# Disruptions Are the Norm: Cyber-Physical Multi-Agent Systems for Autonomous Real-Time Resource Management

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**Abstract**. This paper analyses the new requirements for real time resource management systems based on multi-agent technology. It shows the growing demand for developing autonomous systems which combines resource allocation, scheduling, optimization, communication with users and control in one cycle and can respond rapidly to unexpected events in real time. To solve the problem the cyber-physical multi-agent systems are considered. The paper also dwells on the new impact which such systems bring into design of modern systems on the way from smart Internet of things – to new organizations and ways of user motivation.

**Keywords:** Autonomous Systems, Multi-Agent Technology, Resource Management, Cyber-Physical, Real Time.

## 1 Introduction

In the last decade, global economy has generated such levels of complexity, uncertainty and dynamics that make real-time decision-making on resource management critical for business efficiency, growth and sustainability [1].

Under these circumstances disruptive unpredictable events of any kind become more the norm rather than the exception, for example: new VIP order arrives, the already scheduled and half-implemented order is cancelled, discrepancies between planned actions and reality increase, resource is not available or is becoming more expensive, traffic jams, delays and breakagess, etc.

The typical reaction of current businesses to such disruptive events is to bring more oversized resources, to increase costly safety stocks and to inject slack-time. Such measures dramatically reduce the utilization and efficiency of business and push the increase of costs onto the customer [2], the risk being thus a drastic decrease in competitiveness of companies regarding the international competition.

This tendency is already a changing game for managing resources in many domains: manufacturing and transport, supply chains, aerospace, railways, etc. [3].

As a result new generations of growing businesses would like to become fully online and event-driven to make resource allocation, scheduling, optimization and control "on the fly" in real time (in one "cycle" - when all these processes can be triggered by events and combined) – to avoid peaks and to control bottlenecks in resource utilization, to reduce idle time and empty miles, etc.

To support this global shift of paradigm to real-time economy the new generation of industrial systems for resource management need to become more intelligent, fast-response, adaptive and flexible, scalable and reliable while being able to optimize their operations as much as possible and at a longer timespan.

Gartner, the world's leading information technology research and advisory company, says: "future is a digital thing" [4]. We would like to add: "a smart thing" as well – as a key factor to provide increase in levels of autonomy and efficiency.

From our point of view, the introduced typical reaction of current businesses to disruptive events comes from the centralized, highly hierarchical, monolithic and deterministic architectures inherited from the 70's with the principles of Computer Integrated Manufacturing (CIM). Current ERP systems are aligned with these principles. In the past years, disruptive events were the exception and the principles of CIM were consistent. Nowadays, disruptive events are the norm and these principles find their limits. Since the 90's, concurrent paradigms have emerged, based on a more reactive, local management of operations, assuming that disruptions are no more negligible: distributed control, multi-agent control, holonic paradigm to name a few. Meanwhile, these concepts hardly penetrate the industry and the real market because of their lack of predictability and guarantee of performances (in terms of cost, return of investments, reliability, safety…) [5]. In industries, similar approaches are developed, based on the assignment of more autonomy to lower level controls, such as the Kanban system or the concept of Autonomous Production Entity (ex: EAP in the French car industry first rank suppliers). But all these evolutions remain dependent on a strong relationship with a hierarchically organized decision-making process still inherited from the CIM principles.

Nowadays, the constantly changing environment, the constraints from competition, the nervousness in customers' behavior and the complexity of industrial processes rend these disruptions still more important in number and consequences. From our point of view, disruptions are now the norm and this should be considered as is from the beginning of the design of a manufacturing management system. Some research concepts are currently being improved to take this new norm into consideration, for example using bio-inspired fundamental principles of self-organization and evolution based on multi-agent technology [6-7]. Meanwhile, in our opinion, this is not sufficient since the principle "disruptions are the norm" is not explicitly considered during the design process of such systems.

