Evaluation of Control Systems for Automated Aircraft Wing Manufacturing

by

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B.S., Aerospace Engineering
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Submitted to the MIT Sloan School of Management and the Department of Aeronautics and Astronautics
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Abstract

The Boeing Company is looking to bring aircraft manufacturing technology into the 21st century. As part of this process, several projects have been started to develop the technologies required to achieve Boeing's vision for the future of aircraft manufacturing. To date, much of this work has focused on hardware, including robotic and other automation technologies. However, in order to use this hardware, a significant effort must also be made in the area of factory control and coordination. This thesis advances knowledge in this area by evaluating the suitability of different control system approaches for aircraft wing box assembly.

First, general classes of control systems are discussed and several criteria are proposed for evaluating their performance in an aircraft manufacturing environment. The current wing box assembly process is then examined in order to develop simplified but representative task networks to which various algorithms can be applied. The Tercio algorithm, developed at MIT, is used to generate schedules for several problem structures of interest in order to characterize the algorithm's performance in this context. The Tercio algorithm is then benchmarked against the Aurora scheduling tool, showing that Tercio can generate more efficient schedules than Aurora, but at the cost of increased computation time. Next, management considerations with respect to product design, manufacturing technology development, and implementation associated with advanced manufacturing technologies are discussed. Finally, recommendations are provided for how Boeing can accelerate the development of useful and practical advanced, automated manufacturing systems.

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This thesis is dedicated to the memory of my project supervisor at Boeing, Dr. Thomas Leach Adams, who passed away before the project was complete. He played a significant role in shaping the evolution of this project, and his enthusiasm will not be forgotten.

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Glossary

Agent	A physical entity with the ability to complete one or more types of tasks as part of the manufacturing process. Agents are a type of resource and can be robots, other automated systems, or humans.
Automation	Computer controlled physical systems that are used to fabricate, assemble, measure, apply coatings and/or move materials.
Autonomy	The capability of an entity to create and control the execution of its own plans and/or strategies. [1]
Controller	A decision-making entity in the control system.
Flexibility	The flexibility of the manufacturing process in this context refers to (1) the ability to quickly adjust production rates to match demand, (2) the ease with which the factory layout and production flow can be modified and (3) the degree to which production equipment can be used for multiple purposes.
Holon	An autonomous and co-operative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part. A holon can be part of another holon. [1]
Makespan	The time difference between the start and finish of a sequence of tasks.

1 Introduction

1.1 Background

The commercial aerospace industry in the United States has a long heritage of manual labor intensive manufacturing. This is largely a result of historically low production rates, long design cycles, and long operating cycles for most of these products. Most of the commercial aircraft flying today have been in production for decades, and in many cases the production systems still utilize technologies available when these aircraft were first produced. In particular, Boeing (specifically Boeing Commercial Aircraft or BCA) has a long history of building high quality commercial aircraft with a largely manual assembly process. Boeing is looking to improve its ability to deliver to its customers as well as to gain a competitive advantage in the commercial aircraft market by modernizing its production system. To that end, Boeing is investing significant resources on the development of various robotic and automation technologies that may eventually prove useful in the factory environment.

In addition to requiring significant manual labor, many of the aircraft manufacturing processes require large, expensive, specialized machines and tooling. Boeing's vision for 21st century manufacturing is to use smaller, more flexible robotic systems to assemble aircraft. This vision requires a sophisticated control system to coordinate the activities of each of the agents (robots, humans, etc.) to complete the assembly tasks. Such a system needs to be able to gracefully adapt to the ever-changing factory environment, without stalling production. Ideally, such a system would be able to predict and avoid temporal and spatial conflicts between agents, as well as coordinate agent activities when unexpected events occur (machines break down, tasks take longer than expected, parts are not available on time, etc.).

This thesis focuses on aircraft wing box manufacturing in particular in which relatively little automation has been implemented to date. There are many challenges associated with automating the wing box assembly process. In particular, automation hardware needs to be developed in order to suit the physical scale and demanding tolerances associated with wing manufacturing. Furthermore, these new technologies need to be coordinated in a way that is safe, reliable, and efficient. The unprecedented nature of this type of production system means it will be important to assess risk and understand sensitivities to assumptions since the evolution of these technologies is uncertain. Also, stringent quality and safety requirements will drive the design of such systems. In addition, the constraints on the build process and the cognitive role of humans in this new manufacturing paradigm will need to be carefully considered. All of these factors will impact control system design.

1.2 Problem Statement

This thesis examines two different aspects of manufacturing control system design in the context of a multi-agent manufacturing system, with a focus on aircraft wing box assembly: the control architecture, and the control strategy. The architecture of the control system refers to the physical entities in the system (e.g. agents, controllers), the logical hierarchy that defines the relationships between them, and the communication channels that connect them. The control strategy refers to the method by which resources are allocated to tasks in the manufacturing process under various temporal and spatial constraints (referred to herein as task-level control). The task-level control problem involves solving a combinatorial optimization problem to obtain optimal or approximately optimal solutions. For small problems, optimal solutions can be obtained relatively easily; however, for even moderately complex problems, optimal solutions become computationally infeasible. Thus, more computationally tractable techniques must be developed in order to obtain feasible (and hopefully near optimal) solutions to the allocation and scheduling problem. Further complicating the problem is the fact that in a dynamic factory environment, finding “optimal” solutions is often at odds with generating robust solutions that are capable of tolerating disturbances. As a result, the objective function for the optimization needs to be chosen carefully in order to generate solutions that are efficient, but not so brittle that they immediately become invalid once an unexpected event occurs. This is a significant technical challenge because the most effective control system solution is often dictated by the specific problem to which it is applied. In addition, there are numerous managerial challenges associated with implementing radically different technologies in a well-established manufacturing environment. This thesis begins to examine what type of control system is best suited to aircraft wing box manufacturing and how it can be implemented at Boeing.

1.3 Motivation and Vision for Automation

Boeing's vision for aerospace manufacturing in the 21st century involves the use of coordinated teams of smaller, less specialized robots that are capable of performing multiple tasks in parallel. This vision represents an unprecedented and revolutionary leap in aircraft manufacturing technology. BCA hopes to reap the many potential benefits of automating the assembly process including improved safety, improved quality, increased productivity, increased capacity, improved factory flow, improved product performance, increased customer satisfaction, and reduced operating costs.

Worker safety is a significant motivation for implementing automated manufacturing systems. An aircraft factory is inherently dangerous with large and heavy parts and equipment and many people performing different tasks in the same (often congested) area. In addition, many assembly tasks consist of numerous repetitive motions or other forms of ergonomic concerns that result in injuries, lost work, and significant workers compensation related expenses [2]. An important benefit of an advanced automated manufacturing system is the reduced operator workload, stress and fatigue (both physical and mental). In this environment, operators' intellectual capacity can be used more effectively for complex cognitive tasks rather than repetitive manual labor [3].

Quality is also a primary motivator for automated manufacturing. Automated systems can provide repeatability and consistency to eliminate human errors and reduce product variability. Problem detection and correction also becomes easier with data collection from automated system sensors and instrumentation. The current (manual) assembly process is prone to human error and the amount of time and money currently spent on rework and disposition of non-conformances is significant [2].

Cost is a key consideration in deciding whether to implement automated manufacturing since expenses must be outweighed by the expected benefits in order to make financial sense. Automation technologies have the potential to improve financial performance by reducing safety incidents (reduction in worker's compensation), reducing quality issues (less rework), and improving production rates (faster recognition of revenue). It is also clear that to achieve Boeing's vision for automation in aircraft assembly, significant investments will need to be made in technology development and qualification of those technologies for production use. It is challenging to estimate the required investment since a system like the one being proposed is unprecedented, especially on the physical scale required for commercial aircraft manufacturing. However, benefits from automation technologies have been realized in other industries such as bulk pharmaceutical manufacturing [4]. This evidence is encouraging, but it also indicates that there can be a shallow learning curve associated with implementing automation, and the full benefits may not be realized for several years after initial implementation [4]. Fortunately, the aircraft industry is similar to the pharmaceutical industry in that the product and production life cycles are long. This means that there is a better chance that the benefits of automation can be realized during the production system lifecycle relative to other industries (e.g. consumer electronics) where products change radically every few years.

1.4 Thesis Aims

Fundamentally, a manufacturing system can be defined by (1) the product to be produced, (2) the process by which it is produced, and (3) the resources required to execute the process. The "manufacturing system" is an aggregation of technologies, processes, and physical material which, once integrated, becomes a capability which can provide a significant competitive advantage. This thesis provides some initial insight into what types of control systems will likely perform well for the wing box assembly application and outlines a plan for future work in order to move toward implementing advanced automation systems in the factory.

1.5 Approach and Methodology

In order to provide useful recommendations for how to determine an appropriate control system for wing box manufacturing, it is important to understand the context in which the system will be used both from a technical and managerial perspective. From a technical standpoint, the first step in this process is to study the existing products and processes as well as the expected future products to understand the current and future needs of the manufacturing system. This information was gathered through the review of many Boeing documents, conversations with Boeing employees, and direct observations in the factory. This provided insight into the requirements and constraints for the system. In this process it is also important to consider current and future technological developments that may change what is possible in the factory. With this information, we can then begin developing a vision for the future of automated manufacturing and identify the key interfaces and considerations for the control system. From a managerial perspective, it is important to understand the practical challenges of developing and implementing advanced manufacturing technologies within a large and established organization. Numerous meetings, discussions, and interviews with Boeing personnel were the primary methods of collecting information about the organization that helped to inform the recommendations of Chapter 0. This is the approach that guided the project which is described in this thesis.

1.6 Key Contributions

The primary contributions of this thesis are: (1) a survey of relevant automation related technologies with regard to their applicability and readiness for wing box assembly, (2) a trade study to evaluate the performance of various control system approaches a variety of scenarios, (3) a control system implementation and transition plan, and (4) recommendations for future work that will provide additional insight into control system design.

1.7 Outline of Thesis

This thesis is structured as follows. Chapter 1 discusses the background, motivation, and approach for this project. Chapter 2 summarizes the current wing box assembly process including historical evolution, the structure of the task networks, and considerations for the future process. Chapter 3 provides a high level overview of different control methodologies that exist or are currently in development, proposes a “scorecard” by which these methods can be judged, and attempts to broadly characterize the performance of the various methods using these criteria. Chapter 4 presents a case study using the Tercio algorithm on representative task networks for the wing assembly process and benchmarks the performance against the Aurora scheduling tool. Tercio is a centralized algorithm developed at MIT for use in robotic task scheduling where temporal and spatial constraints exist on robot actions. Aurora is a commercial tool that uses critical chain techniques to perform factory scheduling and is currently in use at Boeing on several aircraft programs. More details on these algorithms are provided in Chapter 4 and in the Appendix. Chapter 5 discusses some of the key management challenges associated with implementing automation technologies in the factory. Chapter 6 provides recommendations and future work in a number of areas that will be critical to the success of Boeing’s automation projects. Finally, Chapter 7 provides an overall conclusion and some final thoughts on this effort.[1]

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[1] Note: Appendix A provides an overview of the state of other automation related technologies and how they are likely to impact factory control systems.

2 The Wing Box Assembly Process

2.1 The Basic Process

At a high level, the wing box assembly process for traditional aluminum aircraft wings is similar across product lines. Differences in the processes primarily arise from the difference in the physical size of the parts (e.g. larger wings require more crane lifts) or other features unique to each wing type (e.g. installation of parts that are critical to engine mounting and alignment). Other than these minor differences, the process proceeds as follows. First, spars and ribs are attached appropriately to build the "ladder", and then skin panels are installed on either side to make the wing "box" (see Figure 1). This is the basic process by which most conventional wings are built; however, embedded in this process are numerous alignment, drilling, fastening, and other tasks. The details of how the parts come together in order to maintain tight tolerances and quality requirements is what makes the problem of automating this process complex from a hardware standpoint. In particular, this requires very precise sensing and positioning capabilities from the automation systems, particularly when they are interacting with the product.

