



Project Coll-Plexity: Collaborative Complexity – Collaborations as Complex Systems
 Project is co-financed by NEST Programme, FP6, under Contract no. 12781

The Coll-Plexity Project

Towards a Generic Model of Complexity

Engaging in collaborations and maintaining relationships within these has become a major concern for managers in industrial companies. Part of this change arises because of the possibilities of information technology and data-communication, the globalisation of markets and the ongoing specialisation of firms. These trends foster the specific characteristics of (trans-national) networks of companies: collaboration, decentralisation and inter-organisational integration. Although collaboration activities among enterprises in the production industry have significantly increased during the past years, there is still a high failure rate and only in a few cases the original objective of collaboration could be reached. From our point of view, the approach of taking the complexity into account when setting up a collaborative system might increase their success rate. Management in highly dynamic environments needs to address the increasing complexity of with adequate collaborative structures. However, direct transfers of current management approaches to enterprise collaborations regularly fail as they lack problem-oriented interdisciplinary inferences.

Therefore, basically new approaches are required to close this gap. The application of principles of complex systems from various different sciences - such as evolutionary biology or philosophy of science - to collaborative, socio-technical enterprise networks might yield these required approaches. The COLL-PLEXITY project targets the interdisciplinary development of a Generic Model of Complexity (GeMoC) that

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www.coll-plexity.net

shows the relations between the complexity of problems occurring during a collaborative order processing on the one hand, and a collaborative system on the other hand. This knowledge about the influence of a certain characteristic of a collaborative system on a certain collaborative problem is a promising step towards the complexity oriented design of collaboration, which is the paramount scientific objective of the project consortium beyond the COLL-PLEXITY project.

There are three main steps that constitute the project: First of all, a common understanding of complexity adequate to the need of the complexity oriented design and management of collaborations has been elaborated (see the complexity definition chapter of the newsletter). Secondly, both the complexity of the real-life problems that occur during the collaborative order processing and the complexity of the collaborative systems that potentially could be applied for the collaborative order processing has to be modelled. Finally, the matching of the complexity of the problems with the complexity of the systems has to be performed in terms of „which problem can be influenced by which system component or design parameter? “. This newsletter provides an overview of the current state of the developments within the project. The results we achieved so far are mainly related to the completed workpackage 0 and the running workpackages 1 and 2 - the elaboration of description models for collaborative problems (workpackage 1) as well as for collaborative systems (workpackage 2).

Editorial

We welcome new and existing readers to the second issue of the Coll-Plexity Project Newsletter. The aim of the newsletter is to keep professionals and those working in the field of collaborations and complexity management informed about the activities and developments of the Coll-Plexity research.

The content of the newsletter as we have envisaged it includes news about the project and theoretical contribution which pertains to the overall subject-matter of the project, namely complexity in management or even more particularly: management of complexity in networks and collaborations.

In this issue you could learn about the Generic Model of Complexity (GeMoC) - the main goal of the Coll-Plexity research that focuses on the relations between the complexity of problems occurring during the processing of a collaborative order simultaneously with an adequate collaborative system. This issue will also present for the very first time the definition of complexity as characterised by consortium members in agreement. An introduction to work package one, which aims at creating a comprehensive description model of problems in network setup and management of collaborative R&D, and manufacturing will be presented in this issue. In the penultimate section of this newsletter a description of work package two, which aims at developing a description model in terms of a framework for both guided and self-organised networks and collaborations in production industry will be presented. Finally we are presetting with great honour a research discussing production structures as complex adaptive systems.

We hope this issue will be of interest to you and we appreciate your comments and contributions. Moreover, we shall be happy to send our newsletter to people and organisations that you would kindly recommend.

You are always welcome to contact us directly, at my E-mail: gititw@precise.co.il.

Nir Yerushalmi, Editor
Precise Management Services for Design Companies Ltd.

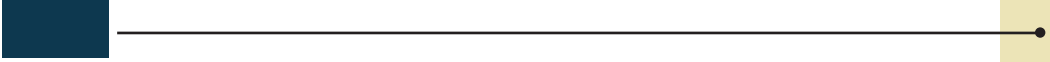


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Definition of Complexity:



The Coll-Plexity consortium characterise a complex system as a system which has a high number of very different involved elements. These elements are connected to each other and the interaction is highly dynamic. In addition many interdependencies exist between these elements. The difference to a complicated system is that a complicated system can be disassembled in its elements.

With the investigation of the different elements, the interaction and the dependencies, a prediction of the development or behaviour of the system is possible. In this case it is assumed that all dependencies and interaction are known. In contrast to a complicated system a complex system is subjected to uncertainty. Hence not all dependencies and interactions of the system are noted. This uncertainty coupled with high dynamics differentiates a complex system from a complicated system. As part of the dynamics a complex system is an open system which allows the appearance and disappearance of influencing factors. These can be caused through internal as well as external factors. Some external factors may be for instance regulations, people, culture, and politics. Recapitulating, complexity is characterised by:

1. large number of influencing factors, (multiplicity)
2. different factors, (variance)
3. high level of interaction between factors,
4. dependencies between some of the factors,
5. uncertainty and
6. high dynamics

Following our definition, the characteristics uncertainty (5) and dynamics (6) need to be fulfilled to talk about complex system. In addition, at least one of the characteristics 1-4 has to be fulfilled.

