Control Theoretic Analysis of Highly Distributed Manufacturing Control Systems

By

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In manufacturing it is desirable to deliver orders on time while minimizing inventory, thus reducing costs. Therefore, planning and control systems are used to adjust work in progress while minimizing order backlogs. Such systems control plant capacity and input rate, and need to adapt to changes in demand and failure of production equipment. Effective production planning and control, combined with effective shop-floor level scheduling, enables manufacturing with a Just-In-Time philosophy while managing the available resources, release of orders to meet due dates, and work-in-progress inventory.

Previous work at the University of Wisconsin-Madison has shown that selecting the proper continuous variables, discrete variables and control laws transforms certain distributed scheduling problems from the discrete sequencing domain to the dynamical systems domain. It is also has been shown that differential equations can be used to model certain distributed shop-floor decision making systems, which makes a powerful set of tools available for analysis and control. This past work has shown that there is an opportunity to expand this approach to encompass higher levels of production planning and control, and to improve understanding of the dynamics of these traditionally multilevel systems, particularly when they have a distributed implementation.

Distribution decision-making in modern manufacturing in the global economy can reduce the effectiveness of such controls, and there is a void in the understanding of such distributed systems and a lack of confidence in their dynamics. The emphasis of this research therefore was on modeling and understanding the dynamics of distributed manufacturing control systems with a focus on integrating dynamic scheduling with a production planning and control system. A distributed order-driven arrival-time controller, which was developed in previous work, was modified to accommodate adjustments in capacity and integrated with control systems for both WIP and due date deviation regulation. A dynamic model was developed and used to predict system performance, stability, and responses to production disturbances.

An order due date deviation regulation topology is presented for workstations that dynamically adjust their capacity and order release times. The relationship between due date deviations and workstation capacity is shown to be nonlinear and time varying, and a method is presented for characterizing the relationship quantitatively in real time and using this information in adaptive capacity adjustment control laws that maintain favorable dynamic behavior in the presence of the nonlinearities. It is anticipated that this work will build confidence in distributed manufacturing control systems and will contribute to the development of better tools for understanding the dynamics of other distributed decision-making systems such as those used in e-design and e-commerce.

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1.1 Background

A key driver in the evolution of manufacturing production control systems is the constant hunt of organizations for an edge against their competitors. Organizations strive to expand their customer base while controlling costs and thus increasing profits. Production of commodities has evolved from mass production, where the customers had to adjust their needs or preferences to what was offered to them in the market, to customized production, where companies try to satisfy the individual needs of each customer. Short and predictable lead-times are necessary for fast product changeover and to minimize the time to market; companies that have the ability to produce a part or product as soon as possible will have a strategic advantage over other companies. For an organization to remain competitive it may have to:

- Provide a wide product mix;
- Keep batch sizes small;
- Adjust to constant changing demand;
- Keep cost low, quality high and lead-times short.

Four main groupings describe Manufacturing Production Control Systems as shown in Figure 1.1: mechanization: points of automation, islands of automation and agile manufacturing [TERM96]. The mechanization stage began in the industrial revolution around the 1800's. Machines replaced human labor (crafts) in the Industrial Revolution. The machines enabled the mass production of commodities; Frederick W. Taylor introduced scientific management and made scientific studies of man-related tasks to increase productivity. The lack of flexibility in manufacturing products and the need of controlling costs did not take into consideration the individual consumers' needs. Henry Ford is the most widely known manufacturer of this era, introducing the T-Line [MATH88].

With developing computer technology, production systems transitioned to points of automation, with Computer Numerical Control (CNC) further replacing human control of machines. Introducing CNC provided companies with [ONG97]:

- flexibility
- repeatability
- quality control through process control
- allows simple to complex parts geometry
- increased productivity
- reduced technology costs
- reduced lead-times
- reduced inventory

As a result, shop floors became more flexible and costs were reduced. An ability to change setups more often thus allowed a high product mix. Organizations therefore had the luxury of changing their strategy in fulfilling customer's needs, providing smaller batches of a particular product.