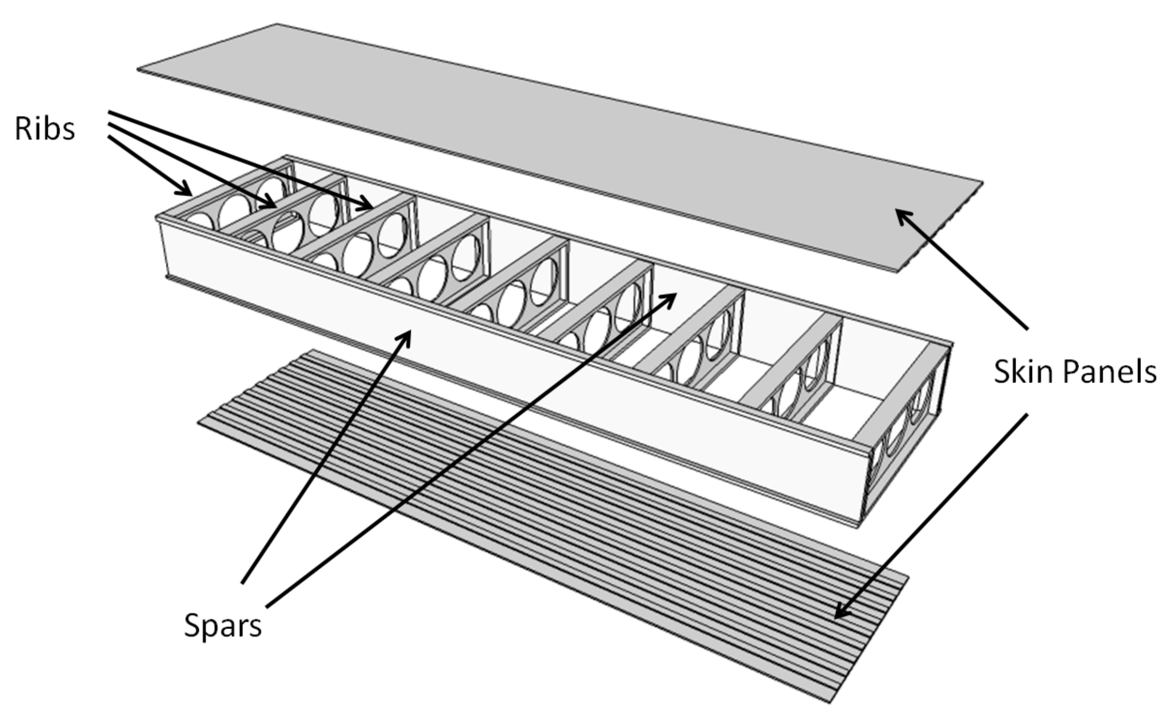

Figure 1. Wing Box Components

2.2 Historical Perspective

Until recently, all of Boeing's wing boxes were built in large fixed tooling, in a vertical orientation. Partly because of increased production rates, Boeing re-evaluated the manufacturing process for the 737. This resulted in the creation of the Horizontal Build Line (HBL), which is currently implemented in the Renton, WA factory. In the HBL, the production line is broken into cells, in which a specific set of tasks are performed as the wing box is assembled. The wing progressively moves down the production line for further processing. Since the HBL is closer to the ideal concept of a moving production line, this manufacturing process is used as a baseline for establishing the relevant constraints for an automated production system.

In the old process, large fixed tooling held the spars in position while the rest of the wing box was assembled in a vertical orientation and wing boxes were processed in parallel on multiple tooling fixtures. In the HBL, the wing box is built in a horizontal orientation, in a production line with multiple stations/positions. Throughout the build process, the wing box is supported by adjustable fixtures, which allow for height adjustment and a relatively quick transition as the wing box moves down the production line. While the HBL facilitates higher production rates, several new challenges arise in maintaining the relative position of all the parts in the structure. Assembly constraints and precedence relationships were re-evaluated when the transition was made because of the different loads, dynamics, and physical orientation associated with the new process. In some instances, the result was additional flexibility in the production process, whereas in others it necessitated additional process steps or sequencing requirements to ensure the product met specifications.

One significant change to the process that resulted from the new build orientation was the addition of alignment procedures throughout the process to ensure tolerance requirements are met. The adjustable fixtures are not as rigid as the old fixed tooling, so alignments must be done after significant weight is added to the structure or forces are applied to it. Alignments are performed using a laser leveling system. This has the effect of creating natural stopping points in the build process where these alignments must be completed before assembly can continue. If this constraint cannot be eliminated (e.g. through some sort of dynamic, auto-leveling technology), then the process lends itself to local (cell) control and global (factory) control is probably not necessary. The alignments have the effect of temporally decoupling the set of tasks that precede it from the tasks that follow it, so there is little reason to try and optimize both sets of tasks simultaneously.

Another key difference with the new process is that all wing box production stops when there is a problem on the assembly line (previously, each wing box had a corresponding tooling fixture and if a problem occurred with one, work could still continue on other units). This means that the production system needs to respond quickly and effectively to disturbances in order to maintain production rates. This will be one of the most significant challenges for an automated assembly system, and is one of the primary challenges this thesis attempts to address.

2.3 Precedence Networks

It is clear from existing literature (and current research) that the optimal control system for a particular application is highly dependent on the constraints and precedence relationships among tasks. Therefore, it is important to examine the precedence relationships and temporal/spatial constraints in the task networks for the process being executed (in this case, wing box assembly). Throughout this thesis, task networks will be represented by circles, rectangles, and connecting arrows. Circles represent the start or end of a network of tasks, rectangles represent individual tasks to be completed, and arrows represent precedence constraints among tasks.

In the current assembly process, three types of task network structures dominate the overall process: unique serialized tasks that must be performed in a specified order (Figure 2), collections of tasks which are similar in nature that can be accomplished in parallel (Figure 3), and a hybrid of these two which is a collection of similar tasks which are partially ordered according to precedence constraints (Figure 4).

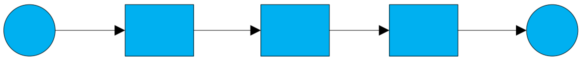

Figure 2. Example of a Strictly Serial Task Network

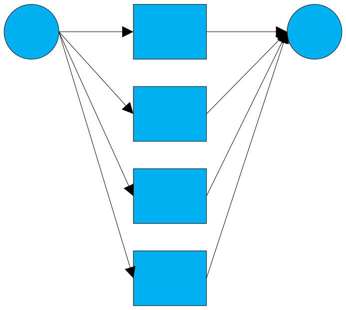

Figure 3. Example of Parallel Task Network

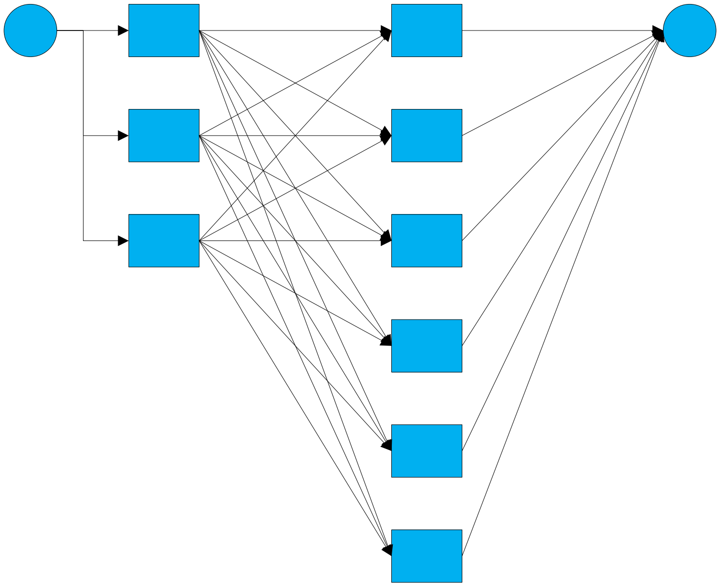

Figure 4. Example of Hybrid Task Network Structure (tasks are similar but some must occur before others)

Although these precedence relationships are a primary consideration in the design of the control system, there are many other considerations that need to be addressed in a factory environment. These include quality, safety, temporal constraints, and spatial constraints. The remainder of this section briefly discusses each of these considerations.

2.3.1 Quality and Safety

Quality and safety requirements are a significant concern for the application of aircraft manufacturing. The precision to which aircraft are designed puts a lot of pressure on the manufacturing processes and tools in order to ensure the as-built configuration is in line with expectations. Quality is a major consideration for ensuring customer satisfaction with respect to performance and safety. Quality is also a concern from the manufacturer's perspective because each defect that has to be repaired or otherwise dispositioned costs time and money which reduces the ability to deliver aircraft and reduces the profitability of the fixed price product.

As aircraft manufacturing moves from almost no automation to highly automated factories there will be a significant transition period where humans are working around or in cooperation with robots and other automated systems. As more automation is implemented, automated systems will be working in tighter physical spaces. As such, there must always be a great deal of attention paid to the inherent safety of the systems that are implemented. Until sophisticated, reliable "sense and avoid" technologies are available, safety is likely to be handled primarily by procedures, keep out zones, and limiting the physical proximity of robots, humans, and other systems. In an environment where robots are not necessarily fixed in place, additional constraints may need to be placed on where and when they can do work, and these will likely need to be considered by any factory control system that is implemented.

2.3.2 Temporal Constraints

It turns out that the wing box assembly process is overwhelmingly driven by precedence constraints, with the exception of tasks which involve sealant application. The sealant used needs to be kept cold until use, and then a cartridge is only usable for two hours. This is not expected to constrain the control system under normal circumstances, so it has not been considered as a relevant constraint for task networks analyzed herein.

2.3.3 Spatial Constraints

Spatial constraints are a significant concern, especially when multiple robots are working in the same area and/or robots are working near humans. One way to address this concern is to ensure robots are never working close to one another or to a human. Another, more complicated, approach is to collect and provide environment information to each of the automated agents in the system so they can take action appropriately to ensure safety of other agents, personnel, and the parts being assembled. For the purposes of this thesis, the sensing and navigation problems associated with this are considered out of scope, but this is certainly a very important technology research area for enabling mobile/agile automation.

3 Evaluation of Control Systems

3.1 Application

One of the goals of this thesis is to identify the key functional and performance metrics by which control systems can be evaluated for use in wing box assembly. The remainder of this section is written from the perspective of evaluating these architectures and strategies for this purpose (and more specifically for application to the task networks described in Chapter 0). For the purposes of this discussion, the manufacturing system includes the parts which are assembled into the wing box structure, tooling, infrastructure, agents (machines and humans), controllers, and control algorithms. The focus here is on the control system portion of the manufacturing system which includes the physical controllers (with processing capability), the communication interfaces between controllers and the agents, and the control logic (algorithms).

3.2 Desirable Characteristics of a Control System

There are several important characteristics of a control system that are desirable for a factory environment. The key characteristics are certainly problem dependent, and the list below summarizes the list of characteristics that, in the author's opinion (and based on literature cited herein), will be most important to the wing box assembly task.

- Balanced workload: It is desirable to have the workload balanced throughout the production line in order to maintain steady flow throughout the factory. This applies both to the number and duration of the tasks to be completed by each agent and the amount of real-time processing required at each controller in order to coordinate and monitor the execution of these tasks. Balancing reduces the possibility that agents or controllers in the system are operating close to capacity (for agents, capacity refers to the maximum speed at which the agent can complete tasks; for controllers, capacity refers to processor utilization), thereby improving the ability of the system to handle disturbances and maintain flow rates under uncertainty.

