PLANNING UNDER CONDITIONS OF UNCERTAINTY

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***Key words**: planning, adaptive planning, multi-agent technology, emergence, selforganisation*

Abstract
The paper provides a case for replacing conventional centralised planning with adaptive planning and proposes a planning method based on a number of principles, including Planned Options, Planned Redundancy, Event-Driven Continuous Planning, Planning by Selforganisation, Emergent Plans and Multi-Criteria Planning.

Introduction

Planning has been recognised as an essential preparation for orderly conduct of social and economic activities since early days of human existence. We have planned holidays, social and political events, wars and, most importantly, work.

For planning purposes we assume that we live and work in a reasonably stable environment with infrequent occurrence of unpredictable events. However in the evolution of our environment there are transitional periods when changes are so rapid that the uncertainty rather than stability is the defining feature. As it happened, we are now in one of these transitional periods with a number of drastic paradigm shifts that cause high uncertainty.

Also, there exists compelling evidence that as the evolution of our Universe takes its course, the ecological, social, political, cultural and economic environments within which we live and work increase in **complexity**. This process is irreversible and manifests itself in a higher **diversity** of emergent structures and activities and in an increased **uncertainty** of outcomes.

Complexity is defined here, as in Complexity Science, to be a dynamic situation characterised by a large number of autonomous players interacting with each other. The overall behaviour emerges from the interaction of players and if these interactions are intensive the emergent behaviour is very difficult to predict. Complex systems are said to operate “at the edge of chaos” or “far from equilibrium" [1, 2, 3]. They are not stable; the smallest external effects may cause large-scale changes in their behaviour, the phenomenon known as "butterfly effect".

The importance of the increasing complexity of our environment is best illustrated by the often quoted statement made by Stephen Hawking, the Newton Professor of Physics at Cambridge University at the end of the 20th century:

"*I think the next century will be the century of complexity*."

1 The Source of Uncertainty

Evolutionary changes occur in steps and we are currently in initial stages of several substantial **paradigm shifts** which are technology driven or at least technology enabled. In the socio-economical sphere there is a very important shift from nation-centred industrial markets to the Internet-based global economy, enabled by the abolition of tariffs and the rapid growth of the Internet. Global economy consists of a vast number of suppliers and customers rapidly matching supplies to demands and then, as rapidly, changing previously agreed matches as soon as better opportunities present themselves, each player trying to increase their gain. The global market has all characteristics of a very complex system. The overall distribution of resources to demands emerges from individual transactions. Globalisation increases wealth across the board (there is a saying among economists "globalisation tide lifts all boats"). According to recent statistics during the last 30 years the world as a whole has enjoyed an unprecedented economic growth.

The ever increasing numbers of players in the global market and the speed of information flow over the Internet accelerates market dynamics to such as an extend that the current generation of data-driven information systems supporting business processes will not be able to cope for long.

Let us illustrate this statement by describing problems experienced by global consumer product supply chains consisting of a large number of suppliers, warehouses, logistics operators, assembly plants and retailers distributed around the world, encompassing together a vast quantity of resources such as machine-tools, robots, conveyers, loading bays, trucks, freight trains, cargo planes and cargo ships, operated by hundreds of crew members, loaders, operators, progress chasers and supervisors. Such supply chains are rendered unmanageable by the current generation of enterprise resource planning systems, schedulers and optimisers because of the frequent and unpredictable occurrence of events such as the arrival of new orders, order cancellations, changes in previously agreed orders and delivery arrangements, delays, failures of logistics resources and human errors.

The key problem is that the frequency of market driven changes is typically **1-2 hours** whilst the time required to modify production plans to accommodate changes in orders is not less than **8-10 hours;** in global logistics, once a pallet is assigned to a pipeline its destination cannot be altered until it emerges from the other end of the pipeline, which may take **several days**.

We have to accept that complexity, and therefore uncertainty, is a norm and that attempts to simplify complex situations and to eliminate uncertainty, which was a useful managerial and technological philosophy in industrial society when complexity was manageable and uncertainty was small, is now harmful. Complexity of markets has to be exploited - it offers rich opportunities for those who master the mindset, skills and tools of adaptation and resilience.

2 Fundamentals of Adaptive Planning

Planning under conditions of uncertainty requires a new method; it cannot be done using conventional planning approaches. This new method I shall call the Adaptive Planning. There are several fundamental principles underlying this method.

Planned Options - When operating conditions are stable the best planning practise is to work out and implement the optimal plan for these conditions. Under frequent and unpredictable changes in operating conditions the concept of optimality does not make sense; planners are advised to consider and work out in some detail a large number of optional ways of fulfilling the plan. Some of these options may never be required; however, due to uncertainty there is no way of predicting which ones will be needed. Using multi-agent technology options can be generated in real time.