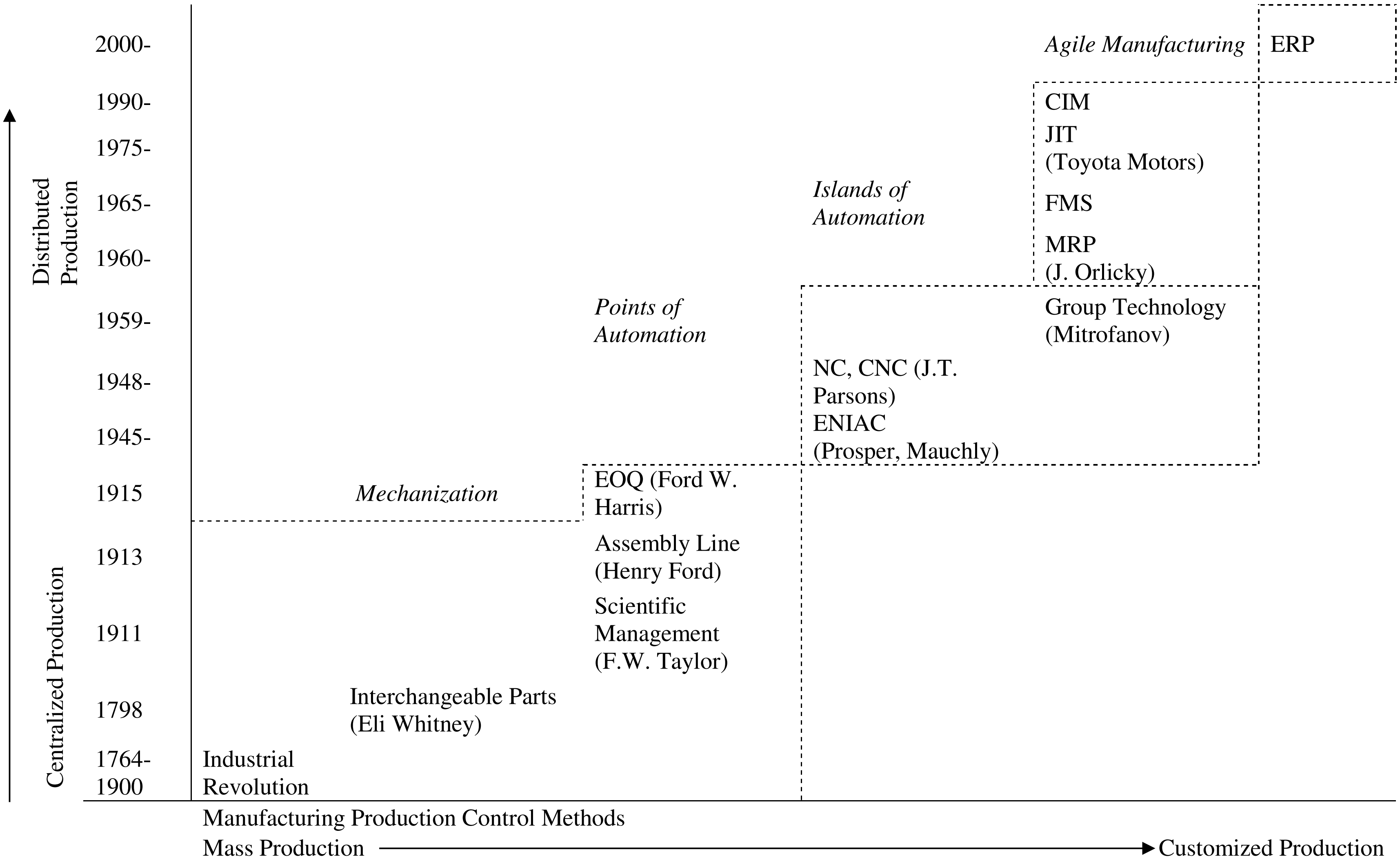


Figure 1.1: Manufacturing Production Control Systems Evolution (Adapted from [MART97])

Further computer technology development led to hierarchical architectures for production management [MART97] and automated systems for decision making in an organization. Separate modules were developed for functions such as production planning and control and scheduling, but there was a lack of integration and real-time feedback among the modules. These separate modules represent islands of automation, where the communication among modules was weak or nonexistent. A system was needed in order to ensure the availability of materials when they are needed. With the introduction of Material Requirements Planning (MRP) these different modules were integrated in a central computer system.

MRP applies to production systems that depend on demand; it controls inventory levels and scheduling of manufacturing product types. MRP changed into Manufacturing Resource Planning II (MRP II) to assess overall decision making in an organization, linking business planning, capacity needs, and production planning among others. Output from these modules were linked to financial reports and budget projections (shipping, purchase); however, they did not provide reactions to uncertainties in real-time.

Toyota Motor Company developed the concept of Just In Time (JIT) and Lean Manufacturing which was an adaptation of the Ford Statistical Process; Lean Manufacturing is a philosophy of total waste elimination from purchasing to production [HAY88]. JIT also analyzes procedures in a manufacturing shop floor and strives for zero inventories, producing the necessary parts at the right time [HO01].

High-speed computers and fast networking capacities allowed integrating decision making modules not only within the organization but among organizations. However a system was needed that integrates the enterprise backend. Enterprise Resource Planning (ERP) was an evolution of MRP and virtual manufacturing; was an expansion from the coordination of manufacturing process to the total coordination of enterprise wide processes. ERP is supported by multi-module application software that integrates activities across functional departments, from product planning, parts purchasing, inventory control, and product distribution, to order tracking [YONG01].

Various architectures for high-level decision making, such as MRP, MRP II, JIT and HPP, are discussed in the next section as well as the differences between hierarchical and heterarchical decision making, transforming these traditional decision making methods using the fundamentals of heterarchical systems is a goal of this research and its benefits including complexity reduction, higher configurability and improved reliability.

1.2 Literature Review

Researchers over the past thirty years have been exploring alternatives for solving production planning problems in manufacturing. There is a need to integrate decision making in organizations and to consider the effect of factors such as capacity, inventory, scheduling and reliability on delivery date. Various approaches have been considered to deal with this integration such as Group Technology (GT), Materials Requirement Planning (MRP), Hierarchical Production Planning (HPP), Just in Time (JIT), Computer Integrated Manufacturing (CIM), Virtual Manufacturing Enterprises (VM) and Control Theory.