Work package 1 – Problem description model

The modelling of the collaborative problems in production industry is the greatest challenge subsequent to enterprise modelling and integration. Identifying, defining and specifying the relevant problem elements, i.e. determinants, are the core challenge in this work package. The core complexity drivers in different collaborative tasks such as product ideation and design are expected to be fundamentally different from those determining the implementation and quality of distributed manufacturing system. At the same time however both collaborative tasks are interlinked and must be reflected in a holistic sense. Collaborative design is challenging because strong interdependencies between design issues make it difficult to converge on a single design that satisfies these dependencies. The dynamics of collaborative design are typically characterised by multiple iterations and heavy reliance on multi-functional design reviews, both of which expensive and time-consuming, poor incorporation of some important design concerns, typically later lifecycle issues, as well as reduced creativity due to the tendency to incrementally modify known successful designs rather than explore radically different and potentially superior ones. Collaborative manufacturing at the same time is chiefly dependent on the outcome of the collaborative design process. The quality and quantity of product information determines to a large extent how well the manufacturing, assembly and distribution process can be performed. The configuration of manufacturing network cooperation follows the optimisation of the combinational process of capacities and competences against the requirement profile of a product's quantity and quality. The complexity of this process depends on the features that are relevant in terms of customer perception. A breadth analysis of complexity problems has been enforced in WP 0. Now the results have to be deepened in WP 1 by the workshop analysis and the ongoing documentation at the industry partners. In a first step, the relevant problems in collaborative Research and Development (R&D) and manufacturing have been assessed in continuous interaction with industry partners in the field of production industry, particularly collaborative R&D and manufacturing. The problems have been collected and structured in the context of the developed workshop concept.

The developed workshop concept consists of three modules: the problem description sheet, the problem description model as well as the workshop and expert interview analysis concept. The problem description sheet was used during the workshop analysis phase and the expert interviews for classifying the problems in network setup and management of collaborations. It was used either during the workshops for taking up the problems or after the workshops and expert interviews for wrap up of the discussion. The problem description model structures the problems in network setup and management of collaborative Research and Development (R&D) and manufacturing. On the basis of different dimensions systematically classification of collaborative problems will be possible. The third module is the workshop and expert interviews analysis concept where the problem description model was matched with practical problems of industrial companies. This for, findings have been deepened and explicated within the expert interviews and the workshops at the COLL-PLEXITY industry partners Schiesser and Virtuelle Fabrik. The final results of the workshops and expert interviews can be summarized in the following list.

-
- Heterogeneous requirements on products and processes causes an increasing product and process complexity
 - A high variant multiplicity cause several problems along the chain of economic added value
 - The interaction between different technological disciplines and company locations cause problems along the product development processes
 - The implementation of interfaces causes problems as a result of a high functional dependency
 - Product data is not complete or the access is not permitted at all locations
 - A global binding development process enables the company to control and operate an allocated development
 - The reliability of agreements depends on the mindset of the participants which is very different determined by the culture.

Work Package 2: Multi-disciplinary hypotheses from network and complexity research

The aim of this work package is to develop a description model in terms of a framework for both guided and self-organised networks in production industry. The basic idea of this framework is to synthesise the ideas, theories, models and approaches of multiple disciplines that deal with complexity in networks or collaborations in a certain way.

Before we started with the development of the targeted model, as a first result of the work carried out in this workpackage a common understanding of the term "complexity" within the project was elaborated (see the complexity definition chapter of the newsletter). The resulting definition is an important base for the further work within the whole project as complexity is the central issue we deal with in the project. Most effort has been spend so far on the multi-disciplinary research on existing ideas, theories, models and approaches addressing complexity in networks or collaborations that potentially contribute to the overall project aim - the development of a Generic Model of Complexity (GeMoC). The main disciplines considered were evolutionary biology, computer science, complexity science, socio-technical approaches, cybernetic management and philosophy of science. In addition, relevant information from other disciplines such as physics has been collected at conferences and meetings initiated by GIACS, a coordination project of complexity related projects within the 6th framework programme of the European Commission. The findings of the multi-disciplinary research were presented and discussed at a workshop. As a result, the main relevant parts that should be incorporated in the GeMoC have been identified.

The next step, which is already running, is the elaboration of description models for both guided and self-organised networks. According to the overall project objective, the focus of the description models lies on the collaboration in terms of an active order processing. However, important aspects of networks (which are considered as loosely connected bases for collaborations) will be taken into account.