Planned Redundancy - Planned options require planned redundancy of resources. In contrast to rigid planning, where redundant resources are considered as a waste and the key notion is a slim process, adaptive planning requires additional resources that are not needed for normal operation and which may be required only in case of the necessity of employing optional solutions.

Event-Driven Continuous Planning - In contrast to rigid planning which specifies what will be done within certain time periods (one-year plan, five-year plan), adaptive planning is a continuous process. As events affecting operation occur, the current plan is modified to accommodate the changes in operating conditions and modifications are immediately implemented. The process of perpetual modifications of the plan continues as long as the operation that is being planned is active.

Selforganisation in Planning - Under stable operating conditions (relative to the planning span) it is rational to conduct centralised planning; therefore if there is a high probability that economic conditions will be stable during the next five years it is rational to have a series of five-year plans. In complex operational environments, that is, when there is high level dynamics and uncertainty, there is a need for a different planning strategy. When changes in operating conditions occur on the hourly or daily basis, there is simply no time for reports on disruptive events to reach the central planning body, for planners to decide what modifications are required and send instructions to executives and for executives to implement the specified modifications. Therefore, under conditions of complexity the best planning strategy is selforganisation, which in a nutshell means that constituent units of the operational system are empowered to make all planning decisions through a process of negotiation with each other. The degree of delegation of decision making depends on specific conditions, although there is a rule acquired through experience, which stipulates that the deeper the delegation the more effective the selforganisation.

Emergence in Planning - By definition, planning by selforganisation means that the plan emerges from the interaction of constituent decision makers and is never imposed on them from higher levels of the hierarchy.

Multiple-Criteria Planning - Conventional planning is optimised using one criterion such as maximum profit, minimum costs or similar, which is applied uniformly to all resources. New methods have been developed for adaptive planning to use multiple criteria for every planning decision and to enable different balance of criteria to be used for different resources. The author and his team have developed systems capable of balancing max. profit, min. costs, level of service and individual preferences.

3 Conventional Versus Adaptive Planning

	CONVENTIONAL PLANNING	**ADAPTIVE PLANNING**
Options	Optimal plan only	Plan includes as many as practical options
Redundancy	No redundant resources	Planned redundancy of resources
Rigidity	Plan is mandatory for the specified period of time	Plan is continuously being modified to accommodate changes in the operational environment
Decisions	Centralised planning	Planning by selforganisation
Emergence	Plan specifies all activities that will be executed within the planning period	Activities that will be executed emerge from negotiations between constituent decision makers
Criteria	A single planning criterion is applied to all activities	Each activity may have a different balance of several decision criteria

4 Conclusions

The author and his team based in Samara have developed the new method of planning under conditions of uncertainty and named it Adaptive Planning. The method is underpinned by a powerful multi-agent technology capable of generating planning options in real time [4, 5, 6]. This paper is the first attempt to outline the key principle of Adaptive Planning and to contrast it with the conventional planning approach.

5 References

[1] I. Prigogine: The End of Certainty: Time, Chaos, and New Laws of Nature. The Free press (1997)
[2] I. Prigogine: Is Future Given? World Scientific (2003)
[3] G. Nicolis, I. Prigogine: Exploring Complexity, W H Freeman (1989)
[4] Rzevski G., Petr Skobelev, Igor Minakov and Semen Volman "Dynamic Pattern Discovery using Multi-Agent Technology". Proceedings of the 6th WSEAS International Conference on Telecommunications and Informatics (TELE_INFO '07), Dallas, Texas, USA, March 22-24, 2007, pp 75-81. ISBN: 978-960-8457-60-7.
[5] G. Rzevski, J. Himoff, P. Skobelev "Magenta Technology: A Family of Multi-Agent Intelligent Schedulers". Workshop on Software Agents in Information Systems and Industrial Applications (SAISIA). February 2006. Fraunhofer IITB.
[6] Rzevski G., P. Skobelev, V. Andreev. "MagentaToolkit: A Set of Multi-Agent Tools for Developing Adaptive Real-Time Applications". Proceedings of HoloMAS 2007.

Appendix 1 Technology for Adaptive Planning

Introduction

Multi-agent technology has been developed specifically to solve *complex problems*, that is, situations in which a large number of autonomous units are engaged in unpredictable interactions. Complex situations perpetually change and therefore there cannot be "the optimal" solution to a complex problem. Solving a complex problem has a completely different meaning - it means achieving specified goals under conditions of frequent changes in operating conditions.

