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Agent-Based Manufacturing: A Case Study

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1 INTRODUCTION

In traditional manufacturing, information systems mimic organizational structures, utilizing a top-down, command-and-control structure. Communicating decisions and information down through the organization is time consuming—making it impossible to respond and adapt quickly to external forces.

Furthermore, traditional manufacturing relies on schedules as a means of forecasting what needs to be produced. Schedulers sequence jobs based on the assumption that the environment will not significantly change during the schedule's time span. This approach works adequately in a predictable market. However, in a turbulent marketplace a schedule is impractical. Any small, unanticipated change in demand or factory floor conditions can substantially affect the schedule, rendering it obsolete.

Another problem with traditional schedulers is that they try to anticipate and plan for every possible change that may occur. Unfortunately, the range of scenarios and the possible combinations of parameters are infinite because manufacturing is so complex. Even if it were possible to pre-code all possible scenarios, the cost of considering and programming all possible combinations is prohibitive. An unanticipated scenario could cause the system to fail.

In short, traditional manufacturing facilities have shortcomings that affect their ability to compete in today's constantly changing marketplace.

- They do not have mechanisms in place to accommodate rapid changes in business conditions caused by global competition and changing market demands.
- They do not have mechanisms in place to modify systems while they are executing.
- They are rigid and slow to make significant organizational or functional changes.
- They do not have a mechanism to recover gracefully from partial failures on the factory floor.
- They are unable to form or to participate in virtual enterprises.

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- They are not scaleable for changes in the market.
- The business model and the operational philosophy are not customer driven.

These shortcomings cause problems such as reduced productivity, increased costs, and missed market opportunities. To remain competitive in today's marketplace, manufacturing must change its approach. In response, a major automotive company is building an agent-based manufacturing system under the direction of Dr. David Greenstein. [1] Here, the agents not only adapt to their environment but can also evolve by learning *from* the environment. Such an approach prepares manufacturing enterprises for the increasingly complex marketplace and enables them to respond rapidly to change.

This section provides a case study describing how agent-based technology can be applied in business applications. While the example is for an automotive company, the general concepts are applicable to many other industries.

2 AN AGENT-BASED SOLUTION

The Agile Manufacturing Information System (AMIS) is a new approach and operational model that addresses the problems of traditional manufacturing practices. Because today's dynamic marketplace is similar to ecosystems, AMIS is modeled after the behavior of the natural world, an approach which is agile, adaptive, and dynamic. It can adjust to changes in the marketplace and in technology—making it effective and competitive.

Traditional manufacturing systems rely on a rather rigid, top-down structure to represent a manufacturing enterprise. AMIS uses a loose aggregation of software agents to represent a manufacturing entity. For example, *resource agents* represent the capabilities and capacity of the various resources available, such as machines, tools, people, and computers. The work performed within a facility is represented by *job agents*. In a small system, the interaction of the resource agents with job agents manages the manufacturing process.

However, in systems involving many jobs and resources, the interaction could tax even modern information systems. Here, resource agents can be grouped into *cells*. Since cells are agents in their own right, they can form virtual organizations—able to adapt constantly to the changing global marketplace. This dynamic structure enables each cell to remain agile. Rather than being constrained by a fixed hierarchy, the cells and, therefore, the overall business can thrive in a continuously changing and unpredictable environment.

Each cell, then, can be treated as a manufacturing business unit. Since it is responsible for its own bottom line, each cell must be profitable over time. When a cell is consistently unprofitable, it is dissolved and other cells absorb its resources. Similarly, each resource in a cell is responsible for maintaining a positive bottom line and contributing to the cell's overall profit. This distributed profit responsibility allows the cell to maintain a suitable size and the right mix of resources for the current workload, while maintaining the flexibility to address future needs.

As David Greenstein states, "For a manufacturer to succeed in today's competitive world, it must have the optimal mix of people, equipment, and knowledge to make the product. The AMIS architecture provides the flexibility and agility in a software system, which enables a manufacturer to monitor, evaluate, and adjust the mix of resources, people, and tools required as market demands change." [1]

3 THE *AMIS* AGENTS IN MORE DETAIL

Cell Agents

In living systems, a cell is a self-contained unit that has its own structure and behavior. It consists of other self-contained structures that interact to support the cell. How well the cell and its components work together determines whether the cell lives or dies. In a manufacturing system, each cell agent is a business unit representing a collection of physical resources, including machines, tools, and people. The cell operates as a self-contained business unit and only continues to exist if it meets its profit and production goals and its responsibilities. The cell also controls its own size—it changes the mix and number of resources over time to maintain its profitability and competitiveness in the marketplace. The architecture of a cell is summarized in Fig. 1.