The targeted structure of the model is the following (see figure 1):

-On the one hand there will be a common model describing all the components and their characteristics used in any model. This model will distinguish between different levels:

- The enterprise level, which describes the characteristics of a single enterprise that are relevant for a collaboration,
- The level of interrelation, which considers all relevant characteristics related to the interrelations between the players in a collaboration,
- The context level, which describes characteristics such as the architecture, the functions, the operational coordination and the development of a collaboration,
- The context management level, which considers the possibilities to influence the context. This is the most important level for the distinction of guided and self-organised networks and collaborations.

-On the other hand, there will be different models which stem from the research findings in each discipline. These models consider the basic components of the common model in a certain way according to the corresponding discipline

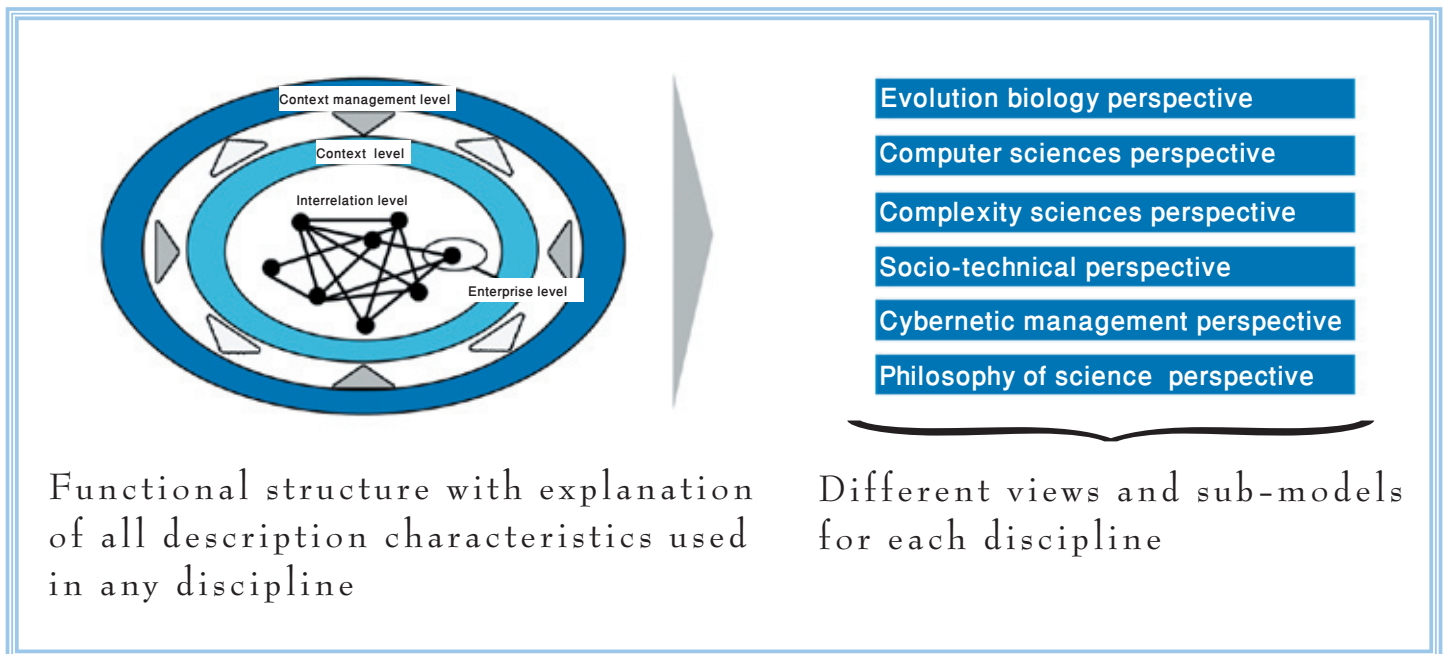


Figure 1: Structure of the targeted description model for guided and self-organised networks

After the elaboration of the draft models, they will be reviewed and - if necessary - adjusted with regard to the model of problems that is currently developed in workpackage 1.

Work Package 6: Dissemination and Exploitation

The aim of this work package is to develop a practical plan for knowledge disseminating and exploiting with relation to the Coll-Plexity research. The dissemination and utilisation activities in this research consist mainly of newsletters, seminars, workshops and conferences. We believe that the work carried out in WP6 is as important as the research itself. In addition, a correct dissemination process will generate comments and interest from other parties in the research sphere, which will enable us to enrich the consortium with external knowledge and information.

Work Package 6 involves various tasks which together make up the objective of "development of dissemination and exploitation strategies". The practical planning of the dissemination tasks uses every possible tool to create "knowledge transfer" between various organisations and institutes and Coll-Plexity consortium members. This includes implementing a way of thinking and raising important questions in the industrial and academic spheres through the publication of this very Newsletter, as well as individual and independent articles written by consortium members in scientific and management related journals and magazines.



