

Distributed Ledger Technology and Cyber-Physical Systems. Multi-agent Systems. Concepts and Trends

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Abstract. This paper describes how Distributed Ledger Technologies can be used to enforce smart contracts and to organize the behavior of multi-agents trying to access a different resource. The first part of the paper analyses the advantages and disadvantages of using Distributed Ledger Technologies architectures to implement certain Cyber-Physical and Control Systems. The second part propose perspective applications of Distributed Ledger Technologies in Cyber-Physical Systems.

Keywords: Directed acyclic graph · Distributed Ledger · Cyber-physical systems · Robotics · Multi-agent systems · Smart contracts · Virtual Power Plant

1 Introduction

Modern society is undergoing a profound transformation of all processes and spheres of human activity. The main trends are focused, in our opinion, in the following major areas:

1. Digital production.
2. The widespread exclusion of man from the contours of decision-making.
3. Increase data processing speed while increasing security.
4. Deep transformation of business models.

The authors suggest that Distributed Ledger Technology has every chance of becoming a new paradigm that will affect the entire landscape of human life. From the point of view of the theory Distributed Ledger Technology has all the signs of a paradigm, namely [1]:

- Paradigm is rarely a copy.
- The use of this technology allows you to achieve success rather than the use of competing ways to solve some problems.
- The use of this technology allows you to solve promising problems, while it is not fully known in advance what these problems will be.

It is important to note that the Distributed Ledger paradigm has already been used one way or another.

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Robots that do not interact with humans, that is, autonomous robots, are becoming more common. Autonomous robots perform their tasks without human control. At the same time, the fact that such robots can interact with each other becomes increasingly important and critical. In this case, the first place goes mathematical algorithms that allow you to build models of interaction between such robots. At the same time, according to the authors, the development of this concept in the framework of the algorithms of System 1 and System 2 [2]. More information about these systems of thinking and decision making can be found here [3].

It should be noted that the task of learning robots or other cyber-physical agents is very nontrivial. In addition to learning already on tagged data, it is important to use robots' self-learning algorithms, as well as the ability to transfer this knowledge to other robots or agents. In this case, we get some kind of closed knowledge system, where system agents extract and formalize knowledge from the interaction environment, transfer knowledge to other system participants via secure communication channels, and also control such transfer using the central arbiter. In fact, we get intelligent machines that are able to communicate with each other and transmit knowledge first of all, that is, learn from each other [4]. And here we come to the next stage in the development of artificial intelligence systems, which we call Machine Reasoning (MR) [5].

2 Hierarchical Control

2.1 Objective Function

Modern control systems for complex objects are characterized by a large number of hierarchies and control loops, which makes it necessary to rethink modern concepts of managing complex systems and data processing [6]. The interaction between management levels occurs through a variety of objective functions for each hierarchy. The objective function is a real or integer function of several variables that is to be optimized (minimized or maximized) in order to solve some optimization problem. In addition to the objective function in the optimization problem for variables, constraints in the form of a system of equalities and inequalities can be specified. Thus, the objective function is the concept of achieving in the process of managing one of the particular goals included in the vector of goals. It is important to understand that if the signals about the state of objects are continuous functions of time, then such control systems are called continuous control systems. In the case of the formation of signals in discrete time, we already get control systems discrete. Consider the control function of the hierarchical system in the general case (Fig. 1):

$$\begin{cases} F_1(x_1, x_2, x_3, \ldots, x_m) = 0, \\ F_2(x_1, x_2, x_3, \ldots, x_m) = 0, \\ F_3(x_1, x_2, x_3, \ldots, x_m) = 0 \\ \ldots \\ F_{N-1}(x_1, x_2, x_3, \ldots, x_m) = 0, \\ F_N(x_1, x_2, x_3, \ldots, x_m) = 0. \end{cases} \quad (1)$$