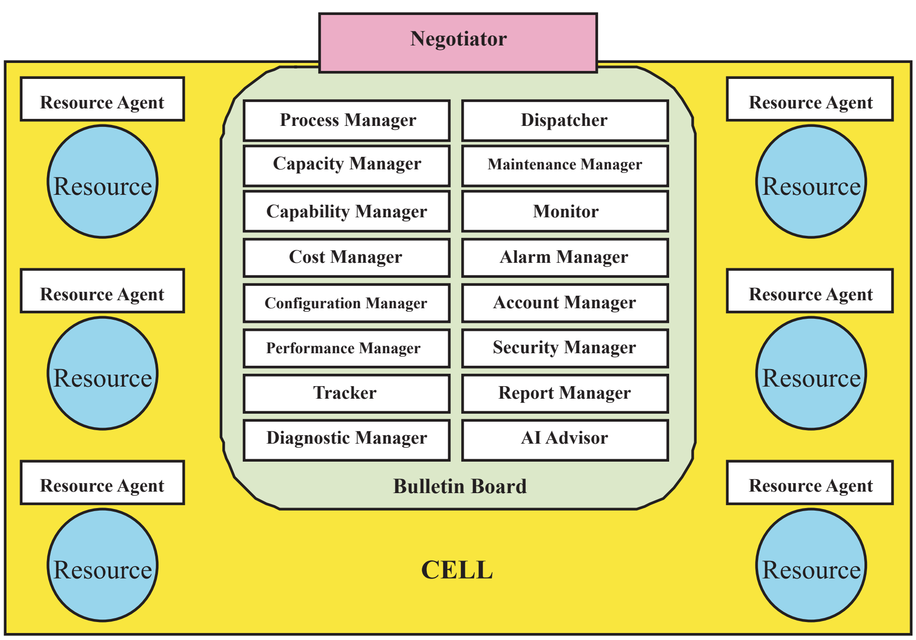

Figure 1 — Typical cell agent architecture for a manufacturing system.

Common Function Agents

The *common function agents* interact with each other and with the resource agents. They provide the complete set of business functionality required to operate the cell as an independent business unit. Each common function agent is responsible for a different business or manufacturing function within the cell. Some of these agents contain information about the resources within the cell, such as the capabilities of the resources. Other agents provide interfaces to the people working in the cell, such as process planners and machine operators.

For example, the maintenance manager schedules and directs maintenance activities whether they are scheduled, opportunistic, or reactive. It also keeps track of the maintenance history.

The *process planner* determines whether the cell will bid on RFQs (Requests for Quote) received by the cell. A broad analysis is made of the cell to judge the cell's ability and desire to produce a quote for this RFQ. The analysis uses criteria associated with the type of product being requested (automotive, pharmaceuticals, electronics, etc.); the processes needed (welding, casting, packing, etc.); and the resources needed (five-axis CNC, drill, sheet metal press, etc.). If it is determined that the cell either lacks the appropriate abilities or cannot subcontract them, then the cell will not bid on the RFQ. If the cell does bid on the RFQ, the process planner generates the process workflow (e.g., a UML Activity Diagram) that will be used to execute the quote, if selected.

The *capability manager* uses the process workflow to verify that the cell has the resources needed to carry out the job. It verifies each step in the process (job agent) with the available resources in the cell. The verification of the capability is based on the information contained in the workflow (time, quality, special characteristics, and cost criteria). If the capability is not present in the cell, the capability manager initiates the subcontracting process through the process planner.

Similarly, the *capacity manager* uses the information from the workflow to provide capacity to the job agents. The jobs currently accepted by the cell are taken into consideration when deciding if the cell has the capacity to take on this new job. If sufficient capacity is not present in the cell, the capacity manager initiates the subcontracting process through the process planner.

Negotiator Agents

Negotiator agents (at the top of the cell architecture diagram in Fig. 1) communicate with the outside world on behalf of the cell. The negotiator provides an interface between the cell and the outside world. It routes messages received from the outside world to the appropriate common function agent. When preparing quotes for new jobs, the negotiator assembles the quote information provided by the other agents and summarizes the final quote information for the customer. Similarly, when the cell receives quotes from subcontractors, the negotiator works with other agents to select the winning quote.