So far the following tasks have been accomplished in work package 6:

- A database of 47 research-related articles published by consortium members was formed. Articles are classified according to being related directly or indirectly to Coll-Plexity and deriving directly from the research or not. Major part of these publications can be found on the website, some are published from time to time in the Newsletter.
- Maintenance of continuous connection between various bodies which deal with complexity and its implications. Up to now we mapped 5 organisations and institutes related to complexity; consortium members joined these organisations as members.
- An overview of related events in the field of complexity, management, manufacturing systems and other relevant topics to the research was drawn. Consortium members examine these events and choose whether to attend and introduce the research or participate as representatives of the research only. To this end, consortium members participated in 17 such events and exposed the project to the international research community.
- **Joint academic publication** - the consortium has decided to publish its first common academic paper to reveal and describe the research achievements to this end. A detailed plan of the topics to be included was drawn, and responsibilities on various tasks were distributed between the members. Moreover, a list of 40 potential magazines and journals was produced.

- **Follow up proposal**- the consortium commenced planning possible follow up research, which will be based on the conclusions drawn from Coll-Plexity. An initial presentation was prepared and the idea starts taking shape.
- **Study Programs** - the basic foundation was laid for teaching Coll-Plexity research findings in the institutes participating in the research.
- **Newsletter** - each newsletter contains various deliverables from the research, along with articles published by consortium members, prepared especially for the newsletter or whether published in other places before. As the project will develop we expect the newsletter to be published more frequently.
- **Website** - the project website was inaugurated by the coordinator in December 2005. The site was designated to bring forth to the research community and the general public information about the project. In addition, the site is an important marketing platform of the project.

This work package is very important as it brings Coll-Plexity to the research community, and to the industry. With the tasks performed on this work package we could identify strengths and weaknesses, and stay tuned to both the industry, as well as research community. We hope to reach as many relevant people and institutes and promote Coll-Plexity which indeed is a state of the art research.



Industrial application of VITAL results

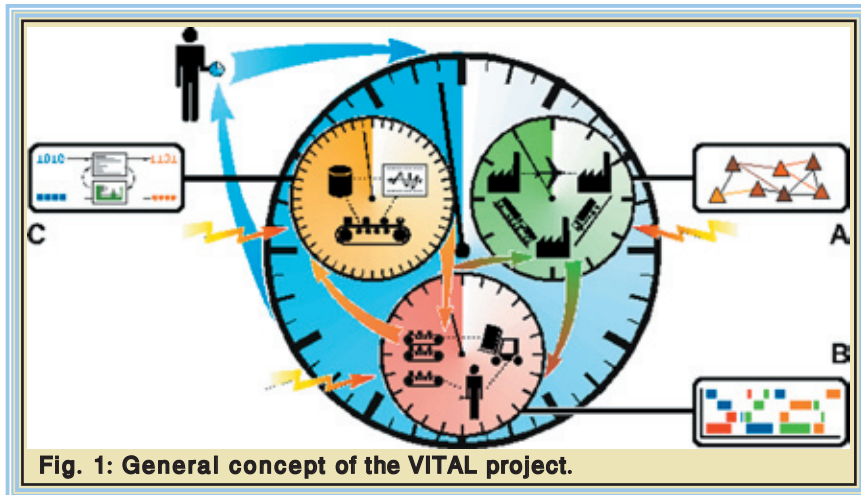
One of the most important trends in manufacturing is manifested in the paradigm of *customised mass production* (at a price near to the level in mass production of customised products) Project *VITAL: Real-time Co-operative Enterprises*, led by Coll-Plexity partner *SZTAKI*¹ aims at the development of IT-solutions for enterprises producing mass customised products and working in networks. Other issues to be dealt by the project include globalisation & increasing competition in frequently changing uncertain environment; increased complexity in production processes, manufacturing systems and enterprise structures and autonomous, partly competing - partly cooperating production structures.

The challenges and the answers offered by VITAL can be summarised as follows:

Challenges	VITAL's answers
Complexity	Autonomy & cooperation
Changes and disturbances	Intelligence
technical-economic solutions	Integration & optimisation
Quick reaction ability	Real-timeness

The project is set to research and develop new methods for the real-time management of complex technical and economic systems that work in changing, uncertain environments. Since the methods come from various, novel areas of informatics, operational research and knowledge-based systems, their integration balances optimisation, autonomy and cooperation.

The project seeks solutions originating at the level of production networks, through single enterprises to production lines, which can ensure optimal / near-optimal behaviour of the entire system, in real-time fashion required by the level of production. The following figure represents the general concept of the project:



Orders are to result in good quality, at the agreed price and on *time*. The customers may not necessarily realise that in fact, they deal with a number - at *time* large of production networks. The importance of the time is illustrated by the watches in the figure, which relays the different levels (network, enterprise, production line) of the production expected to react on the external and internal changes, demands and disturbances (indicated by the lightning signs) with a *reaction time* corresponding to that of the query. The problems to be solved are as follows:

- Integrated production planning and scheduling (B);
- Real-time production control (C);
- Management of distributed, cooperative systems (A).