Systems that are capable of achieving specified goals under conditions of frequent changes in operating conditions are called *Adaptive* and systems that can achieve their goals under attack (by military, by hackers, by computer viruses, by spam) are called *Resilient*.

Under currently prevailing volatile market conditions planning of processes (including business processes, administrative processes, social processes, political processes and cultural processes) should be adaptive and resilient and this includes planning of production, transportation, warehousing, supply chains, order processing, resource allocation, stock control and human resource management.

Multi-agent technology is a currently available technology capable of achieving adaptability and resilience of business (or other) processes.

Intelligent Agent-Based Problem Solving

In contrast to conventional software such as centralised schedulers, planners and optimisers, multi-agent software follows principles of intelligent problem solving outlined below.

Problem domain knowledge is elicited and represented as a semantic network where concepts (classes of objects) are nodes and relations between concepts are links. Each object is characterised by attributes and rules guiding their behaviour. Such a conceptual knowledge repository is called **Ontology**.

A real-life problem situation is represented as a virtual network of instances of objects defined in Ontology and their relations. Such a problem description is called a **Scene**.

The elementary computational element is called **Agent**. An Agent is a computer program capable of solving the problem at hand by consulting Ontology and using thus acquired knowledge to negotiate with other Agents how to change the current Scene and turn it from the description of the problem into the description of a solution. Agents solve problems in co-operation and/or competition with other Agents. As **Events** affecting the problem domain occur, Agents amend the current Scene to accommodate the Event thus achieving Adaptability.

An Agent is assigned to each object participating in the problem solving process (and represented in the Scene) with a task of negotiating for its client (object) the best possible service conditions. For example, in an air taxi booking system, Passenger Agents and Seat Agents will negotiate takeoff/landing times and seat prices for requested flights. Closing a deal between a Passenger Agent and a Seat Agent indicates that a full, or at least partial, matching between Agents has been achieved. In case of a partial matching (eg, a passenger agrees to accept a later takeoff time but it is not pleased), his Agents may attempt to improve the deal if a new opportunity presents itself at a later stage (eg, if other passengers on the same flight agree an earlier takeoff time). The process continues as long as it is necessary to obtain full matches, or until the occurrence of the next Event (say, a new request for a seat) which requires agents to re-consider previously agreed deals.

Agent negotiations are controlled using domain knowledge from Ontology which is far more comprehensive than “rules” found in conventional planners and normally includes expertise of practicing operators. Not all of this knowledge is rigid - certain constraints and if-then-else rules may be considered as recommendations and not as instructions and Agents may be allowed to evaluate their effectiveness and decide if they should be used. In some cases Agents send messages to users asking for approval to ignore ineffective rules or to stress nonessential constraints.

The power of intelligent method is particularly evident when the problem contains a very large number of objects with a variety of different attributes; when there is a frequent occurrence of unpredictable events that affect the problem solving process; and when criteria for matching demands to resources are complex (eg, balancing risk, profits and level of services, which may differ for different participants).

As the process is incremental, a change of state of one Agent may lead to changes of states of many other Agents. As a result, at some unpredictable moment in time a spontaneous self-accelerated chain reaction of state changes may take place, and after a relatively short transient time the overall structure will switch its state completely. Once the resulting structure has settled, the incremental changes will continue.

Agent-based problem solving process appears to exhibit autonomy and intelligence, known as "emergent intelligence" and is therefore often called "intelligent problem solving process". They certainly exhibit the following characteristics of intelligence: (1) Ability to achieve goals under conditions of uncertainty; (2) Ability to learn from experience; (3) Ability to anticipate events and make corrections if events do not materialise.

Architecture

Multi-agent software comprises the following key components: (1) Multi-Agent Engine, which provides runtime support for Agents; (2) Virtual Market, which is an extension of the Engine; it supports rather more complex Agent roles, including those of sellers and buyers; (3) Ontology Management Toolset, which supports the construction and update of Ontology (conceptual problem domain knowledge network) as well as building of Scenes (problem situation network models); (4) Visual Interface Library

How Multi-Agent Software Works

Software consists of a set of continuously functioning Agents that may have contradictory or complimentary interests. Basic roles of Agents, based on extended Contract Net protocol, are Demand and Supply roles: each Agent is engaged in selling to other Agents its services or buying services it needs (Passenger Agents buy seats and Seat Agents sell them).

Current problem solution (current Scene) is represented as a set of relations between agents, which describe the current matching of services; for example, a schedule is a network of passengers, seats, aircrafts and flights and relations between them.