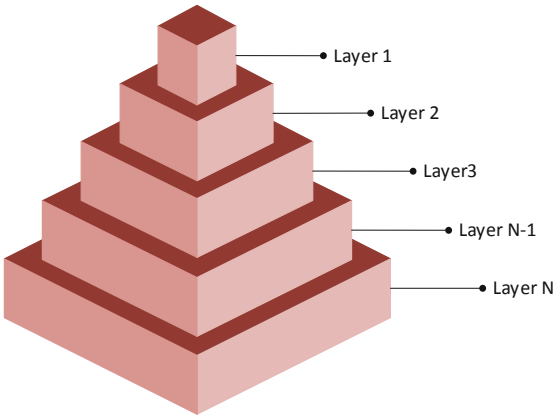

Fig. 1. Hierarchical system.

In this case, the task of managing the entire system will be reduced in the simplest case to minimizing the objective function:

$$S = \sum_{j=1}^{N} F_j^2(x_1, x_2, \ldots, x_m) \tag{2}$$

The task of control such a hierarchical system can be reduced to solving a multi-criteria optimization problem, namely:

$$\min(F_1(x), F_2(x), \ldots F_N(x)), x \in X \tag{3}$$

In this case, a valid solution $\widetilde{X} \in X$, called effective Pareto or Pareto optimal, if there is no other solution $x \in X$ such, that $F_k(x) \leq F_k(\widetilde{x})$ for all $k = 1, \ldots p$ and $F_i(x) < F_i(\widetilde{x})$ at least one $i = 1, \ldots p$.

Modern control systems are hierarchical structures with many possible vertices, as shown in the figure below [7] (Fig. 2):

2.2 Hypergraph Systems Modeling

A hypergraph is a generalization of a graph in which not only two vertices, but also any subsets can be connected with each edge.

In this formulation, a complex hierarchical system turns into a hypergraph in the mathematical sense H_n, which consists of many vertices $V_n(H_n)$ и hyper scraper $E_n(H_n)$ [8]. An example of a hypergraph is shown in the figure below (Fig. 3):

Directed hypergraph H or Dihypergraph is a hypergraph wit oriented hyperedges (hyperarcs). The extremities of a hyperedge have a very specific sense. A directed hyperedge is defined as a couple $E_j = (A, B)$, where A *and* B two disjoint set of vertices (Fig. 4).

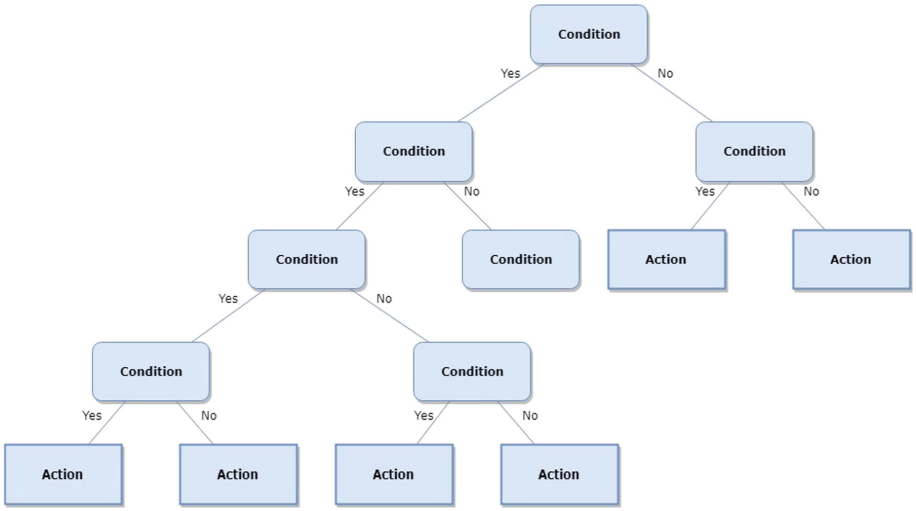

Fig. 2. Multi-hierarchical structure.

