

***Creating Value by Improving Decision Making  
Under Uncertainty***

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## Executive Summary

Optimization technology is ubiquitous in our society. It schedules crews and fleets for airlines, helps discover new drugs, routes packet streams in networks, sequences cars in assembly lines, and dispatches vehicles for courier services. Optimization is an integral part of most major software companies, including IBM, Oracle, and SAP. It is becoming increasingly pervasive and now affects almost all aspects of our daily lives. Optimization is even in your TiVo recorder to select the programs that best fit your profile.

## Accounting for uncertainty

Traditional optimization-based decision systems have focused on planning, resource allocation, and scheduling: they rarely focus on tactical and operational decisions and they largely ignore uncertainties. As a result, they often produce poor decisions and over-optimized plans that are not robust to perturbations, resulting in missed opportunities and significant costs. For instance, the airline industry, a sophisticated user of optimization technology, solves complex fleet assignment, crew scheduling, and gate allocation problems as part of its operations, using some of the most advanced optimization algorithms available. Yet unexpected events such as weather conditions or strikes produce major disruptions in its operations. In August 2005, British Airways took three to four days to resume its normal operations after a strike of one of its catering subcontractors; many of its planes and crews were at the wrong places because of the airline inability to anticipate and quickly recover from the event.

Moreover, organizations often sequentialize their decisions, leading to unanticipated and undesired interactions. The steel industry, also a significant customer of optimization technology, typically separates strategic planning (which orders to accept) and tactical planning (which priorities to assign them) from daily scheduling decisions and order acceptance and rejection. The strategic decisions are based on coarse approximations of the factory capabilities and demand forecasts, sometimes leading to infeasible schedules, missed deadlines, and poor real time decisions on incoming orders.

## Technology enablers create the opportunity for competitive advantage

The last decade has witnessed significant developments in a number of key technologies. RFIDs, GPS, and sensors now enable organizations to monitor their activities, transmit

decisions, and adapt plans in real time. The explosion of data that has resulted from technology advances can be used to an organization's advantage in ways not previously known. The resulting historical data can be used to anticipate uncertainty, which can be used to produce higher quality decisions in a more timely fashion. The trend is further leveraged by the availability of commodity multi-core and multiprocessor systems, which provide the computing power to solve large-scale optimization problems in reasonable time.

Finally, optimization systems themselves have greatly improved in speed and robustness and new approaches to uncertain and dynamic applications have shown tremendous promise. The combination of the explosion of data, combined with advances in optimization technology have created an environment in which organizations can make better decisions, improve services levels, increase revenue and create lasting value for their customers and partners.

## Opportunities in Decision Systems

As the landscape changes, it is becoming increasingly clear that there are significant opportunities for adaptive and integrated approaches to decision systems far beyond comprehension just a few short years ago. Companies such as UPS now have their own meteorologists and political analysts to adapt their operations and schedules in real time. New businesses in transportation (microjets for instance) have created a business model which has essentially abandoned fixed schedules in order to adapt routes that meet their customers' needs. Research has also demonstrated the potential gains of integration: Integrated allocation of aircraft and flight times led to savings of approximately \$20 million dollars a year.

Companies such as Wal-Mart now try to integrate their supply chain with those of its suppliers, merging their logistics systems and replenishing inventories dynamically. Some large steel Manufacturers now require solutions to extremely large scheduling involving several hundred thousands of activities. Other airlines attempt to merge aircraft repairs with the replenishment of replacement parts.

## Adaptive and Integrated Decision Systems

As a consequence, we envision a new era in which decision systems will continuously optimize integrated businesses and applications, reacting and adapting to external events effectively under time constraints, anticipating the future, and learning from the past to produce more robust and effective solutions. These systems will deal simultaneously with planning,

scheduling, and control, complementing a priori optimization with integrated adaptive decision making. This new generation of decision systems will integrate high-performance computing, operations research and computer science to produce a novel generation of tools. It will shift the focus from solving strategic planning problems optimally to finding high-quality solutions quickly in operational settings and under uncertainty, reflecting a change of pace in our societies. The result will be radically different decision systems, moving from offline optimization systems into online tools that will react to external events and return high-quality solutions under tight deadlines. These new decision systems will not only solve existing problems better; they will also open fundamentally novel application areas currently outside the scope of traditional optimization technology.