- Physical correspondence: Controllers in the control system, whether they reside in computers or are part of automated agents, should correspond with physical entities in the factory. From a practical standpoint, this helps to minimize the logical complexity of the system (making it easier to understand and interact with). Also, this feature ensures an appropriate level of abstraction for describing a system that has both human and robotic/automated agents, without introducing additional (agent specific) modeling complexity.
- Scalable: It is desirable to have a system that does not exhibit increased computational complexity for updating and re-computing schedules as agents and/or tasks are added to the system.
- Maintainable: The life-cycle of a control system in the aircraft manufacturing context is quite long, which means it is important to have a control system that can easily be maintained to adapt to the introduction of new or modified products and new manufacturing technologies. Maintenance also tends to be a significant portion of the costs associated with operating highly automated systems. It is important to ensure these systems are designed with maintenance in mind so that the benefits of automation are not negated by the overhead associated with maintaining them.
- Reliable: Ideally, the system should produce reliable and consistent schedules and be able to maintain them while operating over the expected range of known nominal factory conditions (e.g. accounting for things like the expected lifetime of drill bits, different mixes of agent types, travel time for mobile agents, multiple product variants on the same production line, etc.).
- Flexible/Robust: The system should be flexible and able to adapt to unexpected changes in the environment (e.g. parts or resources not being available, faults, etc.) by coming up with a solution that keeps the production line moving.

These characteristics are by no means exhaustive, but are intended to provide a framework in which to think about the quality of the control system for this particular application. In reality, it is difficult to characterize a particular type of system in any generic sense since the algorithms may perform quite well for certain types of problems, but very poorly in others.

3.3 Types of Manufacturing Control Systems

Traditional control architectures have primarily been developed from one of two points of view[2] [5] – centralized or decentralized [6, 7, 8, 9, 10, 11, 12]. These two general approaches have very different performance characteristics depending on the application for which they are used. In an effort to capture the benefits of each type of architecture, several types of hybrid approaches have been proposed. Figure 5 depicts the general classes of control architectures. Centralized architectures are inherently hierarchical – higher level agents direct lower level ones as to what they should do next. Decentralized architectures are heterarchical in nature – agents act as peers and work together or negotiate in some way to decide the allocation of tasks and the order of task execution. Between these two extremes are hybrid architectures. These hybrid approaches can vary from highly hierarchical to highly heterarchical and may even dynamically adjust the characteristics of the architecture structure as they respond to the environment. Each type of architecture is discussed in detail in the following sections.

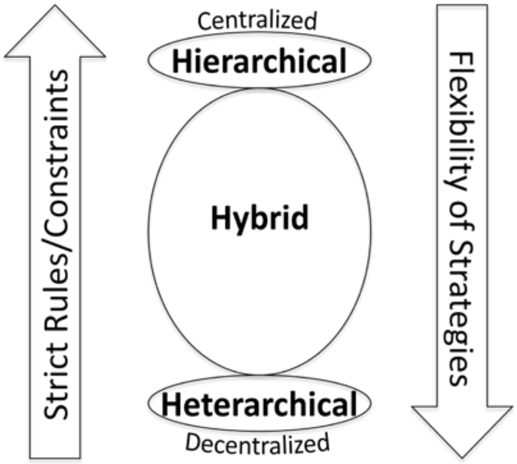

Figure 5. Characterization of Different Control Systems (adapted from [13])

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[2] Distributed approaches are also discussed in the literature. These approaches assume that data is stored in separate memory partitions, and information is passed via communication channels. Distributed architectures generally refer to distributing the computations, not the actual decision-making; therefore, distributed approaches are considered a subset of centralized approaches for the purposes of this discussion.

3.3.1 Centralized Control Systems

Purely centralized architectures utilize a single controller for decision-making and “information exchanged between different modules of the [control] algorithm occurs through shared memory” [14]. Distributed architectures are similar except that they utilize “algorithms that run as separate modules, where each of these distributed algorithmic pieces uses its own memory partition to store data associated with the planning process, and where relevant information is shared between the modules through reliable communication channels” [14]. The centralized architecture is conceptually simple and relatively straightforward to implement in terms of formulation (but may be computationally complicated and/or constrained by the communication infrastructure) [7]. Centralized architectures are often hierarchical in nature.

3.3.2 Decentralized Control Systems

A decentralized control architecture is characterized by “independent agents planning autonomously for themselves in environments with unreliable and sporadic communication infrastructures, where there are no rigid constraints and guarantees placed on message delays, network connectivity, program execution rates, or message arrival reliability” [14]. Agents are able to make their own decisions based on local observations; there is no central location at which global decisions are made. Decentralized controllers exhibit a heterarchical structure where agents communicate as peers. Some of the beneficial features of a decentralized architecture are as follows:

- Modularity: A decentralized architecture is inherently modular since each controller bases its decision-making only on information from local agents/controllers.
- Lower processing overhead: Each controller only needs to process data for a small portion of the system.
- Scalability: The addition of controllers/agents only affects the system locally.

In general, decentralized architectures tend to work well for tasking homogeneous sets of agents without tightly coupled temporal and spatial constraints and/or when communications between agents is difficult because of transmission distances or obstructions. Problems of these types can be naturally decomposed into a set of simpler ones, requiring only limited information, and thus near optimal results can be achieved with decentralized architectures [15].

3.3.3 Hybrid Control Systems

The promise of hybrid systems is that they can achieve a more optimal balance of desired features as compared to purely centralized or decentralized approaches. Hybrid control architectures are employed to achieve the tight coordination benefit of centralized approaches with the efficient computation benefit of decentralized approaches. A number of hybrid architectures have been proposed including bionic manufacturing [16, 17], fractal manufacturing [18], random manufacturing [19] and holonic manufacturing [20, 21, 22, 23]. A detailed comparison of bionic, fractal and holonic approaches is provided in [18]. Most of these concepts are in some way inspired by systems in nature, and each of them is summarized briefly below.

Bionic manufacturing systems view the factory as an organism and are inspired by the way in which cells in an organism work together in order to complete various biological processes. The manufacturing environment is thought of as a collection of "cells" each performing a specific task and acting autonomously when triggered with the appropriate signals and materials. Organizing the activities of these cells is performed at a higher level within the factory (analogous to the functions of organs or a complete organism in a biological system).

The fractal factory concept is based on independent entities (fractals) that perform functions in pursuit of a goal. Goals among these entities need to be coordinated through cooperation. Fractals constantly reassess their own performance and adjust their plans in order to achieve their goal.

Random manufacturing systems are similar to holonic systems in that there are teams of entities (e.g. machines) that group themselves in order to perform a task (and which can dissolve after task completion); however, unlike holonic systems, these groups each place a bid in a competitive auction in order to be assigned a job.

Holonic manufacturing systems have long been proposed as the paradigm for the future of manufacturing. Arthur Koestler originally proposed the concept of the holon in 1967 as a framework to mimic the social organization living organisms [24]. The concept of a holon is that some portions (subunits) of the holon are autonomous and self-reliant, while they are simultaneously subject to control from higher authorities. This allows the holon to respond well to local disturbances while maintaining global functionality. In [1], the authors benchmark the performance of the holonic architecture against purely hierarchical and purely heterarchical control architectures on a prototype assembly system test-bed for four different operating scenarios (nominal, rush order arrival, feeder jamming, and equipment failure). A summary of the criteria used to evaluate the performance of the different approaches and the results of the benchmarking study are provided in Table 1.

Table 1. Benchmarking of Holonic Control [1]

	Hierarchical	Heterarchical	Holonic
Agility: capacity to use different alternatives	Bad	Excellent	Good
Autonomy: capability to work under permanent perturbation	Weak	Excellent	Good
Flexibility: ability to accept modifications in the production settings	Good	Good	Good
Robustness: capability to stay in a legal and stable state under perturbations	Excellent	Weak	Good
Cooperation: quality of the collaboration with the scheduler	Weak	Bad	Good
Initial Cost: duration of the initial development of the control system	Medium	Cheap	Expensive

These results suggest that the hybrid control system approach may indeed be the best compromise from a system performance perspective, but may also be most expensive in terms of up front development cost.

Hybrid control systems are an active research area and more successful applications of these types of systems are required in order to more definitively characterize their potential.

3.4 Control System Performance Trade Study

Quantifying the capabilities of any given control strategy is extremely difficult without extensive testing of algorithms, communication networks, and automation technologies. Eventually, this data will be available, but the best that can be done at this conceptual stage is to create a “control system scorecard” to guide the evaluation of different options. In this section, I propose a set of criteria by which control systems should be evaluated for application to wing box assembly. The remainder of this section identifies these proposed criteria and qualitatively assesses how various architectures would likely perform.

3.4.1 Computational Complexity

A control system is only of practical value in a dynamic factory environment if the associated algorithms that are used to solve the resource allocation and scheduling problem are computationally feasible and converge to a solution quickly. Most optimal scheduling problems with resource constraints are computationally intractable (NP-Hard or NP-Complete). Thus, the more discrete decisions that need to be made for complete task allocation and sequencing (i.e. the more binary decision variables in the mixed integer formulation of the problem), the more difficult it is to solve computationally with a centralized approach. Decentralized approaches rely on decision-making with local information, and therefore the computational complexity does not increase as quickly with the size of the network (assuming new types of constraints are not introduced) as compared to centralized approaches. From a computational complexity perspective, decentralized architectures have a slight advantage (with the trade-off that they tend to produce sub-optimal solutions), but this also becomes less of an issue as available computing power increases.

3.4.2 Communications

Whatever type of architecture is used, there will be some degree of communication among controllers and agents in the system in order to coordinate activities and/or report status information. Perhaps as difficult a design problem as the control system is the design of the communication infrastructure that supports it (particularly for wireless systems). In fact, the communications infrastructure is intimately tied to the performance of the control system and will influence its design. Decentralized control is more robust to loss of communication paths in the communication network, particularly if they are not in a controller's local region. Bandwidth requirements for centralized approaches can become significant if all the relevant sensor data and state information is funneled to a single controller. However, decentralized approaches can also require significant bandwidth if individual agents/controllers require global state information to make decisions. It is unclear a priori which type of control system will perform better in this category without detailed information of the network topology. For this reason, it is important that the communications system and the control system are designed together, from a systems perspective.

3.4.3 Optimality of Solution

Clearly, the optimality of the solutions produced by the task level control system is important – more efficient allocation and scheduling of resources results in higher production rates. Decentralized/heterarchical controllers have been shown to have problems with global optimization [5, 1]. Because centralized controllers have access to global information, they are better equipped to achieve more efficient solutions, but the computational feasibility quickly decreases as the problem complexity grows. For this criterion, centralized approaches will generally do as well or better than decentralized ones.

3.4.4 Response to Disturbances

If the past is any indication of the future, the factory environment will continually evolve in order to re-optimize production flow to allow increased production rates and the limits of the production system will be pushed in order to gain every last bit of available efficiency. In this type of continuous improvement environment, production capacity will continue to increase, but production levels are likely to track close to the maximum. As production rates go up, disturbances that occur today (e.g. missing parts, nonconforming parts, broken tools, assembly errors) will have an even greater impact on production, and disturbances that are currently irrelevant (or new types of disturbances that are created) will become increasingly important to address in order to maintain factory flow. Disturbance rejection will therefore likely become more critical as on the factory evolves and production rates increase. Decentralized control systems often respond faster to sudden localized changes in the environment, whereas many centralized/hierarchical systems have been shown to exhibit poor performance when responding to disturbances [5] (mostly because they often need to generate an entirely new solution when an unanticipated event occurs). Ultimately, the optimal control system approach will depend on the frequency of disturbances and the importance of achieving a near optimal schedule. Frequent disturbances increases the importance of autonomy (when decentralized methods tend to perform better) and scheduling importance favors centralized methods [13].