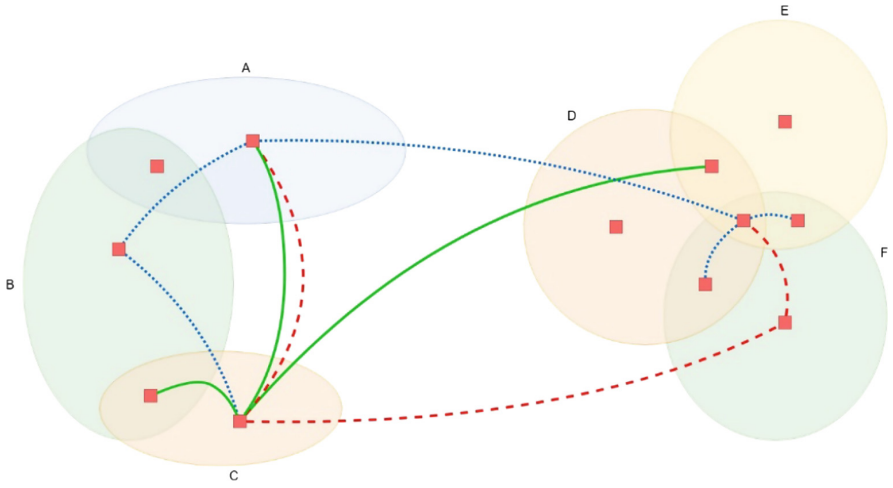

Fig. 3. Hypergraph.

Hypergraphs of various types are becoming increasingly common in systems for managing complex hierarchical structures, which makes it possible to use this mathematical apparatus as applied to Distributed Ledger Technologies [9]. The set of possible solutions is the overlapping sets of optimization functions at each of the levels of the management hierarchy that were presented above (Fig. 5):

A key factor in decision making in such complex control systems is time t, which significantly limits the use of traditional blockchain paradigms [10].

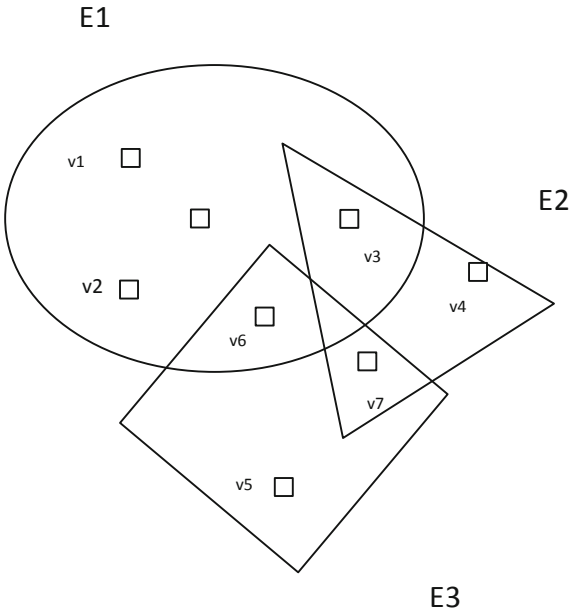

Fig. 4. Hypergraph composed of three hyperedges E_1, E_2, E_3.

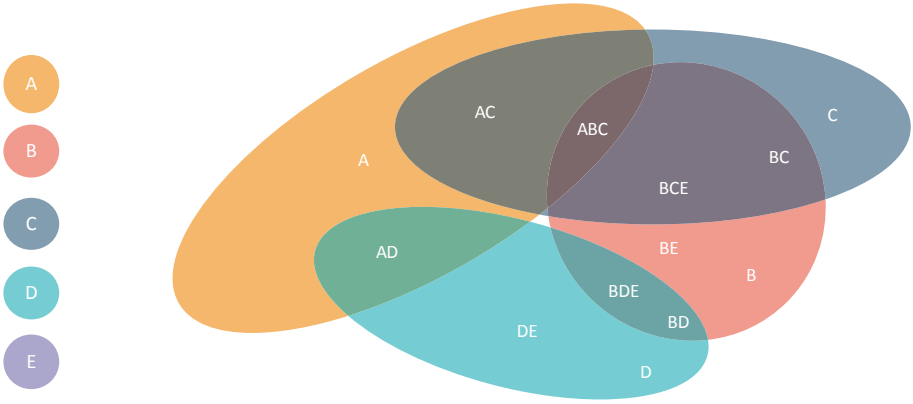

Fig. 5. Sets possible solutions.