Using GT, the planner examines products, parts and assemblies and then groups similar items to simplify design, manufacturing, purchasing and other business processes. In GT, manufacturing cells are used to reduce throughput time and Work-In-Process. Also, schedules are simplified to reduce transport time and ease supervision. Burbidge combined GT with job shop flow, where the flow of work orders in a manufacturing floor is optimized, and outlined seven types of approaches to achieve this integration [BURB78]. There have been several attempts to combine GT with MRP; Sato proposed a procedure for this and Gallagher et al. listed its benefits [SATO77][GALL86]. However, combining GT and MRP incorporates grouping of machines and parts in a dynamic environment but it does not overcome the intrinsic problems in MRP which requires accurate forecast and lead time calculations. Later work in GT included development of algorithms to assign parts to machines, taking into consideration machine capacity constraints [MOUS98][WU98]. Li et al. applied GT as a tool to plan production flow and layout in a modern factory by setting up logical operators for sorting machine into machine cells and part into parts families [LI02].

The purpose of MRP and HPP is to integrate production planning and control planning to deal with material, capacity and scheduling. Research has been done in understanding the effect of the variability of parameters on decisions. For example, Collier used simulations to evaluate the impact of lot sizing, demand variability, and the degree of item commonality on work center load [COLL79].

Anderson et al. predicted customer service level, using a simulation, in a single MRP environment [ANDE89]. Analytic expressions were drawn for assigning priorities between the current period demand and the existing backlog. Caramanis et al. studied the nonlinear relationship between variable lead-time and load, production mix and detailed scheduling, and its potential contribution towards decreasing inventory and backlog costs [CARA99]. Also, the computational load of producing the necessary information through calculations and the communication with the master problem solving coordinator was considered. Agrawal et al. developed an algorithm to control lead-times to perform backward scheduling in order to reduce cycle time, WIP and produce on time [AGRA00]. Du et al. developed a system based on MRP theory that used an object-oriented database, fuzzy logic controllers and neural networks to develop an active, bucketless, and real-time MRP system [DU00]. The system did not need to fulfill inventory replenishment in a period by period basis, which affected the dynamic performance of the system.

Pun et al. studied an integrated JIT/MRP system in the printed circuit board (PCB) industry that used MRP for capacity planning and JIT for parts embedded into the Master Production Schedule (MPS) [PUN98]. In this type of production, orders are released at the right time and stock is held down to a minimum. In Lean Manufacturing the workers are allowed to actively participate in running and improving their own work areas [SUGI77].

Manivannan et al. outlined the flaws of process oriented simulation languages for modeling in JIT [MANI89]. A rule-based simulator was designed that includes a user interface and static and dynamic databases. Yash et al. studied the characteristics of a Pull Kanban system using a dynamic simulation model. Using system dynamics models, the behavior of the system under the stimulus of various exogenous factors is explained [YASH89].

Ozgurler et al. studied the relationship between manufacturing time and productivity with Kaizen (continuous improvement) implementations in an automotive parts manufacturer [OZGU02]. The performance measures studied were in time, length, space, stock level and productivity. Yang et al. presented a lot size reduction model for closed stochastic production systems [YANG02]. Product lot size choice influenced all major aspects of job flow time: waiting time in queue, batch processing time, batch moving time, and finished goods warehousing time.

Mathematical programming has been used in decision making to incorporate capacity constraints. Hierarchical Production Planning (HPP) envisages dividing the planning problem into several levels and optimizing its results. However, early research in HPP was limited to single level problems [GABB79]. Steinberger et al. expanded the approach to a multiproduct, multilevel and multiperiod problem, but this became complex and was limited to a certain number of levels to minimize computational burden [STEI80]. Using HPP, Axsater used the production of various machine groups and the flow of orders in product groups as inputs to planning at lower levels and inventory [AXSA79]. Venkateswaran et al. proposed an HPP approach to simplify the computational intensity of centralized production systems [VENK04]. In this research the interaction between aggregate planning (high-level planning) and detail-scheduling level (low-level scheduling) was discussed.

Karmarkar presented a capacity and release planning model based on a clearing function that included the cost of inventory and the lead-time outcomes of capacity loading [KARM89]. This research illustrated the relationship between releasing job orders based on the loading in the system and the costs in the system. Lasserre worked on an integrated planning and scheduling system, which alternated between a system that solves the planning problem with a fixed sequence of products and a job-shop scheduling problem for a fixed production plan [LASS92]. Gunasekaran et al. developed a mathematical model to find the ideal lot-sizes for a set of products and the capacity needed to produce them in a multistage production system [GUNA98]. Qiu et al. proposed a model to deal with a hierarchical production planning/scheduling problem in a multiproduct multimachine environment with sequence-dependent setups [QIU01].

Espuna applied CIM in a system to optimize production and transport between manufacturing tasks; the transport tasks were integrated with production policies such as tardiness and total throughout time or makespan in order to coordinate the overall plant decision making [ESPU99]. Choi et al. presented a hybrid control system for scheduling on the shop floor in which the controllers decided on scheduling based on unplanned events in the system [CHOI00]. McFarlane et al. presented a holonic manufacturing system [MCFA00] in which the various entities in the system were self-reliant units, which have a degree of independence and handle circumstances and problems on their particular level without asking higher-level holons for assistance. It was shown that responsiveness is improved in a complex manufacturing system using a holonic architecture.

