( A^- = W(p_j, t_i) \) is introduced here, \( A^+ \) is called the output matrix of \( \Sigma \), and \( A^- \) is called the input matrix of \( \Sigma \):

\[
A = A^+ - A^-
\]

According to the definition [20] in the net system \( \Sigma \), \( P = m \) and \( A \) is the incidence matrix of \( \Sigma \). According to the Petri net theory, if there is a non-parallel \( m \)-dimensional non-negative integer vector \( X \), \( A^X = 0 \), then \( X \) is called a \( P \)-invariant of the network system \( \Sigma \). According to the definition [20], the output matrix \( A^+ \) and the input matrix \( A^- \) of \( \Sigma \) can be easily obtained, and the incidence matrix \( A \) of the network system \( \Sigma \) can be solved using the Equation 3 as follows:

\[
A = A^+ - A^-
\]

\[
\begin{bmatrix}
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

In the network system \( \Sigma \), the initial identification \( M_0 = [1000000000000] \), through analysis and judgment, the possible transition path can be obtained by observing the \( P \)-invariant in it:

\[
\sigma_1 = t_0t_1t_2t_3 \\
\sigma_2 = t_0t_1t_2t_3t_4t_5t_6 \\
\sigma_3 = t_0t_1t_2t_3t_4t_5t_6t_7t_8t_9
\]

Then combined with the \( P \) variable, we can know that the path of the change is:

\[
P_0t_0P_1t_1P_2t_2P_3t_3P_4t_4P_5t_5P_6t_6P_7t_7P_8t_8P_9t_9P_{10}
\]

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Table 2 – 2003 Production of various crops in the Inner Mongolia province

<table>
<thead>
<tr>
<th>Crop types</th>
<th>2003 Sown area (thousands of hectares)</th>
<th>Total production (million tonnes)</th>
<th>Yield [kg/ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>541.00</td>
<td>318.20</td>
<td>5882</td>
</tr>
<tr>
<td>Wheat</td>
<td>22.10</td>
<td>6.00</td>
<td>2715</td>
</tr>
<tr>
<td>Maize</td>
<td>2627.20</td>
<td>1615.30</td>
<td>6148</td>
</tr>
<tr>
<td>Soybeans</td>
<td>430.00</td>
<td>150.30</td>
<td>3495</td>
</tr>
<tr>
<td>Vegetables</td>
<td>269.10</td>
<td>881.01</td>
<td>32703</td>
</tr>
<tr>
<td>Sunflower seeds</td>
<td>93.70</td>
<td>16.16</td>
<td>1726</td>
</tr>
</tbody>
</table>

Through the above process, the \( P \)-invariant of the network system \( \sum 1 \) is solved, and the model will be verified by the computer model simulation of PIPE4.3 below.

4. MODEL VALIDATION

First, a brief introduction to PIPE, the simulation tool used for this validation. PIPE (Platform Independent Petri net Editor) is a Java-based editing and analysis system for Petri nets. It has been improved by eradicating bugs, refactoring code to make it more efficient and understandable, and by adding two major pieces of functionality.

Because data on the New Crown epidemic thing are difficult to collect, we chose data from Inner Mongolia for the 2003 SARS period, according to what was published by the National Bureau of Statistics of China, of which we selected vegetables as the crop for this study in the Inner Mongolia province in 2003. Since the duration of SARS was seven months, we used 70% of the total production as the model validation data [21].

In practice, the model built can be verified directly using the Petri net modelling and the simulation tool PIPE. Using animation mode, after many experimental operations, it is determined that the network system \( \sum 1 \) can operate properly. Table 3 depicts the results of the classification analysis of the network system \( \sum 1 \) using the classification function module of the PIPE4.3 simulation tool, which shows that the net system \( \sum 1 \) belongs to an extended free choice net.

The PIPE 4.3 simulation tool Incidence&Marking function module can be used to calculate the output matrix \( A^+ \), input matrix \( A^- \), and incidence matrix \( AA \) of the network system \( \sum 1 \). At the same time, the initial identification \( M_0 \) state of the system and the transition \( t_1 \) that can be triggered and also analysed, and any state identification \( M_0 \) of the system can also be analysed according to the transition change situation. Through simulation verification, the obtained \( A^+, A^- \), and \( A \) are completely consistent with the correlation matrix analysis results. Here, the analysis results of the changes before and after the change \( t_0 \) of the network system \( \sum 1 \) using the Incidence&Marking function module are given, as shown in Tables 4 and 5.

Table 3 – Classification function module is used to classify and analyse the results of the network system

<table>
<thead>
<tr>
<th>Petri net type</th>
<th>Classification result</th>
</tr>
</thead>
<tbody>
<tr>
<td>State machine</td>
<td>false</td>
</tr>
<tr>
<td>Mark graphics</td>
<td>false</td>
</tr>
<tr>
<td>Free choice network</td>
<td>true</td>
</tr>
<tr>
<td>Expand free choice network</td>
<td>true</td>
</tr>
<tr>
<td>Simple net</td>
<td>true</td>
</tr>
<tr>
<td>Extended simple net</td>
<td>true</td>
</tr>
</tbody>
</table>

Table 4 – Change \( t_1 \) before network system \( \sum 1 \) initial logo \( M_0 \)