2.3 Directed Acyclic Graph (DAG)

According to the authors, the use of a Directed Acyclic Graph (DAG) seems to be one of the promising areas for using the technology of a Distributed Ledger. In this type of graphs, there are no directed cycles, but there may be parallel paths that can lead to the end node, but in different ways. It should be noted that directed acyclic graphs are widely used, including in the tasks of artificial intelligence, together with, for example,

Neural Networks (NN), as well as in statistics and machine learning. The key factor in the use of direct acyclic graphs is precisely the speed of transactions, which is extremely important in real-time control systems with the use of a Distributed Ledger [11]. An example of a directed acyclic graph is shown below (Fig. 6):

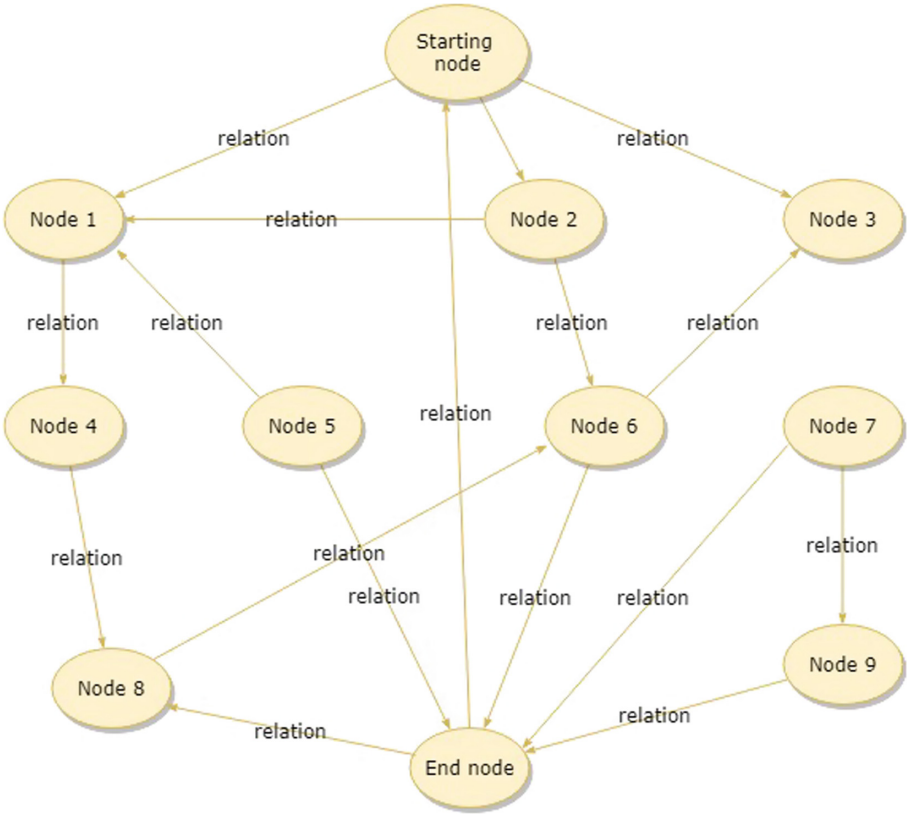

Fig. 6. Directed acyclic graph.

The use of the Directed Acyclic Graph as a mathematical tool is justified, in our opinion, especially in problems of multi-critical optimization. It should also be remembered that the DAG is a co-generalization of trees, that is, forests. Every acyclic digraph has an acyclic ordering of vertices [12].

3 Optimization

The control problem using the mathematical apparatus of graph theory is a complex multi-level optimization problem, which consists of several subtasks, namely:

– Construction of the graph and its nodes.