Resource Agent

Each *resource agent* represents a physical resource within the cell: a machine, tool, computer or person. Each physical resource provides a specialized utility or function to add value to the order completion process. The resource agent captures the attributes of the physical resource, allowing the agent to represent it in the cell and to coordinate the cell's use of the resource.

Each resource agent lists the capabilities that define those processes that the physical resource can perform. For example, a resource might be able to perform several types of milling operations. The capability list allows the resource agent to determine whether to bid on the various jobs in the cell.

Resources keep track of their assigned jobs by maintaining a prioritized list of jobs that the resource wins. Each job defines its job type, the earliest start time for the job, the expected job duration, the latest finish time, and the estimated cost.

The resource agent also maintains profit and loss figures for the resource. The best interest of a resource is to maximize profit by working on as many jobs as possible. If the resource does not maintain a profit over time, the cell may sell the resource to another cell. The resource agent is responsible both for ensuring the resource is optimally utilized and for representing the resource when bidding for new jobs.

Job Agent

The *job agent* represents the customer through the order placed into the system. The *job agent* defines the processes needed to complete the final product specified in a customer order. Each node in the process workflow is a subjob and is handled by an agent. Each subjob agent contains information about that specific process, including the type of process, set-up time, run time, and cost.

The job agent is responsible for monitoring its current status and due dates. As due dates approach for the overall job or for individual subjobs, the subjob agent will raise alarms to initiate corrective action. The subjob also communicates with its neighboring subjobs, passing state information and alarms to allow the previous and following subjobs to monitor more accurately their status and take appropriate action. The job and subjob agents are active agents responsible for making sure that they are completed by the expected due dates and at the lowest cost possible.

Broker Agent

The *broker agent* helps customers find providers of services and products. In the AMIS environment, each provider is a cell that registers with the broker, specifying the types of products and services it provides. For example, car buyers do not have to contact each automobile manufacturer. Instead, they send the attributes of the desired model (including such criteria as price, delivery date, color, and accessories) to the broker. The broker forwards the request to each automobile-producing cell that has registered with the broker.

The customer specifies the date by which all cells must provide quotes. The broker waits until this date and then collects all the cell bids and returns them to the customer. When the customer selects a winning quote, the broker forwards the customer award notification to the winning cell. Losing cells can view the attributes of the winning bid and compare it to their bid, in order to improve their bids in the future.

AMIS organizes brokers in a hierarchy based on geographical regions. First, the local broker forwards the customer request to its local cells that have registered. If no local cell can meet the customer request, the broker forwards the request to the regional broker. The regional broker forwards the request to each local broker within that region. In turn, these local brokers forward the request to every cell within their local area that manufactures the requested product.

The bids from each cell pass back through this hierarchy, going from the local information brokers to the regional broker. The regional broker returns the bids to the customer via the local information broker that originally received the customer request.

If no cells within the region can meet the customer requirements, the regional broker forwards the request to global broker. The process is repeated with the global broker forwarding the request to each regional broker, down through the local information brokers, and to each cell worldwide that produces that product.

In some cases, the customer may wish to solicit quotes from cells worldwide without initially limiting the scope to cells registered with the local broker. In this case, the customer sends the requirements directly to the global broker, bypassing the local and regional brokers.

4 ADAPTATION IN NATURAL SYSTEMS

Adaptation is no stranger to manufacturing operations. Manufacturers that fail to adapt rapidly to the ever-changing world become extinct. They go out of business. Adaptation enables the system to react to changes in the market or in the manufacturing environment. When designed properly, the individual parts of the system can be empowered to change based on their environment and market conditions.

An adaptive agent is one that responds to its environment. The simplest form of adaptation is *reaction*, that is, a direct, predetermined response to a particular event or environmental signal usually expressed by an IF-THEN form. From atoms to ants, the reactive mode is quite evident. A carbon atom would have a rule that states in effect, “If I am alone, I will only bond with oxygen atoms.” An ant would have a rule that if it finds food, it should return the food to its colony, while leaving a trail of pheromones. Reaction rules do not change in and of themselves, but change can come through other mechanisms such as learning and evolution. Without learning and evolution, ants and atoms are still quite able to support complex “societies.” *With* learning and evolution, however, the rules can be changed based on experience—resulting in new and perhaps improved results.