This sequence derives from the fact that high-level resource-management and scheduling of enterprises can give the basis, on the one hand, to reliable, optimal or near- optimal management of supply chains and production networks. On the other hand, it allows for handling changes and disturbances on shop floors or production lines.

The SZTAKI developed scheduling system was successfully integrated in the information system of one of the factories (the largest one of such kind in the world) of the main industrial partner. This can be regarded as a highly successful result of the entire project. The automatic scheduling system is in use by the industrial partner - which operates in the field of customised mass production. It handles some 1,000 orders a week for the more than 100 production lines, resulting in some 3,000 pallets of finished goods. The quick reaction time of the system enables it to be a nearly interactive decision support tool. The tool allows better utilisation of the technical and human resources, increase of productivity, better customer service and improved effectiveness of the entire value creation chain.

Production Structures as Complex Adaptive Systems

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Abstract

Theoretical study of complex systems receives more and more attention as most sciences broaden their perspectives. First, the paper overviews a few important complexity approaches, then it argues that complex adaptive systems (CASs) are especially important for production control research. A CAS based scheduling mechanism is also described in which agents apply reinforcement learning to handle the complex production control task. Experimental results on industry related data and on the adaptive capabilities of the system are presented, as well.

1 COMPLEXITY THEORY

The need to be able to measure the complexity of a system, structure or problem and to obtain bounds and quantitative relations for complexity arises in more and more sciences: besides computer science and engineering, the traditional branches of mathematics, statistical physics, biology, medicine and social sciences are also confronted more and more frequently with this problem.

There are many different kinds of theories and approaches to complexity. In the classical theory of computational complexity, in computer science, complexity is measured by the quantity of computational resources (e.g., time, storage, program, communication) used up by a particular task. Kolmogorov's complexity approach defines the complexity of a structure as its minimal description length, e.g., by a program on a universal Turing machine.

Topological complexity mostly uses graph and network theory as its basis. There are several measures to define the complexity of a graph: e.g., there are symmetry-based measures, which often apply the concept of entropy, other measures include: average- or normalized-edge complexity, subgraph count, overall connectivity, total walk count, and others based on adjacency and distance.

Information complexity, viz. entropy, tries to measure the randomness or disorder of objects. An intuitive understanding of information entropy relates to the amount of uncertainty about an event associated with a given probability distribution. The classical approach of Krohn-Rhodes complexity, introduced in the 1960s, aims at measuring the complexity of abstract algebraic structures, such as groups and semigroups, with the concept of homomorphism and wreath products.

2 COMPLEX ADAPTIVE SYSTEMS

One of the newest complexity approaches, which is also in the center of this paper, is the theory of Complex Adaptive Systems (CASs), which has deep roots in the interdisciplinary field of Multi-Agent Systems (MASs) of artificial intelligence research, [1], [2], [3]. The formers are special cases of the latters which represent a general and flexible framework to describe and model (partially) autonomous systems including their interactions [2]. An agent is basically a self-directed entity, it is an object with its own value system and a means to interact (e.g., communicate) with other objects like this [4].

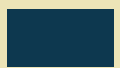
2.1 Multi-Agent Systems

A MAS is formed by a network of computational agents that interact and typically communicate with each other. In hierarchical (guided) architectures, there are multiple levels of subordination relationships. In a heterarchical (self-organized, organic) architecture, agents communicate as peers, no fixed subordination relationships exist and, usually, the global information is eliminated, and, consequently, global optima cannot be guaranteed. On the other hand, advantages of these heterarchical multi-agent systems include: self-configuration, scalability, fault tolerance, emergent behaviour, massive parallelism, reduced complexity, increased flexibility, and reduced cost [4].

2.2 Complex Adaptive Systems as Multi-Agent Systems

What distinguishes a CAS from a MAS is the focus on top-level properties and features like self-similarity, complexity, emergence and self-organization. Basically a CAS consists of large numbers of diverse entities (for example, agents) that are interconnected and have the capacity to change and learn from experience [1], [2]. Many of our most difficult problems centre on CAS.

The typical characteristics of complex adaptive systems include dynamics involving interrelated spatial and temporal effects, correlations over long length- and time-scales, strongly coupled degrees of freedom and non-interchangeable system elements, to name only the most important ones. Both the CAS and its environment simultaneously co-evolve in order to maintain themselves in a state of quasi-equilibrium, i.e., on the edge of chaos [5]. Emergent phenomena [6] are important characteristics of CAS.