– Writing for each of the nodes its own objective function, the solution of which will determine the further direction.
– Solution of the optimization problem of finding the shortest path on a graph [13].

To achieve a sufficient level of generality, the utility of a path is defined by a global utility function built as the normalized weighted sum of the following partial utility functions [13]:

– A *topology*-oriented partial utility function, for which the utility of a path is equal to the opposite of the sum of the cost of all nodes belonging to a path.
– A *cost*-related partial utility function, for which the utility of a path is the opposite of the sum of the cost all nodes belonging to path.
– A *quality*-oriented partial utility function, for which the utility of a path is equal to the minimum quality of a node in a path.

Setting the control task will be as follows. We write the matrix of this form:

$$D_J = \begin{bmatrix} F_{1,1} & \cdots & F_{1,N} \\ \vdots & \ddots & \vdots \\ F_{M,1} & \cdots & F_{M,N} \end{bmatrix} \tag{4}$$

$F_{1,1}, \ldots, F_{1,N}$- control objectives function at the $1-$ level of the hierarchy and $F_{M,1}, \ldots, F_{M,N}$ - control objectives function at the $M-$ level of the hierarchy.

The solution of this problem, we can reduce, in fact, to the problem of optimizing Neural Networks or to the problem of optimizing deep models. In fact, in management and control tasks, often, there can be no single solution, and we thus arrive at a possible set of input data. $D_1, \ldots, D_J$. This set of control input matrices is mapped into a certain set of output data, for example, using Neural Networks [14].

That is, we can consider the task of finding the optimal solution using both DAG and Neural Networks. At the same time, we believe that it is the sharing of these two concepts that can bring a significant useful result [15].

4 Smart Systems

The authors see their use in various intellectual systems, where human participation is minimized, as an extremely promising direction for the development of Distributed Ledger Technologies. The use of this technology in the activities of energy companies in the following areas looks promising.

4.1 Energy

The energy sphere of using Distributed Ledger seems to us extremely promising for a number of reasons. Here are the main ones:

– Integrated Process Automation [16]. Distributer Ledger allows you to transform the landscape of traditional business with well-established markets and relationships. We also assume a significant reduction in the risks of certain transactions within the framework of traditional business processes.

- Intellectual billing. Using Distributed Ledger along with Smart Contracts allows you to automate calculations and measurements in Distributed Energy Systems [17].
- Sales and marketing. The key success factor here is the use of Distributed Ledger in conjunction with artificial intelligence systems (Machine Learning and Deep Learning). This symbiosis allows to ensure the construction of an individual consumer profile with the transfer of all data via secure communication channels.
- Communication with intelligent devices via secure channels significantly changes data transfer algorithms, as well as processes in energy companies.
- Security. The use of cryptography significantly increases the security of transactions and provides an unsurpassed level of trust between the participants of the system. Also, the use of Distributed Ledger technology allows better control of data privacy and identity management.
- Transparency achieved using Distributed Ledger.
- Competition. The use of DL technology makes it possible to qualitatively simplify the task of switching between energy suppliers, thereby increasing the flexibility of choice of suppliers for the consumer. There are few works on this subject, but from the point of view of game theory, in any case, the consumer has flexibility, which increases competition [18].
- Algorithms and business models. Automation of processes in the energy sector using the technology Distributed Ledger allows you to qualitatively change the traditional management paradigms. In fact, with the advent of Distributed Ledger, we will observe a breakdown of established development trends and business models. Traditional companies will become Decentralized Autonomous Corporation (DAC), which operate under completely different business laws [19]. This paradigm is quite new, the number of publications on this subject is extremely small [20] (Figs. 7, 8).