3.4.5 Predictability

Predictability of the control system is important for several reasons. For example, while the transition is made to a fully automated factory, people and robots will likely be working in the same physical space. Unpredictable motions and movement of automated systems can lead to safety concerns. Even when people are not in close quarters with robots, significant uncertainty in the system can make it difficult to control or even to converge on a solution. In fully decentralized/heterarchical systems, the solution to the problem being solved is emergent [21], and therefore the system can exhibit unpredictable behavior [13, 22, 7]. Centralized/hierarchical control results in more predictable reactions to events. More predictability in the system means that humans interacting with the system can more easily train their mental models of the system in order to interact with it more effectively. Predictability of the system is essential for safety critical and time sensitive applications such as the aircraft manufacturing process.

3.5 Summary of Trade Study

The preceding discussion focuses on a comparison of purely centralized and highly decentralized architectures. Obviously, there are varying degrees of centralization/decentralization, and also hybrid architectures that offer properties different from the more traditional architecture configurations. Unfortunately, it is not easy to draw general conclusions – the specifics of the architectures and the problem to which they are applied need to be considered and thoroughly tested to truly understand the relative performance of the different approaches (much of this remains as future work). Thus, trying to assess the relative performance of different architectures becomes problematic, even in a qualitative sense (even the existing literature provides somewhat different views of the potential of different approaches). However, in order to help get closer to having the data required to make these types of assessments, this thesis attempts to further knowledge in this area by applying two different scheduling approaches to representative task networks for wing box assembly and assessing their relative performance. This is the topic of the next chapter.

4 Case Study: Application of the Tercio Algorithm

In this chapter, I compare two different approaches to resource allocation and scheduling algorithms. The first is the Tercio algorithm and the second is the Aurora scheduling tool. These are not the only two types of algorithms but they were the most readily available for the purposes of this study. The case study presented here is meant to be an outline for a more comprehensive future analysis involving additional approaches and rigorous benchmarking.

4.1 Overview of the Tercio Algorithm

The Tercio algorithm was developed at MIT for use in robotic task scheduling. It is a centralized algorithm that seeks to optimize performance objectives subject to temporal and spatial constraints on robot actions. The algorithm uses a heuristic task sequencer as a subroutine to a standard Mixed Integer Linear Program (MILP) solver in order to generate near optimal schedules. The algorithm and MILP is formulated assuming task networks fit the form of a Simple Temporal Problem [25]. Details of the algorithm can be found in [26]. The algorithm is capable of handling moderately complex task networks with a variety of spatial, temporal, and resource constraints.

4.1.1 Tercio's Relation to Prior Art

Tercio represents only one approach to the task allocation and scheduling problem, but it offers some notable advantages over prior art for the application of wing box assembly (and for manufacturing in general). The developers of the Tercio algorithm note in [26]:

> *One of the most promising approaches has been to combine MILP and constraint programming (CP) methods into a hybrid algorithm using decomposition…This formulation is able to gain orders of magnitude in computation time by using a CP to prune the domain of a relaxed formulation of the MILP. However, if the CP is unable to make meaningful cuts from the search space, this hybrid approach is rendered nearly equivalent to a non-hybrid formulation of the problem. Auction methods* (e.g. [15])*…also rely on decomposition of problem structure and treat the optimization of each agent's schedule as independent of the other agents' schedules. These techniques preclude explicit coupling in each agent's contribution to the MILP objective function. While the CP and auction-based methods support upperbound and lowerbound temporal deadlines among tasks, they do not handle spatial proximity constraints, as these produce tight dependencies among agents' schedules that make decomposition problematic.*

> *Other hybrid approaches integrate heuristic schedulers within the MILP solver to achieve better scalability characteristics…These methods solve scheduling problems with 5 agents (or groups of agents) and 50 tasks in seconds or minutes, and address problems with multiple agents and resources, precedence among tasks, and temporal constraints relating task start and end times to the plan epoch time. However, more general task-task temporal constraints are not considered.*

Another approach not mentioned in [26] is the concept of equal mass partitioning, developed by Rus et al. [12, 27]. This method performs task allocation for multiple robots considering structural and geometric constraints for the build process; however, tasks are not scheduled according to upper-bound and lower-bound temporal constraints. This means there are no guarantees on timeline constraints and there is the possibility of a conflict in task assignments. The Tercio algorithm was chosen for use the following analysis in part for the reasons cited here. In order to gain some insight into the relative performance of the algorithm, it is benchmarked against Aurora, which is becoming the standard scheduling tool for many of Boeing's aircraft production programs.

4.2 Scenarios

I use the Tercio algorithm and the Aurora algorithm to evaluate different factory scenarios to learn about how the algorithms might perform and also to gain some insight into whether they would be suitable for wing box assembly. In order to do this, I utilize network structures that are characteristic of the wing box assembly process. A vast majority of the work required in wing box assembly is completed along the centerline of the wing (lower part of Figure 6), or near the trailing/leading edges (upper part of Figure 6).

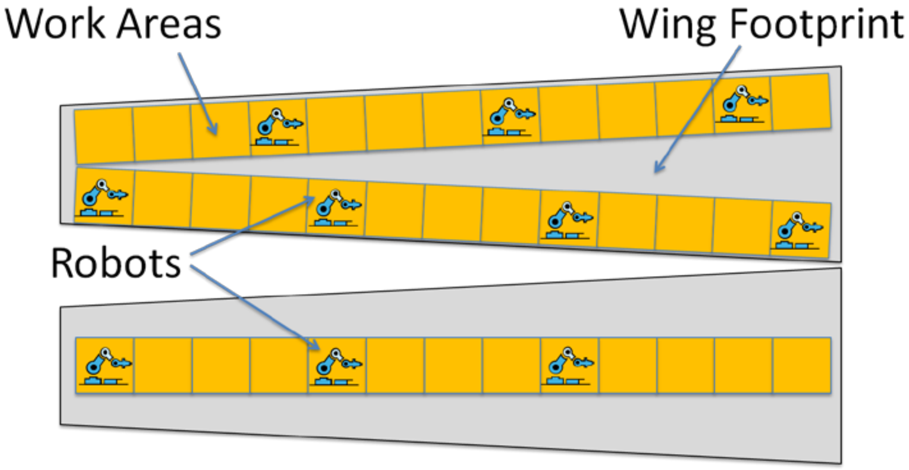

Figure 6. Visualization of Work Locations in the Factory for Wing Box Assembly

The upper part of the figure shows the work areas along the trailing and leading edges of the wing as viewed from above. The lower portion of the figure shows work areas corresponding to the rib locations along the wing. Much of the work done in each of these areas is similar (e.g. multiple drilling and fastener installation tasks) and can be described by simple task networks with multiple parallel tasks, which is the focus of the analysis contained herein.

4.3 Analysis and Results

First, I characterize the Tercio algorithm's performance by examining a variety of scenarios within the design space of interest. In particular, I look at varying the size of the task networks (number of tasks), the number of agents available to complete those tasks, and the capabilities of agents (i.e. whether agents are multi-purpose and thus can perform different types of tasks, or agents are specialized and can only perform one type of task). Next, I examine the data to understand how it may inform decisions about designing the manufacturing system in terms of the physical size and capabilities of automated systems.

The first set of data concerns Nx1 dimensional task networks, where N is the number of tasks without precedence constraints (meaning they can feasibly be executed in any order). Figure 3 provides an example of a 4x1 dimensional task network. Nx1 dimensional networks can represent tasks such as parallel drilling operations or fastener installations. These types of networks can also, for example, represent the combination of drilling and fastener installation, if the agents in the system are capable of performing both tasks. This highlights the fact that the task networks are determined in part by the aggregation of tasks based on agent capabilities. I use this fact later to infer how agent capabilities will impact the overall performance of the manufacturing system. The data for Nx1 dimensional scenarios is summarized in Figure 7.

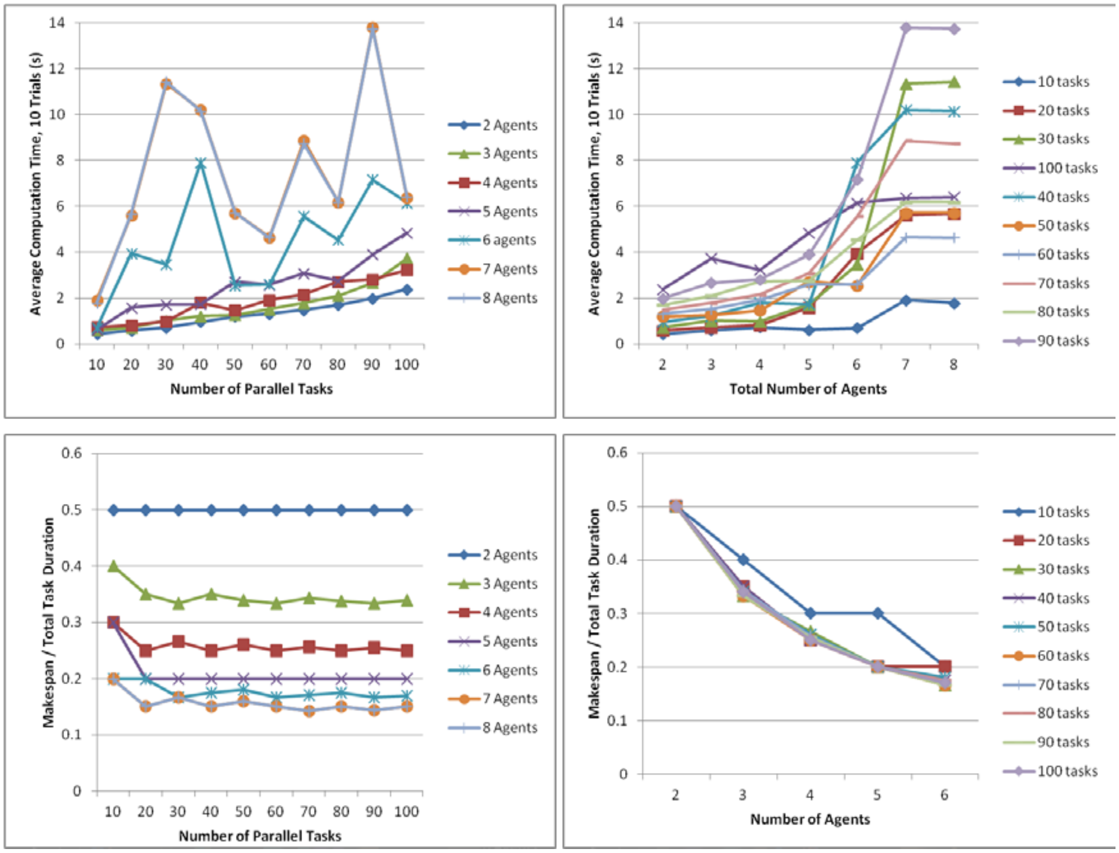

Figure 7. Results for Nx1 Task Networks: Computation Time vs. Number of Tasks (Top Left), Computation Time vs. Number of Agents (Top Right), Normalized Makespan vs. Number of Tasks (Lower Left), and Normalized Makespan vs. Number of Agents (Lower Right)

Figure 7 shows a single set of data, represented in multiple ways. The first graph (Top Left) plots the average computation time over ten trials versus the number of parallel tasks (N) in the network. The purpose of this graph is to see whether and how the computation time of the algorithm is affected by the size of the network. The second graph (Top Right) is similar to the first except the horizontal axis is the total number of agents (resources) available to do work. This graph characterizes the computation time as a function of the number of agents in the system. The third graph (Lower Left) plots the normalized makespan (total makespan of the resulting schedule divided by total amount of time required to complete the task network if only one agent was available to do work) versus the number of parallel tasks in the network. The normalized makespan is used here as a measurement of the efficiency of the algorithm's solution and provides a way to compare the efficiency of solutions regardless of the size of the task networks. Finally, the fourth graph (Lower Right) plots the normalized makespan versus the number of agents available. This graph portrays the marginal benefit (with respect to the efficiency of the solution) of adding additional agents to the system.