Learning

Learning is change that occurs during the lifetime of an agent and can take many forms. The most common techniques enable rules and decisions to be weighted based on positive (or negative) reinforcement. For example, in a basic bidding system, a bid could be selected simply on the basis of bid price. However, other considerations might also be appropriate, such as the bidder's ability to deliver its goods in the quantity, quality, and time frame requested. Over time, a *purchasing agent* can learn to choose from reliable *vendor agents* instead of just choosing the lowest bid. If a vendor's performance improves (or declines), the purchaser's decisions are modified accordingly. In other words, the agent *continues* to learn. Popular learning techniques that employ reinforcement learning include credit assignment, Bayesian and classifier rules, and neural networks.

Evolution

Evolution is change that occurs over successive generations of agents. For example, cell agents in AMIS continually evolve to address changing market and business needs. Here, the mix of resources within a cell dynamically evolves and changes so the cell can produce the products demanded in the market place. Each resource agent in a cell must continue to win jobs and maintain a positive bottom line, thereby contributing to the overall profitability of the cell.

A resource that consistently fails to win jobs will eventually have a negative cash balance. If a resource maintains a negative cash balance long enough, the cell may decide to replace that resource. The nonproductive resource can either "die" due to malnutrition of cash or be sold to another cell. The original cell can then buy a replacement resource possessing different capabilities—ones that are better suited to the products made by the cell. In other words, there is a "survival of the fittest" quality to the mechanism, where each internal change represents a new generation of cell. By evolving in this way, the cell maintains a set of resources that allows it to remain profitable and survive in a dynamic marketplace.

Best Interest

Whether adaptation is by learning or evolution, each agent is responsible for acting in its own best interests to ensure that its goals are met. The cell agent’s best interest is to win as many jobs as possible and keep the cell busy fulfilling customer orders. The cell also generates as much profit as possible, ensuring its continued viability as a virtual business enterprise.

The resource agent’s best interest is to win as many jobs as possible and keep busy processing jobs. The resource also generates as much profit as possible, guaranteeing that it remains a viable member of the cell.

The job agent's best interest is to complete the job quickly, to make certain that it is finished by the customer's due date. The job agent also looks for the cell and resource that can complete the job at the lowest possible cost.

The best interest concept embodies the metaphor of free market behavior, as the cell, resource, and job interact and compromise to reach a solution that balances each agent's best interests. This balancing of best interests between these three entities and their dynamic interaction allows a dynamic, adaptive, and productive structure to emerge in agent-based manufacturing systems.

5 SEVEN-STEP NEGOTIATION PROCESS

When you decide to purchase a product, your decision is influenced by certain requirements. For instance, the cost of the product must be within your budget. Another requirement might be how long it takes to perform the work. Once all the elements of your decision criteria are met, you award the work to the manufacturer that best fits your needs.

AMIS uses a standard seven-step bidding process to form an agreement to provide a product. This bidding process allows customers to obtain products through a common market process, ensuring that they are all purchased at fair market prices. All seven steps of the negotiation process must be completed successfully in order to complete the transaction.

1. **Request for quote**—The Request for Quote (RFQ) is the first step in the AMIS bidding process. A customer (or *customer agent*) creates an RFQ that specifies the desired products or services—along with a response date—and sends it to a broker agent. The broker acts as a liaison, forwarding the RFQ to each cell that has "subscribed" to provide the requested product.
2. **Receive quotes**—Each cell agent determines its ability to complete the job according to the customer's RFQ specifications. If a cell is able to meet the customer's requirements, it creates a quote for the job. Quotes contain estimated information on the delivery date, price, quality, and special characteristics related to completing the job. Cells return their quotes to the broker, which holds the quotes until the RFQ response date has been reached and then returns all the quotes to the customer.
3. **Select winner**—When time has expired for the cells to submit quotes, the customer (or customer agent) begins the selection process. The customer selects the winner from the submitted quotes by finding the most desirable mix of cost, time, quality, and special characteristics, based on its requirements for the job. The customer sends an award notification to the cell with the best quote.
4. **Winner confirms**—The winning cell accepts or rejects the job depending on whether it still has the capacity to do the job. The cell might reject the job, if it has accepted other jobs between the time it prepared the quote and received the award. If the winner rejects the job, the customer offers it to the cell with the next best

quote. This continues until a cell accepts the job. After the winner accepts the job, the other cells that submitted quotes are informed of the decision. At that time, losing cells are able to access data on the quotes, which help them evaluate why they lost the job—and perhaps learn and modify their behavior for future quotes.