3 MULTI-AGENT SYSTEMS IN MANUFACTURING

Engineering design; process planning; production planning and resource allocation; production scheduling and control; process control, monitoring and diagnostics; enterprise organisation and integration; production networks; assembly and life-cycle management; were enumerated in a very recent survey on agent-based systems in manufacturing [7]. The application fields cover all important aspects of manufacturing indicating the viability of the MAS-approach. Agent technology is considered an especially important approach for developing distributed manufacturing systems. Holonic manufacturing systems (HMSs) consist of autonomous, intelligent, flexible, distributed, co-operative agents or holons [8]. One of the most promising features of the holonic approach is that it represents a transition between fully hierarchical and heterarchical systems [9]. HMSs with adaptive agents received a great deal of recent attention [10].

3.1 CAS-Based Adaptive Distributed Production Control

In practice, the agents mostly have only incomplete and uncertain information on the environment (surrounding world) that they have to work in, additionally, this environment could be non-stationary. Moreover, they also have to face algorithmic-complexity problems, viz. even if they deal with static, highly simplified and abstract problems in which the solution is surely exists and can be attained in finitely many steps, they may not have enough computation power to achieve it in practice (as this is the case, for example, with NP-hard problems).

A promising way to overcome these difficulties is the application of machine-learning techniques. It means designing systems which can adapt their behaviour to the current state of the environment, extrapolate their knowledge to the unknown cases and can learn how to optimize the achieved solutions.

Several complex systems can be effectively dealt with approximation. This means that we use a solution/model which is "close" to the one that we have originally aimed at, however, it is much more simpler. For example, a lot of very-hard/complex (combinatorial) optimization problems can be efficiently handled, if we satisfy with approximate solutions, viz. solutions which are not optimal (suboptimal) but close to an optimal one. Similarly, very complex (e.g. continuous) structures can be compactly approximately represented using a class of functions which are easy to manage (for example, parametric functions, such as polynomials, splines, wavelets or even artificial neural networks). Naturally, the effectiveness of the approximation strongly depends on the used architecture and on the way we measure the distance between the objects.

4 A CAS APPROACH TO PRODUCTION SCHEDULING

Now, an adaptive iterative distributed scheduling algorithm is proposed that operates in a market-based production control system. The idea of negotiation based scheduling has emerged long before, for example, a holonic market approach with cooperative agents and local problem solving can be found in [11].

First, the basic frame of the approach is informally defined. In a multi-agent based manufacturing system, autonomous agents control different real world entities. In the presented system the two most important types of agents are the resource agents and the order agents. Resource agents control physical parts (such as machines, furnaces, conveyors, pipelines, material storages, etc.), while order agents control the production of a job. In the presented market-based production control system if a new job arrives at the system, a new order agent is created and associated with that job. An order agent or a group of cooperating order agents announces a sequence of operations and the resource agents can bid for that sequence. Only resource agents being able to do at least the first operation of that job are allowed to bid. Before an agent bids, it gathers information about the possible costs of making that sequence. If the sequence contains only one operation, the agent has all the information it needs, however, if the sequence contains other operations as well, which probably cannot be processed by the machine of the agent, it starts to search for subcontractors. It becomes a partial order agent and announces the remaining part of the sequence. The other resource agents which can do the next operation, may bid for the remaining operation sequence. Consequently, a recursive announce-bid process begins. At the end, when all the possible costs of that (partial) job are known, the agent bids. If the order agent which announced that job, is contented with it (it is the best bidder), the agent (and its subcontractors) get the job (award). Therefore, the schedule generation in the suggested agent-based system is a recursive, iterative process with announce-bid-award cycles based on market mechanisms.

The main problem with the mechanism described above is the combinatorial explosion of the possible schedules. More precisely, it makes a complete enumeration, in some sense, and thus, its time complexity makes it unusable in practice. The agents should not investigate every potential schedule, because this can be extremely time-consuming. If an agent wants to bid for an operation sequence and it needs information about the production costs of the part of the job, which it cannot do, it should not announce the part to every resource agent. It should make only a restricted tendering among the agents that will give a presumably good bid. They can apply adaptive sampling to learn the potentially good partners to cooperate with. These partner-value estimations can be learnt with neurodynamic programming, which is the combination of reinforcement learning and artificial neural networks, especially kernel machines.

4.1 Markovian Production Control

It can be shown that this scheduling approach can be formulated as a special Markov Decision Process (MDP) [3]. The aim of learning in an MDP is to find an optimal (or approximately optimal) policy that maps the states (possible situations) to the control actions available in that state. Formally, if we denote the state by x and the set of actions available in that state by $U(x)$ than an action a (form the $U(x)$ set) is executed by $\pi(x,a)$ probability, where π is called control policy. In an MDP the state transitions are stochastic, however, the Markov property is assumed. There is a reward $r(x,a)$ associated with each state-action pair and the aim is to find such a policy that optimize the expected cumulative rewards over time [12].