There are several things worth noting about these results. First, the average computation time required to generate a schedule is under 14 seconds for all the cases considered (10-100 tasks and 2-8 agents; Top Left of Figure 7). Second, in general, the computation time becomes less predictable when the number of agents in the system increases (also Top Left of Figure 7). It is worth noting that this variation appears to be due to the problem structure rather than variability in the optimization or computing resources since the variance among the trials tends to be small. Third, the computation time (as expected) exhibits exponential growth with respect to the number of the agents in the system (Top Right of Figure 7). Fourth, the efficiency of the solution (minimum duration of the resulting schedule as a percentage of the total work to be accomplished; Lower Left of Figure 7) is essentially constant (except for cases where an individual task duration is a significant percentage of the total work to be done). Finally, the efficiency of the solution does not depend on how the work is split up in the network structure (Lower Right of Figure 7). These last two observations indicate that, for these types of networks, the performance of the system will not improve by breaking a larger task into smaller subtasks without adding more agents to the system.

In order to determine whether the findings from the analysis of the Nx1 dimensional networks case can be generalized, I next examine Nx2 dimensional task networks. Nx2 networks represent tasks that have two steps (the first step must be completed before the second) and for which the ordering of each two step task is not important. As an example, a 4x2 network is depicted in Figure 8.

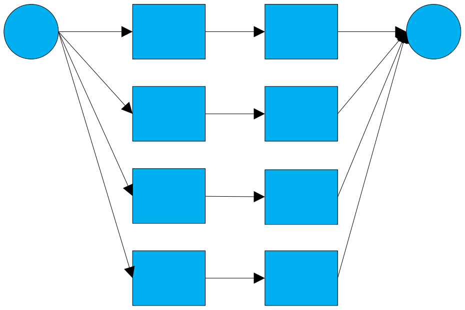

Figure 8. Depiction of a 4x2 Precedence Network

A summary of the data from analyzing networks of this form is shown in Figure 9. The presentation of the data in Figure 9 is identical to that for the Nx1 networks shown in Figure 7.

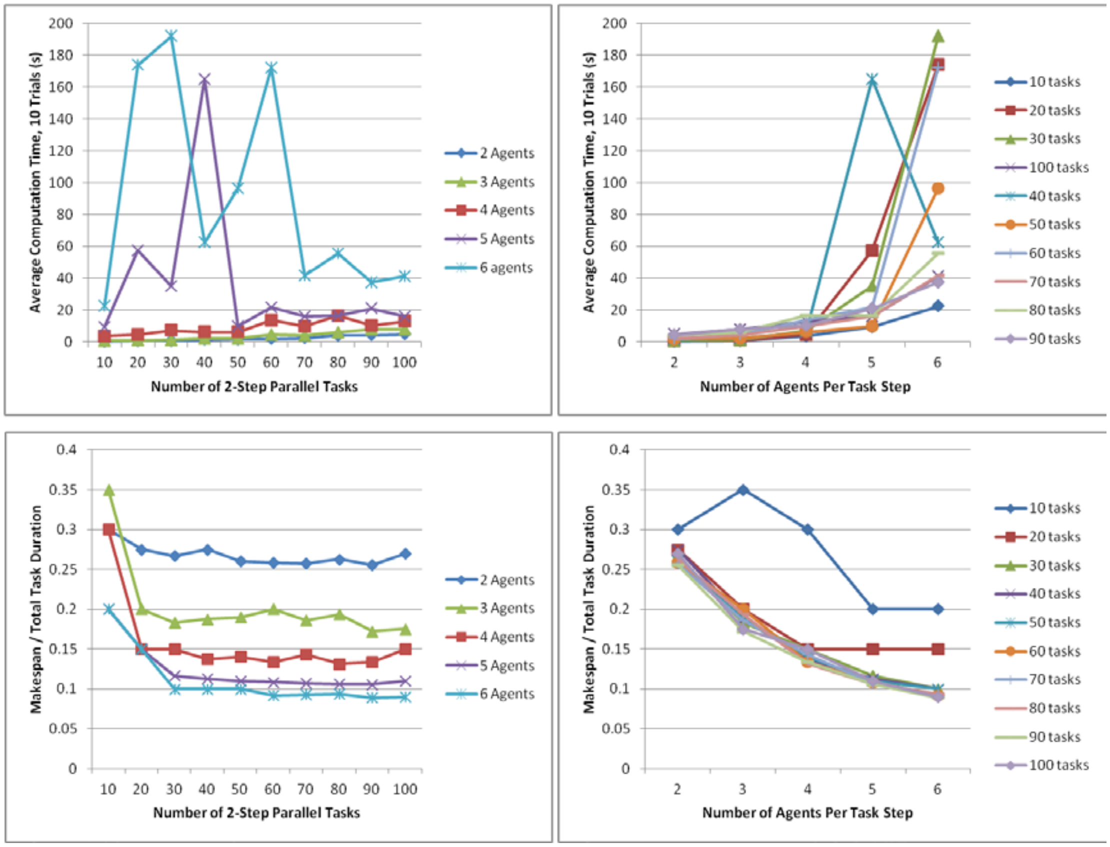

Figure 9. Results for Nx2 Task Networks: Computation Time vs. Number of Tasks (Top Left), Computation Time vs. Number of Agents (Top Right), Normalized Makespan vs. Number of Tasks (Lower Left), and Normalized Makespan vs. Number of Agents (Lower Right)

For Nx2 dimensional task networks, much the same patterns are observed as compared with the Nx1 dimensional task networks. However, the magnitude and variation in the computation times goes up considerably for cases with greater than 8 total agents in the system (computation times are on the order of 1-3 minutes in several cases whereas they remain below 20 seconds for cases with 8 or less agents). This presents problems for performance with respect to disturbance handling in the factory since computing a new schedule can take some time. Fortunately, the Tercio algorithm was designed to be tunable with respect to the optimality of the solution in order to achieve solutions more quickly.

To see the effect of this tuning capability, we can run the same scenarios with a less stringent requirement on the optimality of the solution and see how the performance measures change. Figure 10 and Figure 11 compare the nominal performance of the high optimality version of the algorithm (data from Figure 9) with a modified lower optimality version of the algorithm for the 5 and 6 agent cases respectively.[3]

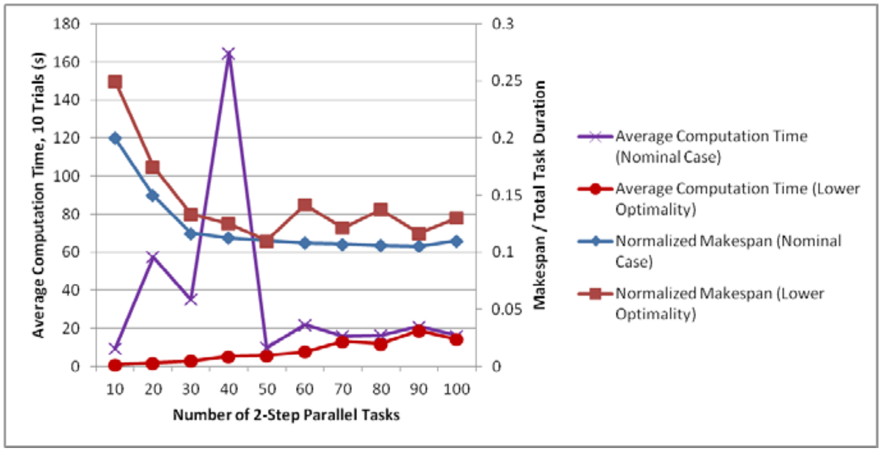

Figure 10. Evaluation of Algorithm Optimality Tuning for 5 Agent Scenarios and Nx2 Task Networks

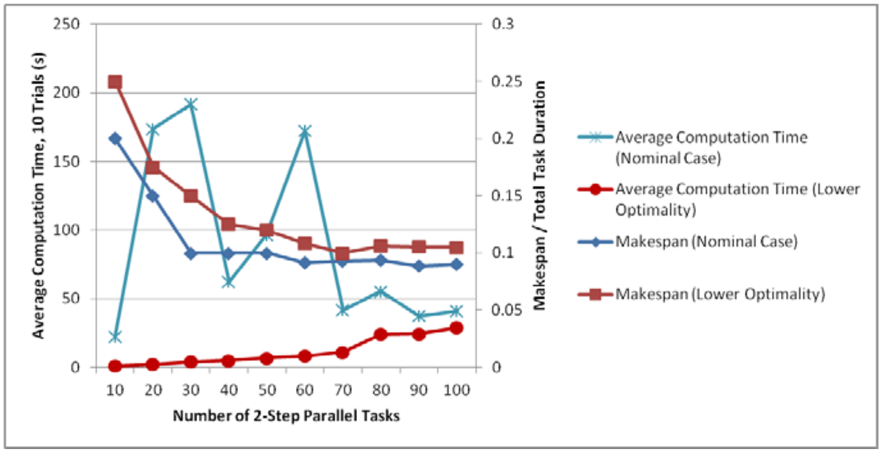

Figure 11. Evaluation of Algorithm Optimality Tuning for 6 Agent Scenarios and Nx2 Task Networks

In both the 5 and 6 agent cases, we see a significant reduction in computation times in the regions where the nominal case was most volatile in exchange for modest losses in the optimality of the solution. This is only an example for illustration purposes of how the algorithm might be tuned to provide better performance. Nevertheless, it shows that the tuning of the algorithm can be used in the final system design to optimize the tradeoff between computation time and solution quality.

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[3] The nominal case requires the agent allocation portion of the solution to be within 0.1% of optimal, whereas the lower optimality case only requires it to be within 1% of optimality.

It is also apparent from Figure 10 and Figure 11 that there is an opportunity to incorporate some form of machine learning into the algorithm in order to automatically adjust to the state of the manufacturing system. If the system knows in advance that it will be operating in a regime which tends to result in unpredictable computation times, it can tune the parameters of the algorithm to generate slightly less optimal schedules to ensure good speed and response to disturbances. Alternatively, if the system can detect when it is not in this regime, it can favor higher optimality in the schedule in exchange for slightly lower speed in computation.

Another question of interest we can examine is how the capabilities of the agents affect system performance. For example, given a task with multiple steps, we would like to know if it is preferable to have a multi-capable robot that can perform each step of the task, or whether it makes more sense to have specialized robots that can each perform one step of the overall task. Figure 12 shows data comparing three different scenarios, each of which includes 12 agents and identical amounts of work to be done. In the first scenario (All in One), each parallel task in the network is assigned to a single (multi-capable) agent to complete all steps of the task. In the second scenario, each parallel task is split into 2 steps, each of which can only be performed by one type of agent (6 agents for each step). Finally, for the third scenario, each parallel task is split into 3 steps, each of which can only be performed by one type of agent (4 agents for each step).