In this context, this paper suggests a new concept of autonomous systems based on cyber-physical multi-agent technology for real time resource management considering that disruptions are the norm. To argue in favor of this statement in the first part of this paper we will make a brief overview of existing models, methods and tools for decision-making and will show their limitations and constraints. The second part will be focused on the new generation of multi-agent systems, which are organized as cyber-physical systems and support full cycle of resource management - to bring new levels of autonomy in decision-making.

In the third part we will discuss the concept and its first results and make recommendations for future developments.

## 2 New Requirements for Real-Time Resource Management

The traditional approach for resource management inherited from the CIM principles includes strategic and operational resource allocation, scheduling and optimization which are usually made separately and on different levels.

Strategic resource management refers to long-term plans according to information about future demand, capacities and costs and is made periodically in batch for a specific time period from several months to years. Operational resource management provides more granularity and deals with months-weeks-days. It also takes into consideration specific technology for order implementation, availability of equipment and workers, their skills, materials and instruments, etc.

Traditionally both approaches are focused on planning problems which are addressed by using a heuristic, rule-based and mathematical optimization solvers, which run in batch mode under the strong assumption that all orders and resources are given in advance and do not change during computations. Currently a number of mathematical optimization solvers are available on the market, e.g., IBM ILOG CPLEX Optimizer, Xpress Optimizer, etc. [2]. These solvers implement different methods of linear or dynamic programming, constraint programming and other methods, based on combinatory search of options, for example, the branch-and-bound methods. Such methods and algorithms are usually centralized and deterministic, top-down and sequential in analyzing all possible options which is very time-consuming and based on sequential achievement of solutions. Heuristics and meta-heuristics methods may combine different concepts and techniques, for example, tabu search, simulation annealing or ant optimization, to reduce the number of combinatorial options and to provide local optimizations to reduce the computational time. To compensate the loss of quality of such solutions, these methods try to use randomization and non-deterministic algorithms to explore and find ways to avoid local optimums.

Other key issues of traditional resource management under circumstances of uncertainty and dynamics are presented in Table 1.

Table 1. Key issues and consequences in resource management

| The issue of resource management | The consequences when disruptions are the norm |
|---|---|
| Planning is usually considered as top-down centralized batch process but in practice it is continuous, distributed and interactive. | Unpredictable events must be propagated to the top of organization and one needs to collect and prepare manually all the data for planning and decision-making. The independency (partition) |

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| | of problems principles can no longer be assumed: an issue emerges when previous ones are still not solved. |
| Delays in event processing cause growing gaps between plans and reality. | Decision lags increase, thus leading to possible instability (control theory principle). |
| A number of decision-makers with different decision-making criteria, logic of decision-making, constraints and preferences need to be involved. | Events may come at any time from any of decision-makers involved – it will require triggering of chain of decision revisions and changes. Impact of serial disruptions is seen globally, thus it is hard to evaluate and to test “what if?” solution scenarios. |
| High variety of objects and relations, factors, situations, orders and resources, technological operations, etc., mass customization and high competition. | A number of different types of events need to be considered: new order arrives, order cancelled, resource broken, etc. |
| Combinatorial search of options is NP-hard and very time-consuming and may require long hours even for small businesses. | Many events require immediate reaction (seconds and minutes), otherwise money and time will be totally lost with the loss of efficiency. Increased complexity increases reaction time. |
| Orders and resources are not usually given in advance. | Events are coming at unpredictable time and dynamically change orders and resources, company strategy, etc. Dynamic and stealth bottlenecks are faced with. |
| Many specific individual criteria, preferences and constrains for orders, products and technology, workers and equipment are often ignored. | There is no “optimal” solution for processing of new event – new balance of many interests of decision-makers must be found (consensus). |
| Interconnectivity of decisions may trigger long ripple effects. | New events may trigger full reconstruction of routes, plans and schedules. |
| Situation-dependencies: the number and value of criteria depend on results and could change during computations. | New events may change criteria, preferences and constraints for creating and revising schedules. |
| Domain-specific knowledge is usually hidden and difficult to formalize and continuously evolve during day-to-day operations. | It is hard to learn from experience and user interventions in decision-making process and manual adjustments of schedules, incl. constraints overriding.<br>Big data approaches need time to be completed, which is no more possible in a constantly changing environment of data and parameters. |