In theory, the optimal control policy of a (finite) MDP can be computed exactly by dynamic programming methods, such as value iteration, policy iteration or the Gauss-Seidel method [12]. However, due to the "curse of dimensionality" (namely, in practical situations both the required memory and the amount of computation is extremely large) calculating an exact optimal solution by these methods is practically infeasible, except very small problems. Reinforcement learning techniques often try to use simulation as a sampling technique to overcome the computational demands by advanced statistical approaches, such as MCMC.

4.2 Three Levels of Learning

The paper suggests using Watkins' Q-learning algorithm [12] to calculate a near optimal policy. The aim of Q-learning is to learn the optimal action-value function Q^* rather than directly learning an optimal policy. The system can search in the space of feasible schedules by simulating the possible occurrences of the production process with the model. The trials can be described as state-action pair trajectories. After each sample (trial, iteration) the system makes updates asynchronously on the approximated values of the visited pairs according to the Q-learning rule. Only a subset of all pairs is updated in each trial.

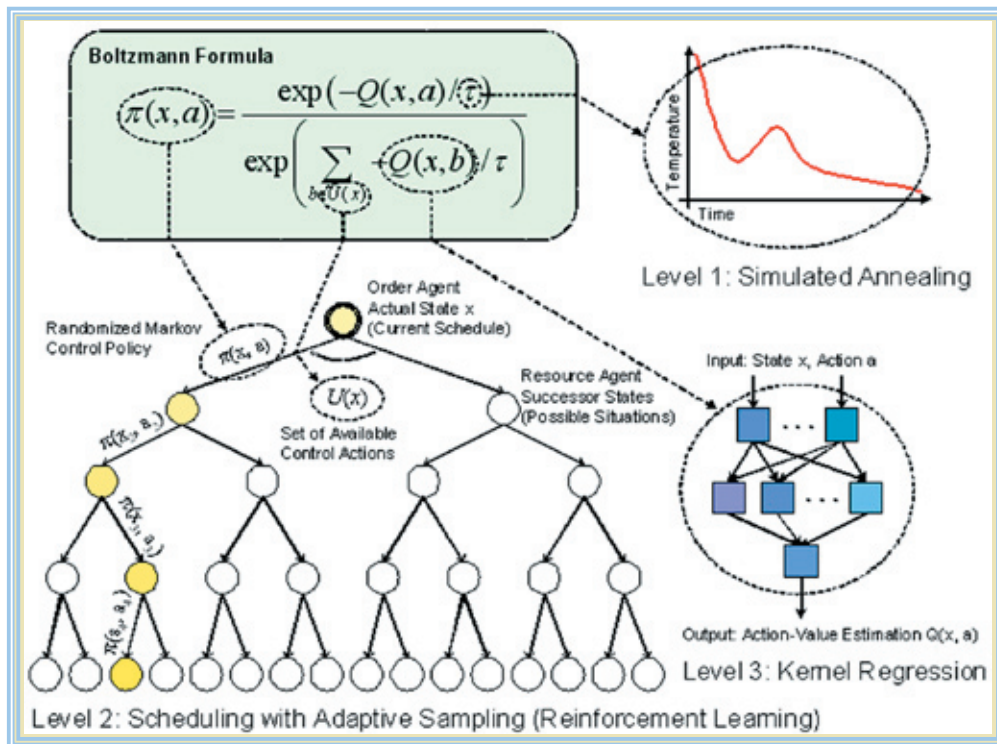


Figure 4.1. The three main levels of learning combined by the Boltzmann formula.

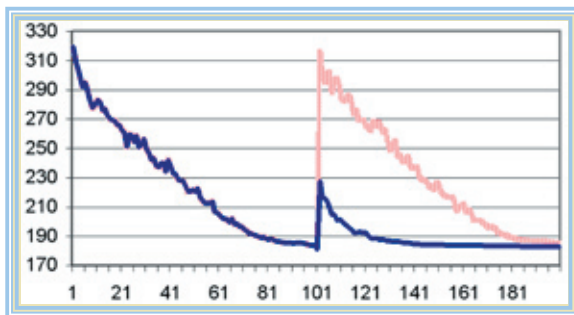
The paper suggests a triple-level learning mechanism to achieve effective production control, see Figure 4.1. The most important learning level is the level of reinforcement learning, since it computes an approximately optimal policy through adaptive sampling. The action-value function is represented as a kernel machine and the temperature of the system is controlled by a Metropolis algorithm. The progress of the system during learning can be described as follows:

- (1) Simulate a state-action trajectory from the starting state using order and resource agents and a policy generated by the Boltzmann formula.
- (2) After a terminal state is reached, back propagate the final performance and update the Q estimates of the visited states according to Q-learning.
- (3) Fit a smooth approximating function to all of the available Q estimates, e.g. by SVR type Kernel Regression (Gaussian kernels).
- (4) Decrease the temperature, except there were changes and disturbances in the system (in that case increase the temperature).
- (5) Increase iteration counter and, unless some terminating conditions are met, go back to (1).