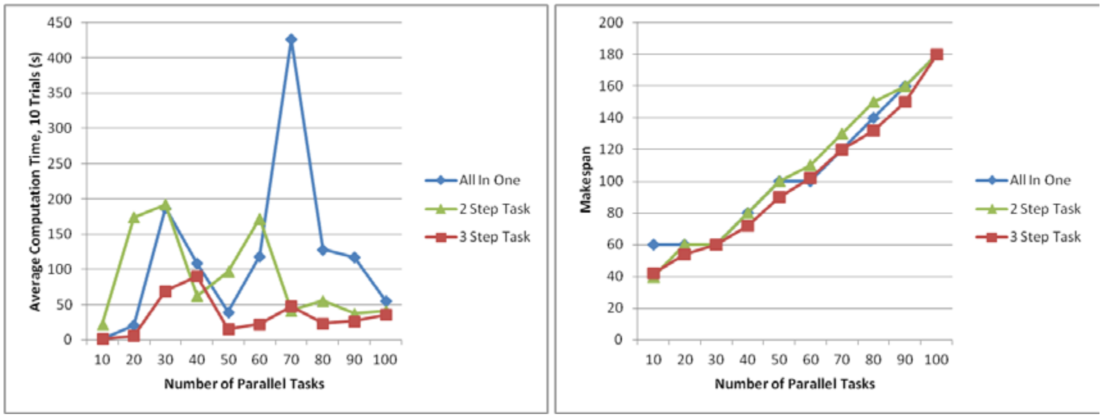

Figure 12. Comparison of Algorithm Performance With Varying Agent Capabilities: Computation Time vs. Number of Tasks (Left), and Makespan vs. Number of Tasks (Right)

The data in Figure 12 implies that, for a given number of agents, computation times and quality of solutions will generally improve (for these types of networks) if tasks can be split into subtasks and assigned to specialized agents. This is intriguing, but far from conclusive since there are other considerations to factor in here. For example, if multiple agents need to utilize the same work areas as other agents in order to complete tasks, then this increases the complexity of the motion planning and navigation tasks (and therefore makes these tasks more important to the efficient functioning of the system).

The data presented in this section provides insight into the types of problems for which Tercio will and will not perform well. The Tercio algorithm is certainly capable of handling more complex task networks and constraints than have been explored here, but these are not as relevant to the wing box assembly process. Ongoing research is exploring how the current version of the algorithm might be adapted to handle more complex constraints like those depicted in Figure 4, which may provide additional performance for this application. Of course, Tercio is not the only scheduling algorithm that can be applied to this problem, but part of its appeal is the ability to handle complex temporal, spatial, and resource constraints simultaneously which is somewhat unique and could be exploited by other automated manufacturing processes in the factory. Boeing’s Aurora scheduling tool provides another option for automated task scheduling, and the next section presents a comparison of the performance of Tercio and Aurora for simple task networks.

4.4 Benchmarking: Comparison of Tercio and Aurora

Prior work has already shown that, in some circumstances, Tercio performs better than many existing approaches to factory scheduling [26], but the performance has not been compared to an “industrial grade” scheduling tool that can handle similar levels of complexity in task networks and associated constraints. A more rigorous benchmarking study is left as future work, but for the purposes of this thesis, I examine the quality of the solutions generated for a limited set of real-world use cases. Figure 13 shows the resulting makespan for 20x2 and 40x2 size task networks using both Tercio and Aurora. The networks used were identical in structure, duration, and resource requirements.

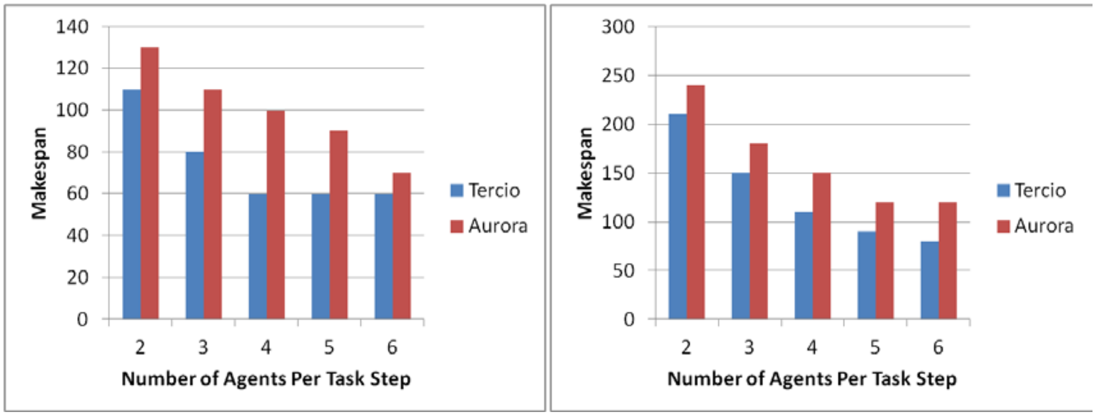

Figure 13. Makespans Generated by Tercio and Aurora for 20x2 (Left) and 40x2 (Right) Task Networks with Identical Precedence and Resource Constraints

In each of the cases examined, Tercio was able to generate a better solution than the Aurora tool used with "default" settings (on average, Tercio generated a solution with a makespan 34% shorter than that of Aurora for the cases examined); however, Aurora does (like Tercio) provide some ability to tune the algorithm objectives, which may improve the quality of the solutions. The proprietary nature of the Aurora algorithms and its "prioritizers" makes it difficult to know exactly how the tool might be modified to achieve this. Although Aurora generates less optimal solutions, the biggest advantage of Aurora is that it is able to generate solutions to complex scheduling problems quickly. For the cases examined here, computation time for Aurora was under one second, and users of Aurora within Boeing have stated that it only takes several seconds to generate a schedule for a network with 1,000 tasks. In some cases, Tercio took over one minute to generate the more optimal schedules shown in Figure 13; however, once the algorithm is tuned to generate solutions in a few seconds (by lowering the required optimality of the solution) the makespan is still lower than the corresponding Aurora result. Anecdotally, Aurora has been a very effective tool in generating schedules for human labor while reducing production time and mistakes, and improving decision-making, so it should be evaluated more thoroughly for application to automated manufacturing systems.

5 Management Considerations

Boeing's goals with respect to implementing automation technologies are ambitious. Clearly, there is a heavy emphasis on technology development; however, in order to gain the full benefits of an automated manufacturing system, there are three areas that must be managed concurrently: product design, manufacturing technology development, and factory implementation. The goal of this chapter is to examine the management and business challenges associated with each of these areas and to provide recommendations for ensuring success.

5.1 Product Design Management

The most important part of a manufacturing system is the product which is produced by the system – this is how a manufacturer makes money and is generally the only part of the system which is of value to the customer. When considering automation for manufacturing, it is critical that the design of the product is one of the variables which can be altered to optimize the system design. For future products, this means choosing design features that lend themselves more easily to automated manufacturing, where appropriate. For existing product lines, the designs should be examined for potential changes that will improve manufacturability in a cost effective manner. Design changes to the product may be less expensive and less time consuming than trying to develop the technologies that need to cope with the existing designs. Essentially, this amounts to evaluating the product and processes simultaneously (rather than independently) in order to optimize the manufacturing system in such a way that achieves the desired results for minimal cost and with minimal impact to the existing system.

5.2 Technology Development Management

Technology development for a revolutionary manufacturing system such as the one Boeing is attempting to create takes significant resources and is critical to its success. If managed poorly, the implication may be a delay in implementation at best and getting surpassed by competitors at worst. There are many ways in which Boeing can improve its ability to deliver useful technology in a timely fashion, but not all of them will be easy.

In order to support technology development, the research and development (R&D) organization needs to remain nimble and focused in order to create the technologies to enable automation. Currently, the R&D organization within Boeing is subject to many of the same restrictions as the production groups. For example, the procurement process for research hardware and software is cumbersome and ill-equipped to support the (ideally) rapid pace of an R&D organization. The delays created by these processes not only impede progress, but also frustrate technology developers and increase the chances that someone else will develop the technology first. The bottom line is that Boeing needs to find ways to make it easier for technology developers to make decisions and to procure resources so they can efficiently develop technologies and prototypes and reduce design cycle times to pull technology forward.

In addition to making the R&D organization more nimble, it will be important to encourage additional collaboration between the various groups and divisions within Boeing that are doing related work. The more this can be encouraged, the better Boeing will be able to leverage the intellectual capacity within the organization. It will also provide greater awareness throughout the organization of what each group is developing, thereby increasing the chances that another use for a given technology will be discovered (which also helps improve the business case for a given technology). There is also an opportunity to partner with other organizations (both developers and users of automation technologies) to share best practices and lessons learned.

Even if the technology development process is improved, without a clear financial benefit for the technology, it will likely not get implemented. This is why it will be critical to put in place methods to track the true cost of quality defects so that these can be included in the business cases for technology implementation. Even in the absence of technology changes, this information will be vital to managing factory operations. This information can disseminated to employees and managers on a regular basis so they can assess their performance and understand the impact of their actions (and also get a much clearer sense of where technology would be beneficial).

Finally, it is extremely important that Boeing management develop and portray a unified vision of the enterprise strategy for automation technologies. Currently, there are several different perspectives within the organization regarding what these systems should be used for and why they are valuable. Unifying the entire organization around a clear set of goals and objectives will help focus the technology efforts and improve morale by showing that the company is committed to a clear vision for these technologies. In order to do this, Boeing should consider employing an operations strategy framework (such as those proposed by Fine and Hax [28] or Beckman and Rosenfield [29]) to link the enterprise objectives to clearly defined needs for automation technologies. This can then be used as guidance for technology developers in order to focus their efforts on what is valuable to the company.

5.3 Implementation and Transition Management

As production rates continue to increase, modifying an existing production line will become increasingly difficult due to the increased risk of integrating a new technology in the factory. This means that the technology needs to be proven thoroughly in as close to a real factory environment as possible before it is introduced into production. As such, a thorough test plan will be necessary for every technology insertion. Furthermore, an incremental/modular approach will be necessary as it will be difficult to make large changes to the factory all at once without significantly disrupting production. This transition should begin as soon as possible in order to develop the skills and internal knowledge required to operate these systems. Also, the project will need to be managed in a continuous improvement environment, so that the manufacturing system evolves along with the products and processes.

Leading up to (and during) the implementation of new technologies, it will be important to ensure that these technologies are developed with support from all of the relevant groups (engineering, operations, technicians, management, associated unions, etc) as appropriate. Without building early support for a technology, it will be far more difficult to implement. This process may require some cultural changes within the organization, but it is an unavoidable necessity if the goal is to achieve functional, practical, and cost effective automation in the factory.

In anticipation of a technology implementation, it will also be particularly important to assess the skills of the personnel required to operate and maintain such technology, and to begin training programs in order to ensure the relevant competencies are developed within the organization prior to implementation. This will create a much smoother transition and reduce the effect of the learning curve in production.

5.3.1 Making the Business Case

Two of the biggest keys to improving the business case for automation technologies are (1) the ability to collect reliable data from the factory and (2) the ability to properly account for the intangible benefits of automation. Each of these points is discussed in turn.

Accurately being able to quantify the cost of defects and rework as a result of human error would remove a lot of the uncertainty in the value that automation can bring to the assembly process from a cost and quality perspective. However, currently this information is largely inaccurate or unavailable. It will be important to improve the data systems that track this information so reliable data is available in real-time and the effects of human error are truly known. Then, the investment decision becomes much clearer. The Automation Strategy Team report [2] is a good start at trying to identify the potential cost savings, but this type of data collection and analysis should be a standard process within the factory. This type of data collection has the added benefit of revealing the areas in the factory that would benefit the most from automation (and where the biggest problems are in general) so management can prioritize the investment in various technologies and consolidate R&D efforts throughout the organization.