The arrival of a new Event into the system is triggered by the occurrence of a change in the external world; for example, when a passenger requests a seat on a particular flight, a Seat Request Event is triggered in the system.

The Agent representing the object affected by the new Event undertakes to find all affected Agents and notify them of the Event and the consequences (eg, the Agent of the failed aircraft undertakes to find Passenger Agents linked to the failed flight and inform them that the flight is not available; the Aircraft Agent breaks the relevant relations and frees the Passenger Agents to look for other available flights.

The process of problem solving can run in parallel and asynchronously and, as a consequence, simultaneously by several active participants; for example, passengers that arrived at the website to book a flight simultaneously can all immediately start searching for suitable seats. All aircrafts assigned to flights can start immediately looking for free pilots. This feature is very effective because it eliminates a laborious building of flight schedules only to find out that pilots are not available for all selected flights.

The driving force in decision-making is often the presence of conflicts, which have to be exposed and settled by reconsidering previously agreed matches; for example, if a new flight finds out that the takeoff time slot it needs is already occupied, negotiations on conflict resolution start and, as a result, previously agreed flight-slot matches are adjusted (the takeoff time slot is moved to accommodate both flights) or broken (the time slot is freed). This capability to make local adjustments before introducing big changes is what makes agents-based problem solving so much more powerful in comparison with object-oriented or procedure-based methods.

A multi-agent system is in a perpetual state of processing either reacting to the arrival of new events or improving the quality of previously agreed matches. The stable solution is reached when there are no Agents that can improve their states and there are no new Events. This solution may or may not be final depending on whether Events will or will not recur.

Solutions developed using multi-agent software fall into the class of open, non-linear and dissipative systems. As the number of relations increases in the system, the level of complexity of the resulting network goes up and, at a certain point, the need may arise to appoint additional Agents to represent certain self-contained parts of the network whose nodes are already represented by Agents. The increased complexity of solution structures may result in the creation of loops and the system may find itself in a local optimum. To avoid being stuck in a local optimum Agents are from time to time given power to pro-actively seek alternative solutions. Attempts to avoid local minima are random (mutations).

Multi-agent systems can learn from experience as follows. Logs of Agent negotiations are analysed with a view to discovering patterns linking individual Agent decisions and successes/failures of the Agent negotiation process. In future negotiations patterns leading to failures are avoided.

The pattern discovery process is itself Agent based. An Agent is assigned to each data element with a task of searching for similar data elements to form clusters. An Agent is assigned to each new cluster with a task to attracting data elements that meet cluster membership criteria. Finally, clusters are represented as "if-then-else rules".

Appendix 2 Complexity

Introduction

The following three paragraphs from Wikipedia are a good introduction to the concept of complexity.

"Complexity has always been a part of our environment, and therefore many scientific fields have dealt with complex systems and phenomena. Indeed, some would say that only what is somehow complex – what displays variation without being random – is worthy of interest.

The use of the term complex is often confused with the term complicated. To understand the differences, it is best to examine the roots of the two words. "Complicated" uses the Latin ending "plic" that means, "to fold" while "complex" uses the "plex" that means, "to weave." Thus, a complicated structure is one that is folded with hidden facets and stuffed into a smaller space. On the other hand, a complex structure uses interwoven components that introduce mutual dependencies and produce more than a sum of the parts… This means that complex is the opposite of independent, while complicated is the opposite of simple.

While this has led some fields to come up with specific definitions of complexity, there is a more recent movement to regroup observations from different fields to study complexity in itself, whether it appears in anthills, human brains, or stock markets."

Following the train of thoughts suggested above, the intuitive interpretation of the term Complex as "difficult to understand" is correct as long as we accept that the main reason for the difficulty is the interdependence of constituent components.

An example that immediately comes to mind is the Internet-based Global Market, where consumers and suppliers are trading, each pursuing their own goals and targets, and where the overall distribution of resources to demands emerges from individual transactions rather than according to a given plan.

On a smaller scale we have a complex situation associated with availability of aircrafts where there is a need to mange interaction between aircraft failures, aircraft locations, maintenance and repair personnel schedules and supply of spare parts.

In general, the behaviour of complex systems cannot be planned, controlled or predicted, and yet it is not random. It follows patterns, which may be difficult to discern. A complex system has a variety of possible behaviours and uncertainty which behaviour the system will pursue. The behaviour of complex systems is often said to be "at the edge of chaos".

Complex systems are said to operate "far from equilibrium". They are not stable; the smallest external effects may cause large-scale shifts in system behaviour, the phenomenon known as "butterfly effect", whilst on occasions, considerable disturbances may have no effect.