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| Part of this knowledge for decision-making is being available on the level of “ground” only. | It requires strong communication and interaction not only with managers, but also with workers, drivers, etc. |

As a result, the majority of traditional solutions require hours to make computations for real businesses but automatically generated plans are in practice only 40% feasible, at the same time requiring full re-run in case of user intervention or arriving of new events which always take place.

The new generation of industrial software for autonomous resource management must take into consideration that now “disruptions are the norm” when dealing with the complexity of the problem and when bringing radically new models, methods and tools for industry applications.

## 3 Multi-Agent Technology for Resource Management

Multi-agent technology usually is considered as one of new software engineering approaches for developing smart applications combining object oriented programming with parallel computations, AI components and telecommunications.

Multi-agent systems (MAS) differs from traditional software by distribution, decentralization, modularity, flexibility and robustness. But what is more important is that it gives new ways of solving complex problems, including resource management, with the use of bio-inspired principles of self-organization and evolution - when classical mathematical methods work not very well or doesn’t work at all [8].

In spite of the fact that MAS is mainly developed by academia, universities and research organizations, there is a number of first industrial applications of MAS which are already bringing real value for business [9-11].

In some applications, it has been showed that MAS technology helps to increase efficiency up to 20-40% [3].

But a new challenge is coming with growing tendency of total “uberization of all businesses” from forward-thinking lead users which are requiring new kind of “Google-mobile for business”.

Such type of applications will require fully autonomous solutions with minimum number of managers and will automatically set priorities, forecast new orders and other events, process new orders and serve resources individually, generate and analyze options for orders execution, recognize patterns, make schedules and adjust them in case of not-foreseen events, communicate, negotiate and coordinate decision with users, learn from experience, etc.

Current multi-agent solutions and applications are mainly used on the level of the basic support of strategic decision making – first of all, it means generation of options, simulations and analysis of results, making choice for further manual controlling of plans execution.

But the new objectives require fully autonomous cycle of decision making on the operational level which core part is the reaction on events, continuous re-scheduling and execution of plans – as it works for any living organisms.

In this paper we would like to outline the possible solutions by introducing the concept of cyber-physical multi-agent systems for autonomous resource management.

## 4 Cyber-Physical Multi-Agent Systems for Autonomous Resource Management

Multi-agent technology can be considered as way of building Smart Internet of Things for Industry 5.0 – where all things will not only represent physical objects but will be able to react on events, make decisions and plans and communicate and coordinate these plans with other agents and end-users.

This step is considered as the key differentiation with Industry 4.0.

Such a paradigm suits the “disruption is the norm” principle. Moreover, from our point of view, it generates an interesting paradox: there won’t be any disruptions anymore since everything is a disruption.

In such non-deterministic systems, based on parallel and asynchronic computations and coordinated decision-making processes, the agents representing the real world entities could not only continuously interact with each other trying to achieve a quasi-optimized solution in a more robust, flexible and agile manner but also simulate the behavior in real world. In this case MAS can be considered as self-completed virtual world which is in fact the computer model of real world where the software agents make the main decisions instead of people as decision-makers – as a result, it could be possible to design autonomous resource management system as a cyber-physical system (CPS).

An example of an autonomous multi-agent solution which is organized as a CPS for trucks management is shown in Fig. 1.