A far more subtle point about making the business case is related to the intangible benefits of automation. Kaplan [30] argues that even precise discounted cash flow methods can understate the value of flexible automation systems and can lead to poor decision-making regarding investment in these technologies. In particular, he highlights an all too common mistake:

> *Although intangible benefits may be difficult to quantify there is no reason to value them at zero in a capital expenditure analysis. Zero is, after all, no less arbitrary than any other number. Conservative accountants who assign zero values to many intangible benefits prefer being precisely wrong to being vaguely right. Managers need not follow their example.*

It is important to avoid this trap when preparing business cases for these technologies. This work has inspired others to try to develop better decision-making models to address these types of issues (e.g. [31]). Boeing may want to explore using some of these alternative methods for justifying future investment in technology development.

5.3.2 Near Term Opportunities

One important feature of task allocation and scheduling algorithms is that they are agnostic with respect to the agents in the system. This means that they can be used to schedule human work as well as machine/robot tasks since both humans and automated systems are simply treated as agents in the system. This is important because it enables incremental implementation of automated systems within the existing production process. Without changing the task definition, a new agent (automated) can be added to the system to complete a task that was previously allocated to a human without disrupting the system. Furthermore, in the event that the automated agent has problems completing the task, a human can be used as a substitute to complete the task and keep the production system running until the problem is resolved. This allows for quick integration of new technologies and a built in risk mitigation for the case where they do not perform as expected. Furthermore, this means there is no reason not to start implementing these types of scheduling algorithms in the factory as soon as possible (even with a fully manual operation). In fact, some programs within BCA have already started using the Aurora scheduling system for manual work with good success. This tool (or something like it) should be implemented early to ingrain it as a part of standard factory operations and to build support for its ability to make scheduling of work more efficient. A lot of internal knowledge about these systems exists within Boeing, and although it will likely need to be supplemented with additional experts in order to support the enterprise, it is a resource that is currently not being exploited fully.

Other top near-term priorities should include the generation of a unified enterprise strategy that is communicated clearly throughout the organization. This should immediately be followed by the creation of collaborative teams (with members from all parts of the organization) who will work together to evaluate the suitability of existing projects and perhaps propose new ones in order to ensure that the ongoing research is aligned with the corporate strategy. Going forward, this should become a regular review process to ensure everyone is driving toward the same goals.

5.3.3 Long Term Objectives

Over the next several years, Boeing will need to remain conscious of the evolution of the key technologies which are essential to the enterprise vision for automation. The long development periods for these systems make it easier for the organization to lose focus on what is truly essential and important to reaching the goals that have been identified. There are numerous advancements being made in areas including factory control, navigation, sensing, estimation, robotics, simulation, human-machine interfaces, communication systems, computing, etc., and Boeing needs to be ready to capture the value of these technologies as they are developed (if they fit within the enterprise manufacturing and automation strategy). In order to do this, it will be vitally important that the initiative to move toward more automated factories is fully supported by the senior and executive management team within BCA.

6 Recommendations and Future Work

Many of the recommendations for Boeing have been alluded to throughout this thesis. The purpose of this section is to consolidate and clarify what should be considered for the future.

6.1 Control Architecture Development

A control architecture for automated aircraft manufacturing will need to be flexible in order to handle changes to the structure, logic, and physical layout of the production line throughout the life of the product (likely 30-50 years). This means that the foundations and interfaces of the architecture will need to be generalized in order to easily accommodate future technology insertion. One way this can be achieved is by using an object oriented framework that will allow for use of current technologies and provide a platform for implementing future technologies once they are available. At this point, the evolution of each technology is highly uncertain and this approach will hedge against the risk of becoming committed to or dependent on a single technology or approach.

6.2 Design for Automation

Although designing products for automated assembly does not seem to be a priority currently, this needs to be brought to the forefront as part of a concurrent engineering effort between product, process, and technology experts in order to optimize the manufacturing system design in a more global sense. A serialized approach to development with respect to these different disciplines will likely result in an inferior production system. Product design changes can help ease the burden on other parts of the system, and should not be ignored.

6.3 Cost of Quality Defects

In order to enable better decision-making regarding automation, reliably collecting and quantifying cost information related to defects and rework as a result of human error will be important. Automation aside, this information will help to expose problems with the current production system and make everyone more aware of the impact of their actions on production rates and profitability. Without this data, there is a lot of uncertainty in quantifying the benefits of automation.

6.4 R&D Procurement Process

In order to maintain a nimble and responsive R&D organization, it will be important to continually look for ways to eliminate overhead and process steps. One example is to simplify the procurement process for R&D hardware and software. These resources do not need to be treated in the same way as production hardware until they are actually being purchased for production implementation. It is likely there are other opportunities like this which can improve the organization's ability to deliver rapid progress in technology development.

6.5 Enhanced Collaboration

A great number of the technology developers in the organization are working in intellectual silos. Although there are occasions for information sharing, this should be a much more common occurrence than it currently is. It is worth considering additional incentives to encourage these different groups to collaborate on projects that will benefit more than simply their own program or division.

Boeing should also explore collaborating with other industries and organizations that are facing (or have faced) similar challenges in automation and find ways to share knowledge that would not compromise their competitiveness. There are plenty of other industries (e.g. consumer electronics, pharmaceuticals) that have implemented automation technologies successfully and who can probably provide useful lessons learned to further improve the chances of Boeing's success.

6.6 Exploit Existing Scheduling Technologies

Although Boeing has spent significant amounts of money in collaboration with an outside vendor to develop the Aurora scheduling system, it is only being used by certain groups within the company. This tool has significant potential to improve the way factory operations are managed and should be thoroughly exploited in the near term. The traditional Bar Chart scheduling process (still in use for most of 737 and 777 assembly) is cumbersome and outdated. Automating scheduling is likely to improve performance and (coupled with the visualization tools in development) likely to be much more useful to factory managers and technicians. Aurora may not be the eventual scheduling tool of the 21st century automated factory, but using it can go a long way toward building the skills and know-how within the organization in order to assess what could/should be improved.

6.7 Mobile Communications Architecture/Infrastructure

Access to information is essential for any factory control algorithm. Without knowing the communication infrastructure and architecture, it is difficult to say what type of control system will be most appropriate or even feasible. Boeing should put much more effort in developing firm concepts for a communications architecture to support mobile automation and factory control.

6.8 Potential Future Internship Opportunities

There are a number of potential projects that would be valuable to pursue with future LGO internships in the effort to make agile automation a reality. On the technical side, I believe that implementing automated scheduling systems for existing factory work (particularly on the 737 and 777 lines) is an extremely important step toward automated scheduling for robotic systems. A project like this will provide valuable knowledge about how to operate and maintain these systems and how to better design interfaces for human interaction. On the managerial side, I believe that developing and implementing a reliable system to track the cost of quality defects is essential to making the business case for automated systems and for understanding where automated systems can do the most good (and also where they may not be necessary). Automation aside, this is a worthwhile project that, in the long term, will provide vital information about the Boeing production system.

7 Conclusion

The vision Boeing has for automated manufacturing presents a significant technical and management challenge for the organization; however, there are many steps that can be taken to shorten the timeline for development and improve the chance of success. The technical expertise within the organization is more than adequate for hardware development, but probably needs to be supplemented with additional software and artificial intelligence expertise in order to achieve the vision for automation. Throughout these efforts, it will be extremely important that the quality of management matches the excellence of the technical work. There is a great deal of work still to be done, but if the existing hindrances to innovation are removed and collaboration and coordination are made a priority then Boeing will be able to advance its manufacturing system far ahead of any current or potential competitor.

Appendix – Overview of Automation and Related Technologies

This appendix identifies some of the key technologies that are required to run a highly automated factory, assesses the current state of these technologies, and identifies technology gaps that need to be overcome in order to achieve the vision of flexible/agile automated assembly. The purpose of this appendix is to provide the technological context in which control systems will need to be developed.

Resource Allocation and Scheduling (Task-Level Control) Systems

The majority of automated (robotic) manufacturing lines have been implemented by preprogramming the agents in the system with a set of deterministic motions and actions in order to build a product. This has resulted in many specialized machines that need to be reprogrammed any time there is an off-nominal situation. For the future automated factory, it is desirable to have a control system that can adapt to these off-nominal situations by automatically reallocating resources effectively based on their capabilities and the constraints of the manufacturing process/environment. Historically, the Program Evaluation and Review Technique (PERT) and Critical Path Method (CPM) have been the dominant tools for scheduling work in the factory. A brief history of the development of these techniques is provided in [32]. These have proven to be useful tools, but they generally require intimate knowledge of the process for a human planner to use them effectively since they are not designed to handle uncertainty in task completion times. These tools also focus on minimizing the total time to complete the manufacturing process rather than minimizing costs and/or utilizing available resources efficiently. Thus, these tools do not lend themselves to use in fast dynamic scheduling that is required for complex manufacturing environments. Until recently, these techniques were the dominant tools available for such environments, but recent research advancements are resulting in algorithms that are capable of automatically scheduling large numbers of tasks in multi-agent systems in short amounts of time.

Aurora[4] is one such factory scheduling tool. It was developed by Boeing in conjunction with Stottler Henke Associates, Inc. primarily for use in scheduling human labor in the factory. Aurora uses critical chain scheduling techniques to quickly create schedules for completing work given appropriate precedence, temporal, and resource constraints. It is designed to be flexible and able to handle disruptions and changes to the baseline execution plan in real-time. This tool has been extremely successful in improving the way human labor is scheduled and could easily be adapted to commanding automated systems.[5] Early implementations of the Aurora tool included a visual user interface application for factory personnel to interact with the scheduler. This application was originally called the "Visual Build Tracker" which is described in [32]; however, it has since evolved and been renamed "PTrack". PTrack is in an evaluation phase and is continually being improved to make it useful for factory personnel. Although not yet widely adopted within the organization, support is growing for these tools as they continue to show significant benefits over the legacy tools.

The Tercio algorithm, developed at MIT, is another scheduling tool that can handle (relatively) large and complicated task networks [26]. Although still in development, this algorithm shows great promise over prior art in its ability to handle large scale combinatorial problems, while generating close to optimal schedules. An important contribution of this thesis is to assess how this algorithm might perform if applied to automated aircraft wing box assembly.

Communications Systems

For an automated manufacturing system as complex as that expected for manufacturing aircraft wings, the communications network can become equally complex. Complexity arises not only in terms of the logical connections between devices but also in maintaining robust communication channels. In part because mobile robotics are expected to be a part of the manufacturing system, wireless communication capabilities are likely essential, making these issues even more of a concern as compared to wired

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[4] The version of Aurora referenced herein is called Aurora-CCPM (Critical Chain Project Management) and is proprietary to Boeing.

[5] Based on interviews with Aurora experts at Boeing.

communication. For example, sensor and state data are more likely to exceed bandwidth limitations for wireless networks in the factory and reliable communication is more difficult to maintain due to the existence and movement of large, metallic structures like aircraft parts and machines which cause reflection, scattering, and diffraction [33]. The communications architecture is closely coupled with the choice of the control architecture for the system since it determines which communication channels are available and thus what data is accessible from any node in the network. Regardless, it will be important to transmit only relevant data through communication channels. Wireless communication among automated systems is highly desirable to limit the number of physical cables in the factory, but this presents challenges in terms of noise and signal obstruction within the factory. A separate and thorough study on the feasibility of complex wireless communications networks in the factory is likely required to address these concerns.

Power Systems

The concept of a flexible factory with minimal infrastructure may dictate the use of mobile robots that carry their own power supplies. This fact, combined with the inherent size and weight of a commercial aircraft wing, results in the need for large robots with comparably large batteries. Sizing of power supplies will affect the availability of agents, and this is another factor the control system will have to account for. Additionally, the physical size of these robots may limit the number of agents that can be working in parallel in a given area on the production line. It is expected that the quantities and capabilities of these robots will be such that they can support desired production rates, so they are not of great concern to the control system design.