4.2 Robotics

The use of Distributed Ledger in cyber-physical systems, such as robotics, is a very promising direction, especially in the field of interaction and intellectual training of elements of such systems. Consider briefly the main directions and prospects for the possible use of Distributed Ledger in such systems:

- Intellectual interaction between robots. In this context, refers to the ability to share information, participate in training and decision-making without human intervention [21].
- Distributed solution of the problem. In this case, we use Distributed Ledger to collect distributed control robots and control the overall goal.
- Distributed Ledger for voting [22].
- Task optimization. In this case, Distributed Ledger is used to optimize the problem being solved from the point of view of controlling the interaction between each other intelligent agents and robots.
- Control of integrity, access, confidentiality and integrity.

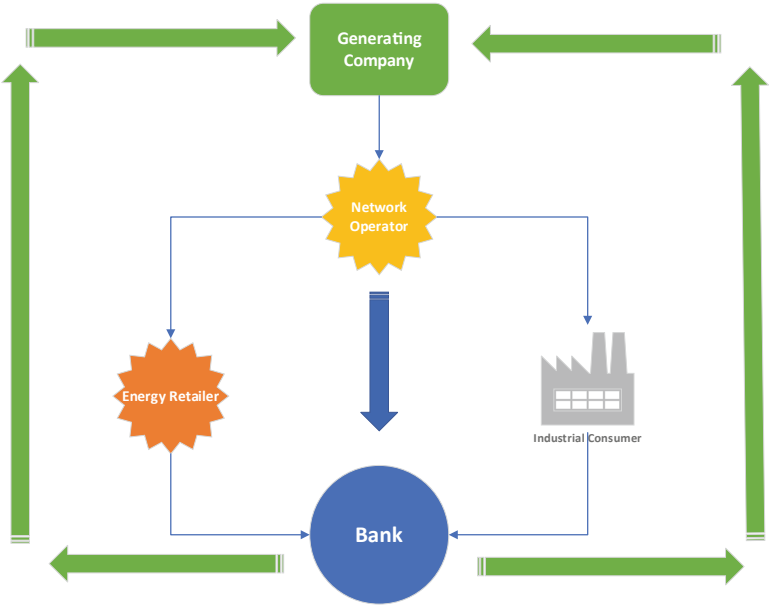

Fig. 7. Traditional market.

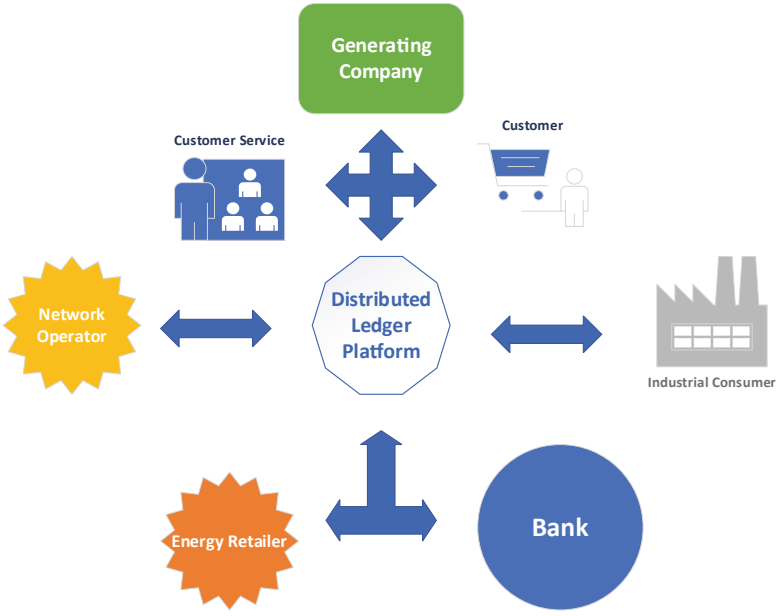

Fig. 8. Distributed ledger market.

The main problem of describing these advantages now is that all solutions are more prototypical in nature without any introduction into real activity. But all this is also explained by the innovation of the Distributed Ledger technology, the development of which is fraught with certain risks and nuances.