Virtual Manufacturing Enterprises are more complex systems in which total cooperation and exchange of information for decision making among corporations is possible because traditional methods of transactions are replaced with e-commerce features. Zhao et al. described a distributed virtual manufacturing system that supported remote collaboration [ZHAO02]. Wu et al. presented a computerized model that can integrate concurrent planning and scheduling and make decisions in a distributed system [WU02]. A cost function was used that considered an organization’s manufacturing capacity, work order processing time, location and product due date.

Previous research has been conducted in the regulation of Due Date Deviation (DDD), which is defined here as the deviation of the time of completion of an order from the order due date. Arakawa et al. proposed a backward/forward simulation combined with a parameter space search improvement method, based on a shop floor model, for generating schedules to minimize DDD [ARAK02]. Kuo et al. used a time-buffer control using, Theory of Constraints to regulate DDD, with first-in-first-out and earliest-due-date scheduling heuristics, and illustrated improvements in on-time delivery rate and average absolute due date deviation [KUO09]. Srirangacharyulu et al. described an algorithm for minimizing mean square deviation by solving a completion time variance problem using dynamic programming; however, the method was computationally intensive for a large number of jobs [SRIR13]. Sakuraba et al. addressed the minimization of mean absolute deviation from a common due date in a two-machine shop; the authors used mixed integer linear programming to obtain optimal sequences [SAKU09].

Anderson et al. defined an input vector for the desired commands in a linear feedback system for a manufacturing system, where the state equations described the behavior of inventory, backlog and production rate over time [ANDE89]. The authors discussed the synthesis of control policies for a single-input system. Pekelman used control theory to decide in a production process based on forecast over a time horizon [PEKE79]. This study focused on finding the ideal changeovers in different production processes where a cost was assigned to the change in setups.

Bonney et al. used discrete linear control theory to analyze production systems, studying the change in the step response due to changes in system structure [BONN89]. They also proposed the use of dynamic models to study the properties of a system before its implementation. Towill et al. examined the design parameters within an adaptive model, highlighting how the backlog in the system can be used to decide the work load in the production system [TOWI97]. The system linked marketing and production to improve the company competitive advantage.

Control theoretic approaches have been proposed as a means for understanding fundamental workstation dynamic properties in regulation of backlog, Work In Progress (WIP) and lead time. Toshniwal et al. used discrete event simulations to assess the fidelity of control theoretic models of the dynamics of WIP regulation and capacity adjustments [TOSH11]. Duffie et al. used control theoretic methods to coordinate modes of capacity adjustment [DUFF13], and Kim and Duffie used control theoretic methods to analyze and design WIP regulation for interacting multi-work-station production systems [DUFF05].

Pritschow and Wiendahl used control theory to define the control variables in a manufacturing system and developed a dynamic model to represent the behavior of inventory and capacity through their relationship in the logistic operating curve [PRIT95]. This curve represents the “growth” of system utilization with respect to inventory (WIP). Wiendahl et al. used a funnel model to design a continuous flow model of a single work center [WIEN00]. Scholz-Reiter et al. introduced a dynamical approach for modeling and control of production systems that included an analysis of the dynamic behavior in the presence of disturbances [SCHO02].

Duffie and Falu presented a dynamic model of a PPC system that contains a backlog and a WIP controller [FALU01]. The dynamic relationship between the system inputs and system variables was defined, and control laws were selected according to the needed system performance. Also, Duffie and Ratering used a discrete dynamic model of a single workstation, including the characteristic equations obtained from transfer functions that were useful in choosing control parameters values according to the desired dynamic performance and response [RATE03].

Duffie et al., presented a lead time regulation topology for a workstation that autonomously adjusts its local production rate to eliminate deviation between desired and actual lead time; a control theoretic topology was presented to illustrate the dynamic behavior of the system [DUFF10]. Duffie et al., presented a dynamic model for a production network with a large number of stations with local capacity control [DUFF08].

1.3 Previous Work Done at the University of Wisconsin-Madison

At the University of Wisconsin-Madison, distributed manufacturing control system has been an active area of research since 1977 [PAUL77]. Major milestones include:

1980 - A design methodology for distributing machinery control [DUFF8O, DUFF82]

1984 - A centralized, hierarchically controlled manufacturing cell [HART86]

1985 - A hierarchical cell control system with part driven scheduling [HART86]

1986 - A distributed, heterarchical control system for a group of machines [DUFF87]

1988 - A heterarchical system with robotics machining and assembly cells [DUFF88]

1989 - An automated mold production system based on a heterarchical architecture. [DUFF90]

1991 - A cooperative scheduling system using distributed simulation for heterarchical systems. [DUFF94, PRAB91]

1995 - A real-time distributed arrival time control for heterarchical manufacturing systems and dynamics analysis of single machine systems. [PRAB95a, PRAB95b]

1999 - Implementation of a distributed control system for manufacturing using heterarchical architectures. [BECE99]

1999 - Performance improvement of distributed arrival-time control for heterarchical manufacturing systems. [DAND99]

1999 - Nonlinear Dynamical Systems Theory of Real-Time Control of Heterarchical Manufacturing Systems. [KALT99]

2001 - Control-Theoretic Analysis of a Closed-Loop PPC System. [FALU01]

2003 - Design and Analysis of a Closed-Loop Workstation PPC System. [RATE03]

2005 - Design and Analysis of Closed-Loop Capacity Control for a Multi-Workstation Production System. [KIM05]