Sensing and Estimation

Sensing and estimation systems will be essential to the use of mobile automation technologies. If the accuracy of the sensing and estimation system does not allow for complex navigation tasks, then a mobile/agile automation concept may not be possible, and the control problem is reduced to the far simpler case of fixed in place automation. For agile automation, the tight tolerances required for the manufacture of a wing dictates a high precision system for positioning tools, which presents a significant technical challenge in the factory. Laser based systems, for example, have line of sight issues. Furthermore, high precision metrology systems are incredibly sensitive and can easily be affected by temperature, pressure, and humidity fluctuations which are not currently (and probably cannot be) well controlled in the factory. Furthermore, these types of systems tend to require significant infrastructure, which is counter to Boeing's vision of the future factory. At present, there does not appear to be a technology solution that is capable of meeting the requirements for a full scale automated factory[6]. It is likely that an entirely different approach, possibly involving estimation theory and/or sensor fusion techniques, will be required to overcome this challenge.

Navigation

In recent years, advancement in robot navigation and coordination has allowed for the development of sophisticated fulfillment and delivery systems in factories, hospitals, and other organizations. Companies like Kiva Systems[7] and Vecna Technologies[8], have been able to capitalize on these advancements, but technologies like these either rely on low uncertainty in the operating environment (i.e. known paths of travel and static "keep out" zones) or are not used for time critical applications. In a truly agile factory however, robots need to be able to go where they are needed without adhering to predetermined paths of travel. Furthermore, if humans will be working with or around these robots, they need to be able to navigate in uncertain and dynamically changing environments. In these circumstances, navigation capability will be important not only to ensure timely delivery of resources to work areas, but also to maintain a safe environment. For a more decentralized system, the number of independent agents performing navigation tasks becomes larger, and thus the navigation task becomes more complex for each of them (especially if they are working in close proximity). Many traditional methods of navigation can

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[6] Based on interviews with Boeing sensing, estimation and navigation experts.
[7] www.kivasystems.com
[8] www.vecna.com

fail in this type of environment (the agent cannot find a solution to the path planning problem), but recent developments in cooperative, probabilistic path planning algorithms show some promise [34]. As mentioned earlier, the navigation capabilities are in part dependent on the capabilities of the sensing and estimation system. Navigation capabilities will eventually need to be incorporated into any control system design in order to optimize the workflow while accounting for the time required for repositioning and recalibrating equipment, for example. There is still work to be done toward developing algorithms that are suitable for the aircraft manufacturing environment.

Human-Machine Interfaces

Human-machine interfaces will be a critical part of the automated factory environment for the foreseeable future, and these interfaces will need to facilitate human decision-making. As automated systems become more complex, the cognitive role of the human is becoming more critical to ensuring optimal system performance. Poor design of human-machine interfaces can significantly degrade system performance despite the sophistication of the underlying technology in use. Interfaces need to be designed with the end user in mind, and they need to provide clear and relevant information to human operators and/or system monitors. An overview of the relevant research in this field can be found in [35].

A good starting point for Boeing to develop these types of interfaces for automated manufacturing systems is to build on the ongoing development of the PTrack software for monitoring, adjusting and analyzing production schedules generated by the Aurora scheduling tool. While there is still room for improvement, significant effort has been made in making this tool useful to the factory personnel and there are certainly lessons to be learned and knowledge that can be shared within the company.

References

[1] P. Valckenaers, F. Bonneville, H. Van Brussel, L. Bongaerts and J. Wyns, "Results of the holonic control system benchmark at KU Leuven," in *Computer Integrated Manufacturing and Automation Technology, 1994., Proceedings of the Fourth International Conference on*, 1994.

[2] "Automation Strategy Team Findings/Report," Boeing, 2012.

[3] R. Breton and E. Bosse, "The Cognitive Costs and Benefits of Automation," in *The Role of Humans in Intelligent and Automated Systems*, Warsaw, 2003.

[4] D. J. Adler, J. A. Herkamp, J. R. Wiesler and S. B. Williams, "LIFE-CYCLE COST AND BENEFITS OF PROCESS AUTOMATION IN BULK PHARMACEUTICALS," *Isa Transactions,* vol. 34, no. 2, pp. 133-139, 1995.

[5] D. M. Dilts, N. P. Boyd and H. H. Whorms, "THE EVOLUTION OF CONTROL ARCHITECTURES FOR AUTOMATED MANUFACTURING SYSTEMS," *Journal of Manufacturing Systems,* vol. 10, no. 1, 1991.

[6] A. G. O. Mutambara, H. F. Durrantwhyte and Ieee, "A FORMALLY VERIFIED MODULAR DECENTRALIZED ROBOT CONTROL-SYSTEM," *Iros 93 : Proceedings of the 1993 Ieee/Rsj International Conference on Intelligent Robots and Systems, Vol 1-3,* pp. 2023-2030, 1993.

[7] W. Ren and Y. Cao, "Distributed coordination of multi-agent networks [electronic resource] : emergent problems, models, and issues," Springer, London, 2011.

[8] F. P. Maturana, P. Tichý, P. Šlechta, F. Discenzo, R. J. Staron and K. Hall, "Distributed multi-agent architecture for automation systems," *Expert Systems with Applications,* vol. 26, no. 1, pp. 49-56, 2004.

[9] M. Sinai, "Decentralized Control and Estimation: An Overview," Rockwell International (Proprietary), 1988.

[10] N. Ayanian, D. Rus and V. Kumar, "Decentralized Multirobot Control in Partially Known Environments with Dynamic Task Reassignment," in *IFAC Workshop on Distributed Estimation and Control in Networked Systems*, Santa Barbara, CA, Sept. 2012.

[11] H. Hanna, "Decentralized approach for multi-robot task allocation problem with uncertain task execution," in *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on*, 2005.

[12] S.-k. Yun, M. Schwager and D. Rus, "Coordinating Construction of Truss Structures Using Distributed Equal-Mass Partitioning," in *Robotics Research*, Springer Berlin Heidelberg, 2011, pp. 607-623.

[13] L. Bongaerts, L. Monostori, D. McFarlane and B. Kadar, "Hierarchy in distributed shop floor

control," *Computers in Industry,* vol. 43, no. 2, pp. 123-137, 2000.

[14] S. S. Ponda, "Robust distributed planning strategies for autonomous multi-agent teams," Thesis (Ph. D.)--Massachusetts Institute of Technology, Dept. of Aeronautics and Astronautics, 2012., Cambridge, 2012.

[15] B. Luc, C. Han-Lim and H. Jonathan, "Consensus-Based Auction Approaches for Decentralized Task Assignment," in *AIAA Guidance, Navigation and Control Conference and Exhibit,* American Institute of Aeronautics and Astronautics, 2008.

[16] S. Quinn and W. Gaughran, "Bionics-An inspiration for intelligent manufacturing and engineering," *Robotics and Computer-Integrated Manufacturing,* vol. 26, no. 6, 2010.

[17] W. Gu, D. Tang, K. Zheng and L. Wang, "A NEUROENDOCRINE-INSPIRED BIONIC MANUFACTURING SYSTEM," *Journal of Systems Science and Systems Engineering,* vol. 20, no. 3, 2011.

[18] A. Tharumarajah, "Comparison of the bionic, fractal and holonic manufacturing system concepts," *International Journal of Computer Integrated Manufacturing,* vol. 9, no. 3, pp. 217-226, 1996.

[19] K. Iwata, M. Onosato and M. Koike, "Random Manufacturing System: a New Concept of Manufacturing Systems for Production to Order," *CIRP Annals - Manufacturing Technology,* vol. 43, no. 1, pp. 379-383, 1994.

[20] J. H. Christensen, "Holonic Manufacturing Systems: Initial Architecture and Standards Directions," 1994.

[21] D. C. McFarlane and S. Bussmann, "Developments in holonic production planning and control," *Production Planning & Control,* vol. 11, no. 6, pp. 522-536, 2000.

[22] H. Van Brussel, J. Wyns, P. Valckenaers, L. Bongaerts and P. Peeters, "Reference architecture for holonic manufacturing systems: PROSA," *Computers in Industry,* vol. 37, no. 3, pp. 255-274, 1998.

[23] V. Botti and A. Giret, ANEMONA: A Multi-agent Methodology for Holonic Manufacturing Systems, Springer-Verlag London Limited, 2008.

[24] A. Koestler, The ghost in the machine, New York: Macmillan, 1968.

[25] R. Dechter, I. Meiri and J. Pearl, "TEMPORAL CONSTRAINT NETWORKS," *Artificial Intelligence,* vol. 49, no. 1-3, pp. 61-95, 1991.

[26] M. Gombolay, R. Wilcox and J. Shah, "Fast Scheduling of Multi-Robot Teams with Temporospatial Constraints," 2013.

[27] A. Bolger, M. Faulkner, D. Stein, L. White, S.-K. Yun, D. Rus and Ieee, "Experiments in Decentralized Robot Construction with Tool Delivery and Assembly Robots," in *IEEE/RSJ International Conference on Intelligent Robots and Systems,* Taipei, 2010.

[28] C. H. Fine and A. C. Hax, "MANUFACTURING STRATEGY - A METHODOLOGY AND AN

ILLUSTRATION," *Interfaces,* vol. 15, no. 6, pp. 28-46, 1985.

[29] S. L. Beckman and D. B. Rosenfield, Operations strategy: competing in the 21st century, McGraw-Hill/Irwin, 2007.

[30] R. S. Kaplan, "Must CIM be Justified by Faith Alone?," *Harvard Business Review,* vol. 64, no. 2, pp. 87-95, 1986.

[31] C. H. Fine and R. M. Freund, "OPTIMAL INVESTMENT IN PRODUCT-FLEXIBLE MANUFACTURING CAPACITY," *Management Science,* vol. 36, no. 4, pp. 449-466, 1990.

[32] J. L. Chen, "787 mid-body job precedence networks for improving production rate," Thesis (M.B.A.) Massachusetts Institute of Technology, Sloan School of Management; and, (S.M.) Massachusetts Institute of Technology, Engineering Systems Division; in conjunction with the Leaders for Global Operations Program at MIT, Cambridge, 2012.

[33] B. Aurel, S. Volker and F. W. Joerg, Wireless Technologies in Factory Automation, 2010.

[34] P. Trautman, A. Krause and Ieee, "Unfreezing the Robot: Navigation in Dense, Interacting Crowds," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Taipei, Taiwan, 2010.

[35] P. Oborski, "Man-machine interactions in advanced manufacturing systems," *International Journal of Advanced Manufacturing Technology,* vol. 23, no. 3-4, pp. 227-232, 2004.

[36] F. P. Maturana and D. H. Norrie, "Multi-agent Mediator architecture for distributed manufacturing," *Journal of Intelligent Manufacturing,* vol. 7, no. 4, pp. 257-270, 1996.

[37] M. J. Mataric, G. S. Sukhatme and E. H. Ostergaard, "Multi-robot task allocation in uncertain environments," *Autonomous Robots,* vol. 14, no. 2-3, pp. 255-263, 2003.

[38] B. P. Gerkey, M. J. Mataric and Ieee, "Multi-robot task allocation: Analyzing the complexity and optimality of key architectures," in *20th IEEE International Conference on Robotics and Automation (ICRA)*, Taipei, Taiwan, 2003.

[39] A. D. Baker, "A survey of factory control algorithms that can be implemented in a multi-agent heterarchy: Dispatching, scheduling, and pull," *Journal of Manufacturing Systems,* vol. 17, pp. 297-320, 1998.

[40] R. F. Zammuto and E. J. Oconnor, "GAINING ADVANCED MANUFACTURING TECHNOLOGIES BENEFITS - THE ROLES OF ORGANIZATION DESIGN AND CULTURE," *Academy of Management Review,* vol. 17, no. 4, pp. 701-728, 1992.