<table>
<thead>
<tr>
<th>Library</th>
<th>( P_0 )</th>
<th>( P_1 )</th>
<th>( P_2 )</th>
<th>( P_3 )</th>
<th>( P_4 )</th>
<th>( P_5 )</th>
<th>( P_6 )</th>
<th>( P_7 )</th>
<th>( P_8 )</th>
<th>( P_9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial logo</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Current logo</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5 – Initial identification of the transition \( t_1 \) of \( M_0 \) network system \( \sum 1 \) has occurrence right

<table>
<thead>
<tr>
<th>( T_0 )</th>
<th>( T_1 )</th>
<th>( T_2 )</th>
<th>( T_3 )</th>
<th>( T_4 )</th>
<th>( T_5 )</th>
<th>( T_6 )</th>
<th>( T_7 )</th>
<th>( T_8 )</th>
<th>( T_9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>
The invariant analysis function module of PIPE4.3 simulation tool can realise the P-invariant and T-invariant analysis of the network system \( \sum 1 \) to verify the relevant properties of the model system. Tables 6 and 7 respectively show the P-invariant and T-invariant analysis results of net \( \sum 1 \) obtained by simulation tools.

The analysis results in Table 6 show that there are three P-invariants in the network system \( \sum 1 \) and the analysis results in Table 7 show that there is no T-invariant in the network system \( \sum 1 \). During the analysis of the invariants of the net system \( \sum 1 \) using the invariant analysis function module of the PIPE4.3 simulation tool, the analysis conclusions related to the invariants are given in addition to the output of the invariants present. For the P-invariant in the network system \( \sum 1 \), the simulation analysis gives a conclusion that the net has a definite P-invariant coverage and that it is therefore bounded. For T-invariants, the simulation analysis gives conclusion that the net has no definite T-invariant coverage and therefore it is not possible to know whether it is bounded and active. The results of this analysis are in full agreement with the result of the invariant in the network system \( \sum 1 \) calculated through the incidence matrix analysis in Chapter 2, which also justifies the results of the previous analytical calculations.

At the same time, for the three P-invariants in the network system \( \sum 1 \), the simulation tool also gives the corresponding P-invariant equations after the analysis:

\[
\begin{align*}
2M(P_0) + 2M(P_1) + 2M(P_2) + 2M(P_3) + 2M(P_4) + 2M(P_5) + 2M(P_6) + 2M(P_7) + M(P_8) + M(P_9) + M(P_{10}) &= 2 \\
M(P_0) + M(P_1) + M(P_2) + M(P_3) + M(P_4) + M(P_5) + M(P_6) + M(P_7) + M(P_8) + M(P_9) + M(P_{10}) &= 1 \\
M(P_0) + M(P_1) + M(P_2) + M(P_3) + M(P_4) + M(P_5) + M(P_6) + M(P_7) + M(P_8) + M(P_9) + M(P_{10}) &= 1
\end{align*}
\]

The above analysis and calculation of the net system \( \sum 1 \) using the Petri net incidence matrix and solving the P-invariant, and using the PIPE4.3 simulation tool to carry out simulation verification, thus ensuring that the Petri net model shown in Figure 3 is conserved, reachable, bounded, and safe. It also fully shows that the designed agricultural product intelligent traceability service system architecture and its overall operating process are reasonable, reliable, and feasible in actual application development.

5. CONCLUSION

In view of the lack of widespread application of the blockchain technology in agricultural emergency logistics, this paper applies the Petri net and blockchain coupling technology to construct a coupling model of the Petri net and blockchain based on the main influencing factors of agricultural emergency logistics, and conducts a coupling feasibility analysis. Then, through model validation, a feasible solution is provided to a certain extent for the application of the Petri net and blockchain technology in agricultural products emergency logistics. After the analysis of the emergency logistics process, the advantages of the blockchain and Petri network in solving related problems are combined. The model not only provides a certain reference for the actual process, but also provides a case study for the application of blockchain and other technologies in agricultural logistics.

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葛慧敏 (1979-) 江苏连云港人，江苏大学副教授，工学博士，从事驾驶行为研究、载运工具运行安全、运输
规划与设计、物流系统规划与设计等。
刘海生 (2000-) 江苏大学本科在读, 主要研究方向: 物流系统优化
王 瑞 (2000-) 江苏大学本科在读, 主要研究方向: 物流系统优化
朱 帅 (1998-) 江苏大学本科在读, 主要研究方向: 物流系统优化
邵麒麟 (1999-) 江苏大学本科在读, 主要研究方向: 物流系统优化

基于 PETRI网和区块链耦合的农产品应急物流模型研究

摘要
在此次新冠疫情中, 由于现阶段对于突发性公共卫生事件对农产品物流造成影响的认识不够充分, 使得农产品滞销、积压, 损失严重。在配送过程中, 要保证时间周期短, 避免外来细菌对农产品的污染, 又要注意人力、物力、财力的浪费。因此, 本研究主要通过对PETRI网与区块链耦合进而构建农产品应急物流模型, 然后利用PETRI网络建模与仿真工具PIE对构建模型进行直接验证。通过PETRI网和区块链结合构建的农产品物流系统的结构和整体业务流程是合理可靠的, 在实际应用和发展中是可行的。同时希望本次研究能够为农产品应急物流提供一个参考方向。

关键词
Petri网；区块链；耦合模型；农产品应急物流

REFERENCES