2006 - Performance of Coupled Closed-Loop Workstation Capacity Controls in a Multi-Workstation Production System. [KIM06]

2008 - Dynamic modeling of production networks of autonomous worksystems with local capacity control. [DUFF08]

2009 - Maintaining constant WIP-regulation dynamics in production networks with autonomous work systems. [DUFF09]

2011 - Assessment of Fidelity control-theoretic models of WIP regulation in networks of autonomous work systems. [TOSH11]

2012 - Dynamics of Autonomously Acting Products and Work Systems in Production and Assembly. [DUFF12]

1.4 Decision-Making Architectures

The traditional architecture used for planning and control of manufacturing systems is hierarchical. Managers tend to prefer hierarchical architectures because they mimic the hierarchy commonly found in human organizations; this eases the assignment of responsibilities and authority among people or control nodes in the system [VEER92]. Figure 1.2 shows the architecture of a hierarchical organization where three levels are separated by time horizons in their planning decisions. At the top level, demand forecasts control decisions made in a long-range; at this level the future is imprecise, meaning the quantities or due dates of the products are subject to change. At the middle level, medium-range planning gets information from the Bills of Materials (BOM) and the product manufacturing demand. This information provides the manager with the raw material and capacity data needed to set due dates that meet the demand efficiently. At the lower level, short-term scheduling-related decisions take place; lower level management calculates the production sequence that helps minimize cost strives to produce the demanded products on time.

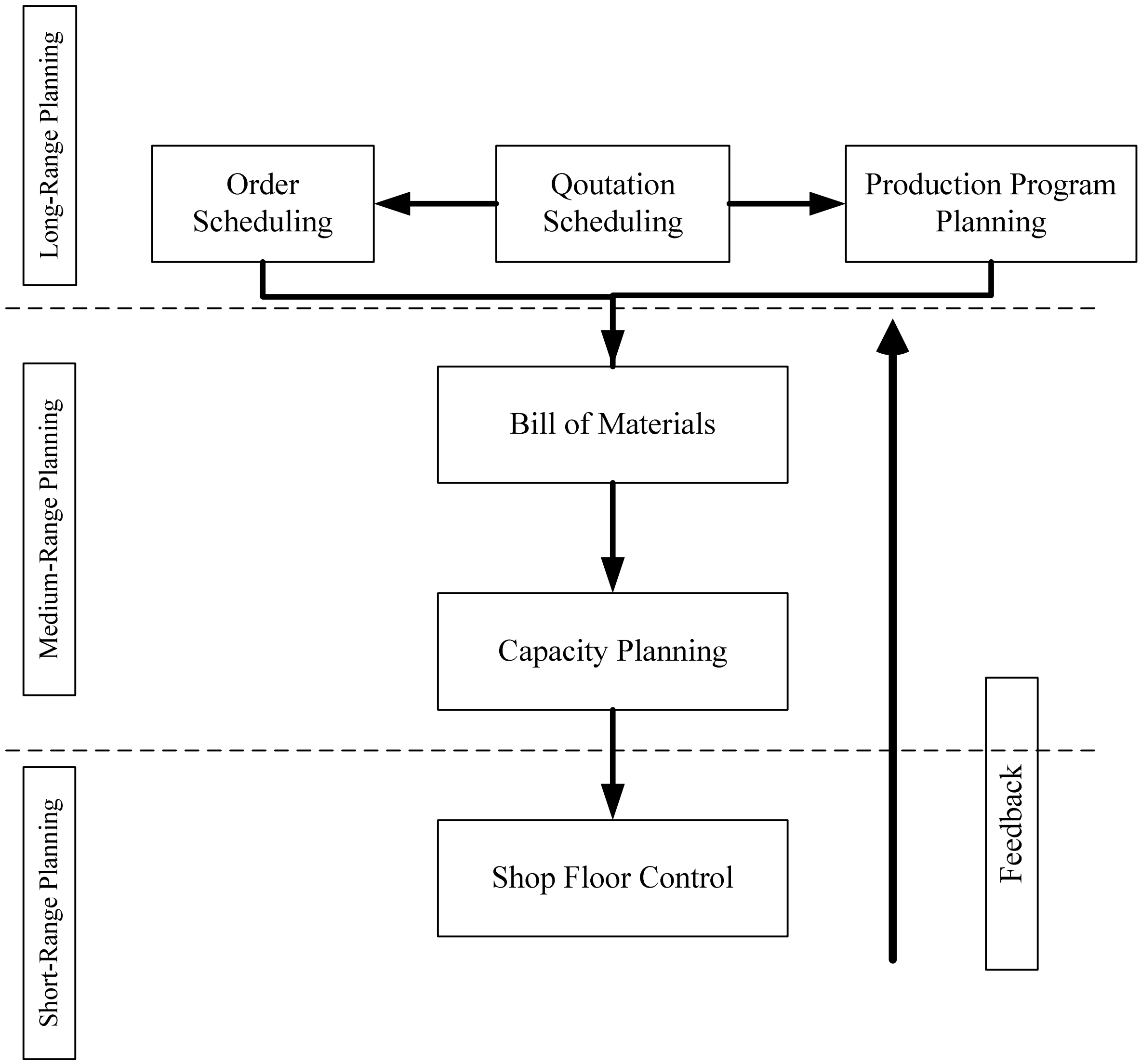


Figure 1.2: Hierarchical production planning and control (adapted from [BRAN73])

Hierarchical architectures create several difficulties. At the top level where managers look at the organization as a whole, it is difficult for management to notice details or single events that could have high-level implications. On the other hand the managers at lower level must restrict their actions in carrying out the goals set by the top management; thus they can pass down errors in management. Errors might take weeks or months to correct, and adjustments to unexpected events can take weeks to implement because feedback must come from the bottom up and decisions may come from the top down.