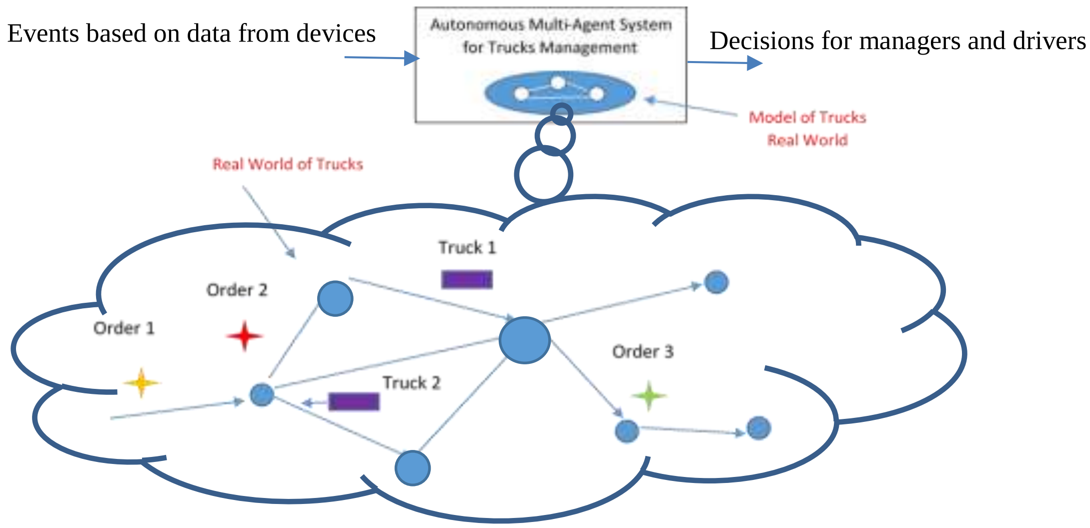


Fig. 1. Cyber-physical system architecture: an example for trucks management

To support such kind of decision-making, it is required to provide the full cycle of resource management including fast reaction on events, allocation of orders to resources, scheduling of orders/resources, optimization of orders execution (if time is available), communication with users, monitoring of plan execution, re-scheduling in case of growing gap between the plan and reality, and, finally, learning from experience to get and make available new domain knowledge which affects decision-making.

As it is shown in Fig. 1, the system considers multi-agent world as a model of real world which is continuously updated by events and is used for generating decisions through negotiations of agents representing orders, trucks, etc. The decisions made are forwarded to mobile phones of users in real world as instructions and schedules which can be adapted by users.

Such cycles help autonomous system to keep schedule up-to-date with reality and generate reasonable and feasible decisions.

In this context the multi-agent technology is suitable to face the current challenges associated with industrial strategical and operational planning problems, especially when facing the need to be extremely adaptive.

## 5 New Functionality of Autonomous Solutions when disruptions are the norm

The new functionality of autonomous multi-agent solutions will require challenges and make impact on the following levels:

- Smart Internet of Things – it will be required to support the full cycle of decision-making on the level of physical or abstract entities.
- Models of Technology Processes and/or Business Processes – classical approach for control and accounting will be extended to the models of physical world objects and processes.
- Decision-Making Support Systems – start with support of decision-making but will move to fully autonomous systems.
- Knowledge Bases – extremely important for decision-making as a tool to separate domain knowledge from source code and provide learning from experience for the future.
- Organizations – will be significantly changed by “uberization” of all resources, discovering new opportunities for people, motivating them by sharing profit in case of more efficient decision-making.

As a result, not only the software solutions will become more open, less centralized and hierarchical – but also the organizations. At the next stage they will become more open, distributed, flexible and efficient overriding barriers between departments for supporting teamwork and developing human-centric organizations with full focus on talented, active, knowledgeable and well-performed people.

Cyber-physical multi-agent systems for autonomous real-time resource management must be considered as a decision-making tool for such innovations helping to handle unpredictable disruptions which are becoming the norm now.

## 6 Conclusion

The aim of this paper is to develop the new concept of autonomous systems based on the principles of cyber-physical systems, multi-agent technology and Internet of Things where disruptions are considered as the norm.

New generation of autonomous multi-agent systems will allow enterprises to move to real-time economy and help improve efficiency of resources, quality of the service, reduce expenses and time, risks and penalties.

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