### ***Innovative Applications of High-Performance Adaptive Decision Systems***

#### **Logistics**

The applications of high-performance adaptive decision systems in logistics are too numerous to mention. They include "traditional" courier services and technician dispatches, where communication technologies will enable adaptive decision systems to improve quality of service, reduce costs, and explore novel business models. They encompass novel applications such as grocery deliveries and on-demand dial-a-ride for seniors, which are inherently dynamic. Moreover, high-performance adaptive decision systems are at the core of fundamentally innovative businesses such as air-taxi operations which fly 3-4 persons point-to-point using Eclipse 500 aircraft. Because of onboard computer systems and progress in communication systems, logistics is clearly an area in which high-performance adaptive decision systems are likely to bring significant benefits and opportunities

#### **Humanitarian and Military Missions**

An extreme case of a (one-time) logistics system is the deployment of humanitarian and military missions, which involve joint large-scale airlift routing, equipment assignment, and crew assignment problems under uncertainty. The planning for such deployment is often performed by hand and can take hundreds of people days or weeks to create a schedule. During uncertain events, the human planners usually fallback on the easiest solution, which is often inefficient. The existing solutions often use simple techniques and are reactive, not anticipatory, with respect to uncertainty. High-performance adaptive decision systems, by taking a fresh look at these problems, have

the potential to bring significant benefits over the state of the art.

#### **Services Industry**

The services industry also features a wealth of applications for high-performance adaptive decision systems. It is a challenging problem to assemble teams of workers with different skills to complete projects whose outcomes, durations, and resource requirements are uncertain, while exploiting synergies between people, avoiding conflicts, and allocating time for training. IBM has recently started a new initiative, Services Sciences, whose goal aims to find "better ways to use mathematical optimization to increase productivity and efficiency on demand." This clearly indicates that services are in strong need for adaptive decision systems in an industry whose products, resources, and orders are much more uncertain than traditional manufacturing.

#### **Manufacturing**

Manufacturing at the same time has been evolving too, also moving toward a more flexible, on demand model. Moreover, as mentioned earlier, there is a clear trend in manufactures toward much larger scale and integration, to avoid the artificial separation between the strategic, tactical, and operational levels. As a result, the application size has grown significantly and there is a need for more scaleable and high-performance solutions. In more traditional manufacturing, the focus is also shifting from deterministic problems toward dealing with uncertainty and accommodating external events. Current optimization systems are poor in dealing with uncertainty coming from machine deterioration, failures, and the uncertainty in the manufacturing process itself. High performance adaptive decision systems also have significant opportunities in manufacturing where optimization technology is already well-established.

#### **Project Management in the Pharmaceutical Industry**

The pharmaceutical industry also offers some interesting avenues for adaptive decision systems. A critical asset of a pharmaceutical company is its drug portfolio. The portfolio should be balanced, covering the main type of drugs. It should bring new drugs to the market regularly, ideally ahead of its competitors. The schedule of drug design projects thus represents some of the most important decisions a pharmaceutical company takes. The goal is to produce a balanced portfolio, through research and development or through acquisitions, within budget and resource constraints, in order to optimize the firm position on the market. The problem

is highly uncertain, each project having multiple outcomes (representing different degrees of success or failure), and uncertain durations, costs, and rewards. Its complex underlying optimization problem combines scheduling and resource allocation. Our preliminary experience indicates that high-performance adaptive decision systems have a fundamental role in such applications which are highly combinatorial and stochastic: They outperform existing methods and smoothly accommodate new market and research information, as well as risks.

### **Communication Networks**

Computer networking systems provide another area with significant opportunities for adaptive optimization systems. With companies like Cisco moving to the "quality of experience" slogan and with the increasing demand for multimedia streams, the focus will be on adaptively optimizing the application flow through the network, exploring and recognizing scenarios of activities. In other words, high-performance adaptive decision systems will optimize the underlying network based on user activities (using techniques such as deep packet inspection), scenarios capturing user behaviors, and the topology of the network.

### **Emergency Response Systems**

The area of emergency-response systems has a wealth of potential applications for adaptive optimization systems. They range the containment of bushfires, ambulance dispatching and diversion, search and rescue operations, evacuation procedures, and pandemic containment. These applications must typically solve complex dispatching and resource allocation problems under uncertainty and time constraints, and react quickly to new events and requests. To illustrate these issues concretely, consider the problem of ambulance dispatching and diversion in conjunction with the emergency admission process. In order to develop a true emergency response system, ambulance dispatching and relocation must be considered globally for a number of hospitals in the same region. The system should include (1) all the interdependencies in the admission process where bottlenecks continuously evolve due to critical resources (e.g., MRIs) whose operations have inherently uncertain durations, (2) the competition between elective patients and emergencies for in-patient beds, and (3) the complexity of transfer and discharge procedures. Some of these issues (e.g., ambulance dispatching) have been addressed by a priori optimization approaches and, even though these approaches try to incorporate uncertainties (in general, by building redundancies), they fail to account for the inherently dynamic nature of emergency response systems. Our recent

work has shown the significant benefits of adaptability for vehicle dispatching and reservation systems. Ambulance dispatching and diversion combine both problems in complex ways and its complexity makes it an ideal candidate for a new generation of optimization systems.

### ***Technological Assets***


As should be clear<sup>TM</sup> from the innovative applications, adaptive decision systems impose fundamentally different requirements on optimization technology. The focus is no longer on finding optimal solutions to deterministic problems. Rather the goal is to find high-quality, robust solutions under time constraints and uncertainty for large-scale, integrated applications. This shift in requirements will alter the relative strengths and balances between different optimization techniques, favoring speed and scalability over optimality guarantees, which are elusive in uncertain and dynamic environments.