In general, handling global information is a difficulty in a hierarchical architecture because large amounts of information must flow back and forth among levels. Databases must keep information current and error free, which is a difficult task in complex systems. This makes large hierarchical architectures difficult and expensive to design, implement, maintain and modify [DUFF88]. Today's businesses need to be more flexible for their survival; decisions must be made in real-time respond to customers needs and changing demands within the shortest lead-time possible [BEAU94]. New approaches and organizational architectures are needed that move the decision-making lower in the organization.

Many manufacturing control approaches base their philosophy on traditional hierarchical architectures as shown in Figure 1.3. The master planner uses large amounts of information such as due-dates, demand, and processing times to provide schedules for the shop floor. These architectures base their communication and decision-making on strong master-slave relationships and extensive global information. The complexity of this architecture tends to grow exponentially according to the size of the system; making decisions harder to execute in real-time [PRAB95b] [VAMO86]. Hierarchical controls generally are not suitable for controlling chaotic behavior and have problems reacting in real-time to changes in demand (unexpected disturbances), affecting the overall performance of a system [MASS96].

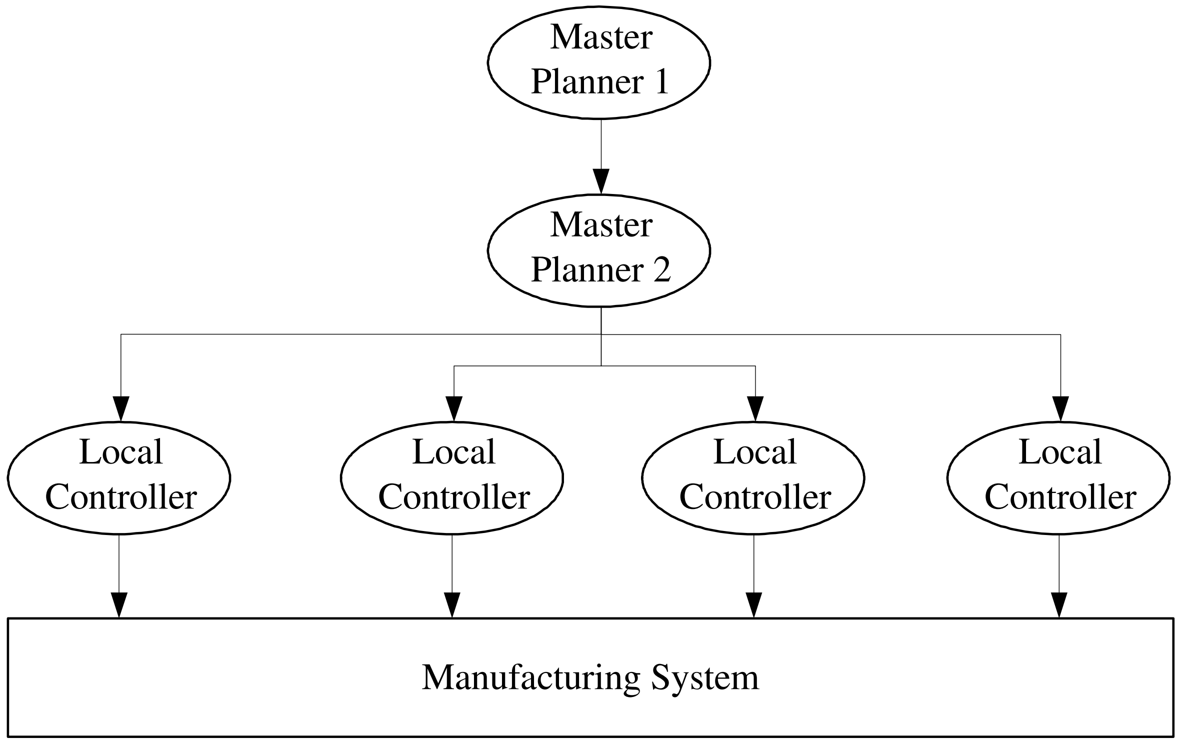


Figure 1.3: Hierarchical Manufacturing Architecture (adapted from [PRAB95a])

1.4.1 Hierarchical Production Planning

In a typical hierarchical organization, time horizons divide levels of decision-making; also, the types of decisions made at each level are determined by the frequency at which they are made. Figure 1.4 shows a hierarchical architecture with various management levels and time horizons. Each organizational level must track the higher-level targets as well as refine the targets for the lower organizational levels. Also, each level must solve a control problem to set the targets of the lower levels using the targets set by higher organizational levels [SHAR91]. The computational effort for combinatorial optimization can make real-time control impractical [GERS89].