5. **Issue purchase order**—After a cell has confirmed the customer order, the customer authorizes the cell to begin production by issuing a purchase order to the cell.
6. **Generate product**—The cell completes the work on the product, delivers the product to the customer, and sends an invoice to the customer.
7. **Make payment**—The customer ends the process by paying the cell for the work done.

The seven-step process establishes a common approach for business interaction between cells. The same process is followed when a cell wants to subcontract part of a job to another cell.

6 SUMMARY FOR AGENT-BASED MANUFACTURING CASE STUDY

Distributed Organizational Control

To be agile, large centralized manufacturing organizations must be decomposed into simpler, smaller business units that are responsible for their own business, financial, and production success. This distributed organizational control allows these smaller units to reorganize and react quickly to changing market conditions. These smaller units—cells—can easily be reconfigured to maximize efficiency or to respond to a change in the market. Distributed organizational control enables the system to respond locally to unexpected failures or shutdowns by quickly reallocating the necessary resources.

Furthermore, distributed organizational control can be based on the concept of survival of the fittest. Therefore, if a cell within an organization consistently fails to contribute to the greater well-being of that organization, that cell ceases to exist. On the other hand, if every cell is successful, the entire operation is successful. Distributed organizational control allows a successful manufacturing operation to emerge from the interaction of smaller units.

Another benefit of a distributed organization is the ability to quickly form *ad hoc* formations of business units that achieve common business goals. Here, individual cells cooperate as a unit for a common benefit—and then dissolve when no longer needed. The components of such a virtual organization do not have to be aligned with a physical organization, adding another degree of flexibility not found in traditional systems.

Capacity Management

The more unpredictable the manufacturing environment, the more significant the problems associated with advanced scheduling. For that reason, AMIS does not use the concept of scheduling. Instead, it manages the *capacity* of the resources.

As a business entity, each cell has limited resources that have limited capacity. All jobs in a cell are temporarily put into the holding capacity queue of that cell. Then, just before a job starts, each resource in a cell bids on the job in the queue. Because the bidding is done right before the job starts, the chance of an unexpected event affecting the completion of the job is significantly reduced.

However, if a problem occurs during the production process, the system is not disabled. This is an important benefit of capacity management. Because the resources in the cell are self-loading and balance the load among themselves, a job that cannot be completed by a resource is returned to the cell's queue for re-bidding and re-allocation. This dynamic allocation of jobs to resources greatly reduces the effects of the unpredictable nature of the shop floor. While this is not the only technique for capacity management, it works well in the automotive industry.

Market-Driven Economy

In a market-driven economy, manufacturers build products in response to market demand, rather than in anticipation of demand. Businesses compete for limited resources and customers but cooperate when it is beneficial. Change is constant as new products emerge and customer demands evolve.

AMIS relies heavily on the economic laws of supply and demand. Rather than try to forecast market demand and schedule production based on rigid plans, AMIS provides an architecture that adapts to the dynamic marketplace. Both inside and outside the cell, agents operate in a profit-driven economy. The competition between cells or resources will drive the market to an equilibrium or market-clearing price. The producer's need for higher profit and faster production times interact with the customer's need for lower prices and higher quality. These opposing forces result in the best prices and products for everyone involved.

7 CASE STUDY CONCLUSION

As designed by David Greenstein, AMIS provides a means for a manufacturer to be more productive and adaptive in responding to changing market demand. Specifically, it will allow a manufacturer to:

- Increase machine (resource) utilization by better matching capacity to workload.
- Increase throughput by making the right products at the right time.
- Reduce the number of late jobs by better capacity planning and monitoring.
- Utilize/tune the correct resource types and mix by monitoring resource efficiency.

- Create a flexible and dynamic architecture that responds rapidly to a continuously changing market.
- Enable an Activity Based Costing (ABC) approach to collect and calculate actual production costs.
- Reduce "single points of failure" in production systems.

Agent-based manufacturing is a new way of thinking about and applying information. The primary benefits of the agent-based approach are that they provide dynamic, reliable, and agile systems. As such, it will enable organizations of the future to accommodate rapidly changing business conditions, increase market responsiveness, lower cycle times, increase productivity, and better utilize their resources—and most importantly, it will benefit the bottom line. In other words, the agent-based approach will be the way modern manufacturers develop their systems to compete in the twenty-first century.

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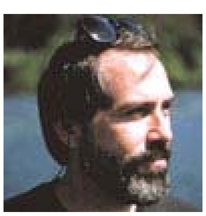
About the author



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