The need for time-critical solutions implies the use of parallel and distributed computing, since improvements in microprocessor speed are increasingly harder to obtain. Multicore and multiprocessor systems are quickly becoming a requirement from high-performance applications.

As a result, the development of high-performance adaptive decision systems will have to rely on software platforms that provide significant support for scalable and fast optimization algorithms and systematically exploit parallel and distributed programming. Without such platforms, the development of adaptive optimization systems will simply be too costly, too risky, and not flexible enough. The rest of this section describes the technological assets our group developed in the last 7 years in the context of research projects in optimization systems and stochastic combinatorial optimization.

### **The Comet<sup>TM</sup> System**

One of Dynadec's main technological assets is the Comet<sup>TM</sup> system, a platform for the development of high-performance optimization systems. Comet<sup>TM</sup> consists of about 700,000 lines of C++. It is a full-fledge programming language described in the 2006 MIT Press book which has been used at various organizations around the world and has solved open problems in a variety of areas. The main benefits of the Comet<sup>TM</sup> system



are its expressivity, its scalability, its support for high-performance computing, its event-driven architecture, and its advanced visualizations. These rich features make Comet™ a unique platform for the development of high-performance adaptive decision systems.

### **Expressivity**

Comet™ provides a very-high modeling language for optimization applications, dramatically reducing development time, easily accommodating side-constraints which typically plague industrial applications, and simplifying maintenance and extensibility thanks to its compositional architecture. A combinatorial program in Comet™ describes which constraints must be solved and which function should be optimized, not how to do it, which is left to the optimization engine of the system. These modeling capabilities make Comet™ particularly appealing to deploy early prototypes of an application, getting early feedback from users, and easing the integration the technology in the business processes.

### **Scalability**

Comet™ is the only optimization system whose models can be solved using local search (also known as stochastic search), a highly-scalable technology which often finds high-quality solutions under time constraints. Local search typically proceeds by incremental improvements, a process which users are typically familiar and which eases acceptance of the technology. Comet™ features a highly optimized, flexible, and extensible local search engine, often using optimal algorithms in its implementation. Local search also has the ability to accommodate soft constraints, which are of primary importance in many application domains. Note also that the open nature of the Comet™ system, and its advanced control structures, make it easy to incorporate additional computational paradigms.

### **High Performance Computing**

Comet™ provides transparent exploration of parallelism, both on multicore and multiprocessor systems. Its very-high level abstractions for parallel computing are especially suited for optimization applications and dramatically reduce the distance between sequential, parallel, and distributed programs. As a result, Comet™ removes the significant cognitive gap that typically plagues optimization tools for which it is a major challenge to move from a sequential to distributed implementations. Moreover, the performance evaluation of Comet™ has shown that the transparent parallelization does not come at the expense of efficiency, because optimization

applications inherently offer coarse-grained parallelism and the Comet™ implementation directly relies on low-level features of the underlying operating system.

### **Event-Based Architecture**


Comet™ provides an event-based architecture, allowing the system to react to events during execution, which is a fundamental requirement for adaptive decision systems. Comet™'s event-based architecture cleanly separates various aspects of the adaptive decision systems, simplifying extensibility, and favoring interoperability with other tools within a unique platform.

### **Adaptive Optimization Under Uncertainty**

One of Comet™'s most valuable capabilities is a collection of anticipatory algorithms for adaptive optimization under uncertainty. These anticipatory algorithms take a fundamental novel approach to optimization under uncertainty which combines computer science with from operations research. Experimental results on complex logistic problems have shown that anticipatory can bring orders of magnitude improvements in customer services and reductions in costs, especially for highly dynamic problems. The performance of the algorithms has also been studied and validated theoretically. These algorithms are inherently parallel and significantly benefit from multi-core and multiprocessor architectures.

### **Summary**

The tremendous advance of modern technologies and the corresponding data that they generate have created a unique opportunity for organizations to improve decisions, operational performance, and ultimately value. Dynadec was founded to help that vision become realized in a meaningful way. The next generation optimization technology upon which the company has been based is certain to create significant benefits to those organizations who are looking to remain profitable and continue to execute at a high level of efficiency.





### **About Dynadec**

Dynadec develops next generation hybrid optimization solutions that solve complex problems to reduce costs, increase operational efficiency and maximize revenue. Dynadec's optimization solutions for vehicle routing, workforce scheduling, and resource allocation are based on the company's proprietary Comet™ platform, which includes patent pending dynamic stochastic combinatorial optimization algorithms developed by world-renowned optimization expert Pascal Van Hentenryck, Dynadec's founder. Comet™ enabled solutions are used by both large enterprises and mid-market companies in a diverse range of industries including Transportation, CPG, Healthcare and Energy. For more information, visit [www.dynadec.com](http://www.dynadec.com).