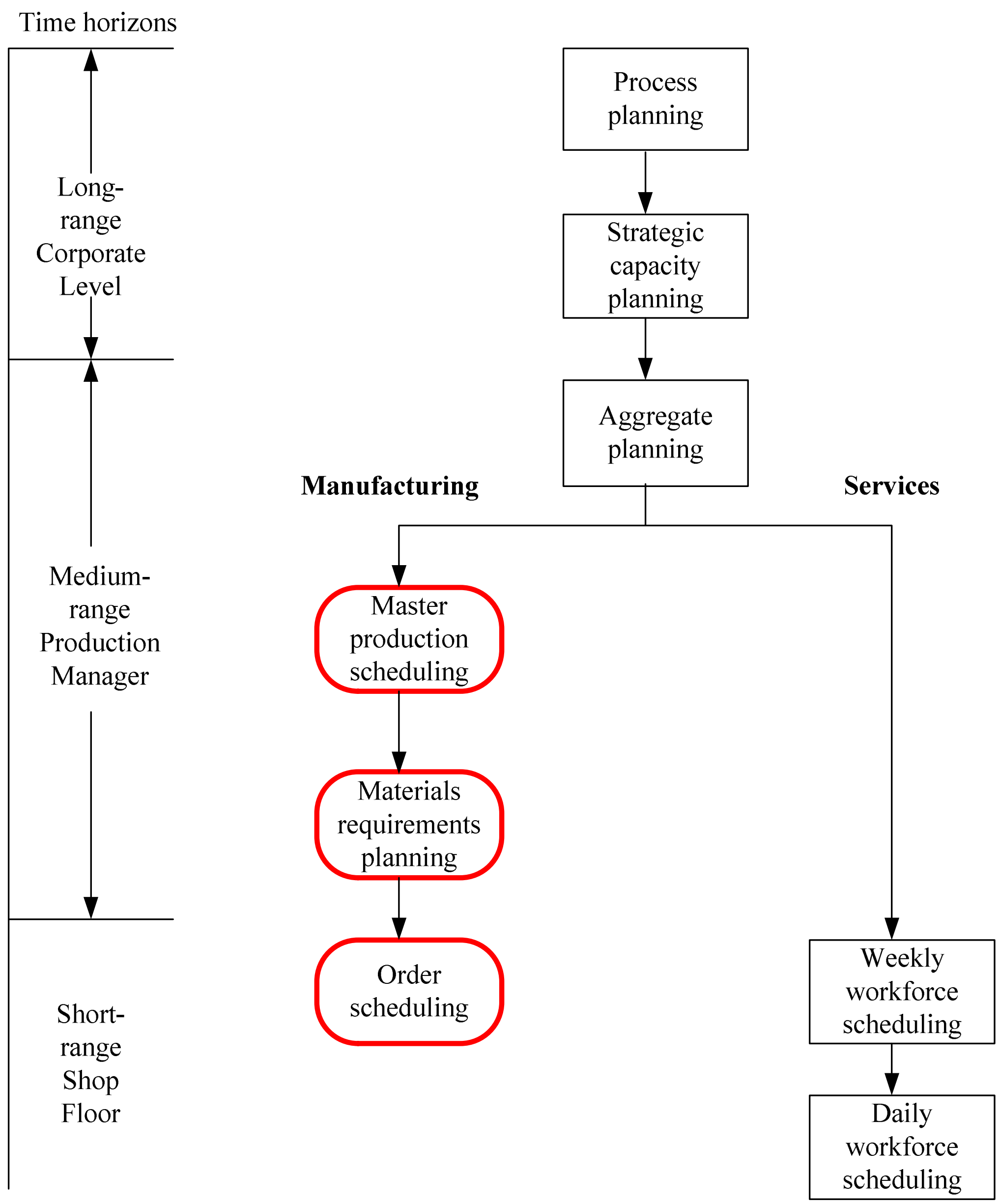


Figure 1.4: Overview of Major Operations Planning Activities (adapted from [CHAS95])

Every one to five years the corporate level typically performs long-range planning. In the process planning meeting the executives decide the technology to be used and the process design needed to produce specific products. Financial decisions are made at this level. In the strategic capacity planning the location of the facilities and the long-term capacity needed in meeting demand is determined.

At the medium-range level, the production manager determines the production, inventory and personnel needed [MART97]. These goals are typically planned three to twelve months ahead of time; the aggregated plan provides information for both manufacturing and services departments [CHAS95]. This information consists of the levels of the workforce and overall production and capacity strategies to meet the demand in each period. The medium-range planning for manufacturing often starts with Master Production Scheduling (MPS) activity. During this period input demand forecasts, customer orders and capacity data are collected. With the available information the manager creates a report that states amounts of products needed with their respective due-dates. This report is used to ensure the availability of raw materials to obtain the desired production levels.

There is a need to plan efficiently in hierarchical architectures for the proper functioning of the manufacturing system, and Materials Requirement Planning (MRP) is one solution [MORT93]. The main role of MRP is to develop cost-effective production and purchasing schedules, and to estimate the needed capacity and balance the load among work centers [MART97]. The main advantage of using MRP is that it optimizes decisions such as setup frequencies at a higher level by taking into consideration setup cost, work-in-progress and due dates. The tradeoff is that these calculations are often done several days in advance, and in this time frame conditions on the shop floor can change.