In a classification of systems according to their predictability, complex systems are between random and stable systems, as shown in table below.

CLASSES/ *Features*	**RANDOM SYSTEMS**	**COMPLEX SYSTEMS**	**STABLE SYSTEMS**	**ALGORITHMIC SYSTEMS**
Predictability	Total uncertainty	Considerable uncertainty	No uncertainty	No uncertainty
Behaviour	Random	Emergent	Planned	Deterministic
Norms of behaviour	Total freedom of behaviour	Some external guidance is essential	Governed by laws and regulations	Follows instructions
Degree of organisation	None	Self-organisation	Organised	Rigidly structured
Degree of control	None	Self-control by self-organisation	Centralised control	No need for control
Irreversible changes	Random changes	Co-evolves with environment	Small temporary deviations possible	None
Operating point	None	Operates far from equilibrium	Operates at an equilibrium	Operates according to the specification

Physics, often referred to as the queen of sciences, was for centuries preoccupied with studies of systems in equilibrium, such as the movement of solid bodies and fluids. The laws governing the behaviour of such systems are valid at any place and any time and are reversible. The elegance and power of these "natural laws” led many scientists to believe that, with the advancement of science, it will be possible to reduce the understanding of all systems to a similar set of simple and logical laws. This notion is known as Reductionism.

Recent research has shown that, to the contrary, in physics like in all other branches of science, many interesting phenomena are complex, consisting of richly interlinked elements, and are not reducible to simple laws.

Key Features of Complex Systems

Complex systems are primarily of interest to designers because of their capabilities to Selforganise in response to events that affect their behaviour and to Co-Evolve with their environments and, consequently, their properties are Emergent and behaviour is Adaptable to changes and Resilient to attacks.

Self-Organisation is the ability of a complex system to autonomously change own behaviour and structure in response to environmental changes. For systems with a network structure, selforganisation amounts to: (1) Disconnecting certain constituent nodes from the system; (2) Connecting previously disconnected nodes to the same or to other nodes; (3) Acquiring new nodes; (4) Discarding existing nodes.

Co-Evolution is the ability of a system to autonomously and irreversibly change its behaviour and structure in response to permanent changes in the system environment and, in turn, to cause changes in the environment by its new behaviour. Complex systems perpetually co-evolve with their environments: they are affected by their environment and they affect their environment.

Emergent Properties are properties that emerge from the interaction of constituent components of a complex system. These properties do not exist in the components and, because they emerge from the unpredictable interaction of components, they cannot be planned or designed.

Adaptation is the ability of a complex system to autonomously adjust its behaviour in response to the occurrence of events that affect its operation.

Resilience is the ability of a complex system to achieve its goals under conditions of external attacks.

Examples

Examples of Complex Systems include: global economy, a national economy, ecology, a swarm of bees, a human being, society, culture, an epidemic, a terrorist network, road traffic, the Internet, a swarm of software agents, life span of an aircraft or a car.

A common feature of all systems listed above is that they do not have a centralised control – their behaviour emerges as a result of the interaction among their components and between components and the environment. The decision making power of different Agents may vary, but as a rule, Agents have certain autonomy limited only by intrinsic norms of behaviour; they do not work under external instructions. The trajectory of such a system in time is not possible to predict.

Complexity versus Determinism

There are two contrasting philosophical theses:

The first thesis is that the world is predictable (deterministic). It is based on the "grand design" and any uncertainty is due to our inability to understand it. Great philosophers and scientists subscribed to this worldview, including Aristotle, Kant, Newton and Einstein.

The second thesis is that the world is inherently unpredictable (complex). It evolves with time due to autocatalytic properties of some of its elements. Its evolution is irreversible and leads to an increase in complexity. The future is not given it is under perpetual construction. Supporters of this thesis include Buddha, Maxwell, Darwin, Popper and Prigogine.

Two Contrasting Paradigms

During the last couple of decades we have moved away from highly regimented Industrial Society built on ideas of Economy of Scale, Mass Production, Strong Hierarchical Control, Large Monolithic Corporations and Two Rigid Political Blocks.

We are moving towards Information Society characterised by Global Economy in which competing suppliers and customers form temporary links (often over the Internet) and where the dynamics and uncertainty rule out any centralised control; make-to-order manufacturing and services; teamwork and learning organisations; virtual enterprises characterised by adaptability; a multitude of political ideas, movements and modes of governing.

New social, economic, political and business conditions are characterised by frequent occurrence of unpredictable events which causes a lack of stability. Environment in which we live and work appears to be in perpetual change. In such a volatile environment organisations and products/services that we design would benefit from rapid adaptability to environmental changes.