4.3 Virtual Power Plants (VPP). Definition

Recently, the concept of a Smart Grid (SG) of power supply has become very popular. A much more impressive continuation of this concept, according to the authors, is the concept of Virtual Power Plants. By introducing the Artificial Intelligence (AI) function into this concept, we are able to generate and sell energy in more flexible realities, taking into account possible supply and demand, which should allow the theory to maximize profits to energy suppliers not through high prices, but rather by reducing generation losses. At the same time, from the point of development of this direction, the authors do not yet have an established terminology. Different authors define this promising direction in their own way. In fact, VPP is defined as a combination of several players, namely, generating companies, consumers of different levels, other players who both produce and generate energy on demand or demand in accordance with requests or demand with minimal human participation [23]. There are alternative definitions, which, under VPP, understand a certain system that is capable in one way or another to generate and accumulate energy demand and supply [24] (Fig. 9).

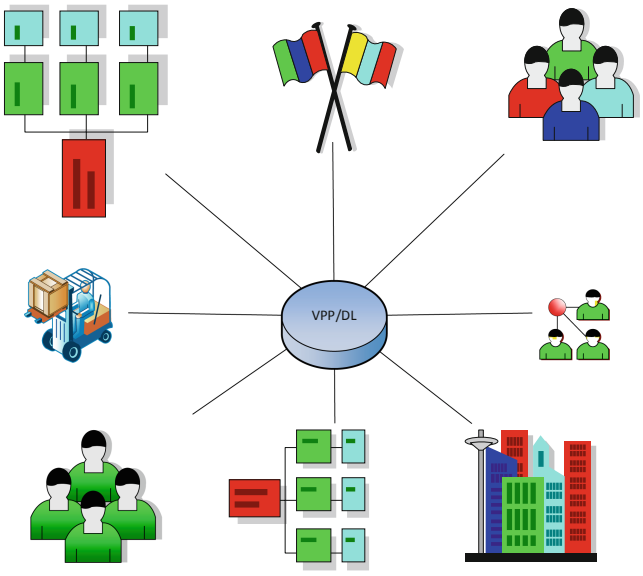

Fig. 9. Virtual power plants.

5 Algorithmic, Management and Technological Limitations

In the process of developing Distributed Ledger, a number of obstacles and limitations must be overcome. The key factor here will be the human factor, since this paradigm substantially rebuilds the landscape of traditional thinking and current business processes, for example [25]. Many authors completely do not take into account the human factor, which can be a significant constraint on the way of implementing these solutions. The next factor that can have a serious impact on the implementation of technologies in the near future may be legislative and legal restrictions that will not allow Distributed Ledger to develop quite rapidly. Various industry standards and regulations will not allow in this case to see rapid and explosive growth in the near future. The authors positively look at this paradigm. In this case, of course, we are aware that the development of this concept will require serious time and effort. An important, in our opinion, restriction may be the algorithmic and mathematical apparatus of this concept. Classical algorithms are not always applicable to real industrial automation solutions [26]. Many algorithms and approaches require more detailed study in the process of implementation in real smart devices, which hinders the development of automation processes based on a Distributed Ledger. Requires serious engineering adaptation of solutions in terms of process automation [27]. At the same time, the authors prudently do not consider open and closed platforms in this case, since the use of the latter will require serious improvement taking into account the features of each specific implementation. Well, an extremely important factor from the point of view of automation of management processes in real cyber-physical systems is the need to build target functions and their multi-criteria optimization [28]. All this will require extremely serious efforts both from the point of view of mathematics and of the engineering final implementation [29].

Nevertheless, the authors believe that the development of Distributed Ledger technologies will continue, which will lead to a profound transformation of all existing and future business processes.

6 Conclusion

In our opinion, Distributed Ledger is a unique technology of the future. Its peculiarity lies in the complex influence on the processes taking place in society. The breadth of future solutions is truly impressive. At the same time, most of the works focus on the technological nuances of technology, going into the field of classical Computer Science, which, in our opinion, is not very true [30]. In fact, it seems to us that the problem lies not so much in technology, but in the management and changing paradigms of doing business [31].

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