4.3 Experimental Results

Our RL-based scheduling solution was tested on both artificial (benchmark) and real-world (industry related) data. First, experiments were carried out in order to verify the above algorithm in dynamic and uncertain environments. In the left part of Figure 4.2 the aim of scheduling was to minimize the make-span (Cmax).

The adaptive features of the algorithm were tested by confronting it with unexpected events, such as: machine breakdowns, new machines, new jobs and/or job cancellations. In the left part of Figure 4.2 the horizontal axis represents time, while the vertical one, the applied performance measure. It was made by averaging one hundred random samples. In these tests a fixed number of 20 machines were used with few dozens of jobs. In all test cases at time $t = 100$ there were unexpected events. The results, blue (solid) line, show that the system presented is adaptive, because it did not re-compute the whole schedule from scratch, but it tried to use previously acquired information. The performance measure which would arise if it recomputed the whole schedule is drawn in red (dotted).



resources	tasks	1000 iter.	5000 iter.	10000 iter.
16	140	4.26 %	3.28 %	2.45 %
25	280	7.05 %	4.15 %	3.61 %
30	560	7.56 %	5.96 %	4.57 %
50	2000	8.69 %	7.24 %	6.04 %
100	10000	15.07 %	10.31 %	9.11 %

Figure 4.2. Left: management of changes and disturbances during scheduling; right: average error on industry related data relative to the number of machines and tasks in the system.

By modelling the structure of a real plant producing customized mass-products we initiated experiments on a simulated factory with randomly generated orders (jobs) with due dates. The operations (tasks) and the process-plans of the jobs, however, covered real products. In this plant the machines require product-type dependent setup times, and there are some special tasks that have durations but that do not require any machine to be processed (e.g., cooling down). Another specialty of the plant is that at some previously given points; it is allowed to have preemptions. The applied performance measure was to minimize the number of late jobs and an additional secondary performance measure was to minimize the total cumulative lateness, to compare two schedules having the same number of late jobs. In the right part of Figure 4.2 the workload of the system was fixed to 90% and the convergence speed relative to the plant size and the number of tasks was tested.

The RL based approach proposed here was also tested on Hurink's benchmark dataset [13] which contains flexible job-shop scheduling problems. The used performance measure was the maximum completion time (make-span). These problems are "hard", which means, e.g., that standard dispatching rules or heuristics perform poorly on them. This dataset consists of four subsets, each subset contains about 60 problems. The subsets (sdata, edata, rdata, vdata) differ on the ratio of machine interchangeability, which are shown in the "parallel" column in table shown in the left part of Figure 4.3. The columns with label "n iter." show the global error after carrying out altogether "n" iterations. The execution of 10000 simulated trials (after the system has achieved a solution with less than 5% global error on the average on the tests accomplished) takes only few seconds on a present day PC. Clustering the tasks according to their expected slack times also increases the performance considerably as demonstrated on the right part of Figure 4.3.

clusters	cluster size	speedup	average error
1	1000	1.00	6.53 %
5	200	1.52	4.13 %
10	100	3.01	3.49 %
20	50	6.37	1.95 %
30	33	7.07	3.02 %
40	25	7.29	3.55 %

dataset	parallel	1000 iter.	5000 iter.	10000 iter.
sdata	1	8.54 %	5.69 %	3.57 %
edata	1.2	12.37 %	8.03 %	5.26 %
rdata	2	16.14 %	11.41 %	7.14 %
vdata	5	10.18 %	7.73 %	3.49 %
average	2.3	11.81 %	8.21 %	4.86 %

Figure 4.3. Left: average error on a benchmark dataset of "hard" flexible job-shop problems right: the effectiveness of clustering on industry related data.

The presented results show, that our RL based resource control algorithm can perform efficiently on large-scale problems, even in uncertain environments.

5 CONCLUSIONS

The paper argued that the CAS approach is viable at different levels of manufacturing. Special emphasis was laid on CAS-based production scheduling and control, by introducing a reinforcement learning based solution.

In designing CAS, non-linear phenomena, incomplete data and knowledge, a combinatorial explosion of states, dynamic changes in environment and the frame problem are some notable examples of difficulties to be faced. The central question is realising an artifactual system that achieves its purpose in unpredictable conditions. Complex systems, however, exhibit patterns of behaviour that can be considered archetypal or prototypical. One can benefit from the knowledge of these patterns [14]. Managing such systems an appropriate balance between control and emergence must be found [14].

The difficulty in understanding the effects of individual characteristics of the agents on their collective behaviour underlines the importance of using simulation as primary tool for designing and optimising such systems. In this respect, the proper balance between simulation and theory is to be aimed at [15].

Our further research activities will also go in this direction, i.e., to find the appropriate balances between simulation and theory, on the one hand, and between control and emergence, on the other.

6 ACKNOWLEDGEMENTS

The work was supported by the NKFP Grant No. 2/010/2004 (VITAL), the OTKA Grant No. T049481, and by the EU-project Coll-Plexity 12781(NEST).

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