With the proper information, MRP systems are used to prepare a report with times of when to order material and when subassemblies should be prepared to allow production of products. MRP is a deterministic tool that is used to calculate the amount of inventory needed in order to comply with the schedule set by the MPS; MRP typically does not incorporates system constraints in the calculations [LÖDD13]. Also, MRP systems provide information on utilization, inventory and backlog performance. Manufacturing Resource Planning II (MRP II) is an extension to MRP and incorporates the limit in capacity of work centers. MRP II can be modified to become a closed-loop system and provides reports on system performance. With the capability of obtaining the performance of the system, effective resource planning reports and detailed schedule can be produced [COX84].

Short-term planning controls daily scheduling of equipment and personnel, and the planning horizon at this level typically ranges from one day to one month. Managers typically schedule production at the beginning of the workweek; however, daily adjustments are used to adapt to sudden shop-floor emergencies and rush orders.

1.4.2 Closed-Loop MRP and ERP

Original MRP systems were used to schedule purchasing of raw materials and production of subassemblies. The manager prepared the schedule without considering constraints on resources and then performed constraint calculations outside MRP; another MRP calculation is needed when these constraints are violated. Information feedback in MRP overcomes this problem, converting MRP into closed-loop MRP as shown in Figure 1.5. The American Production and Inventory Control Society defined closed-loop MRP as:

> "A system built around material requirements that includes the additional planning functions of sales and operations (production planning, master production scheduling, and capacity requirements

> planning). The term “closed-loop” implies that not only is each of this element included in the overall system, but also that feedback is provided by the execution functions so that the planning can be kept valid at all times.” [APIC92]

Figure 1.5 shows the information feedback in closed loop MRP. At a higher level, management uses this information to corroborate and change plans. To obtain the Master Production Schedule, information such as customer orders and forecast demand to produce schedules of the products that satisfy the demand are needed. MRP uses this information and the Bill of Materials to calculate the raw material needed to meet the demand. Capacity Requirements Planning will determine if the schedule is practical according to the resources available at the time. A manager releases a schedule to the shop floor in the case of a realizable schedule, or changes the schedule according to capacity constraints. At the end of plan execution, the outcomes in terms of capacity performance and materials use are returned to MRP and Capacity Requirements Planning for proper adjustments in the inventory and capacity levels.

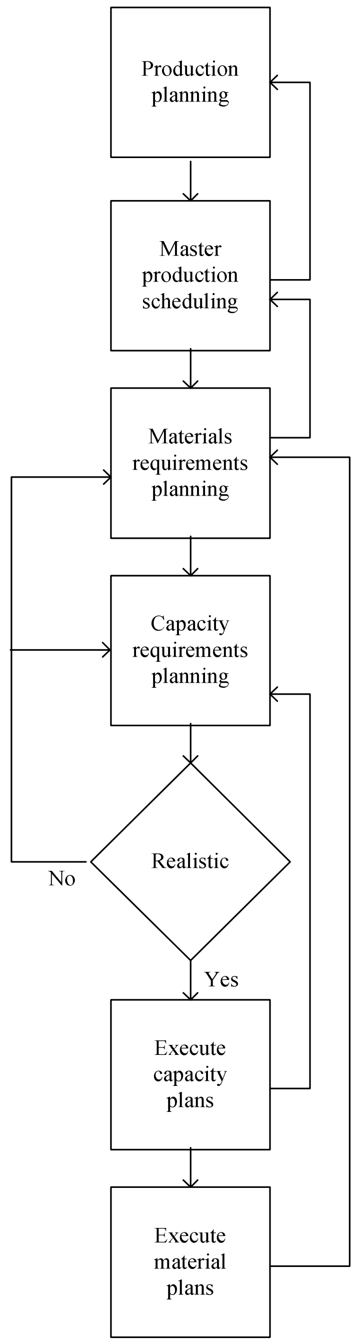


Figure 1.5: Closed–Loop MRP System Showing Feedback (adapted from [CHAS95])

MRP II integrates other business roles that together plan and control the resources of a manufacturing firm [NOOR95]. Business units included are manufacturing, finance, engineering and purchasing among others. However integration is needed between different operations that occur outside the company, where the goals set by the manufacturing department are tied with the customer demand, suppliers and transportation of the final product. ERP eases the exchange of information among corporate divisions in the MRP II model [JOHN98][HOLL99] and incorporates other business modules outside the corporation. A single family of software modules unites business units; these modules help in product planning, parts purchasing, managing inventories, and interacting with suppliers. For example, ERP can assist in cutting production and inventory costs, improving customer service, plans, forecast demand and cost allocation. ERP helps companies to become more efficient, but has some disadvantages such as high costs in installation and maintenance, as well as difficulty in its use. Robustness is limited by the weakest department, and the systems require commitment of all the companies that are related to the enterprise, suppliers and shippers. ERP systems may not be suitable for small to mid-size companies [YONG01].

1.5 Heterarchical Architectures

Heterarchical architectures consist of distributed, autonomous, loosely coupled entities that hold limited amounts of global information [DUFF94]. Entities in these architectures autonomously seek the resources they need by cooperating, using well-defined communication protocols over a local area network [DUFF96]. These communication protocols allow entities to have equal access to resources; including equal accessibility to each other to exchange information when needed to make local decisions [DUFF94]. Figure 1.6 shows a heterarchical architecture, where there are no higher levels. Each entity has its own local planner and local controller that make decisions based on local information. In a heterarchical architecture there is minimal global information; a controller seeks information only when needed. Each entity controls its own actions and reacts depending on the state of the system, which it is determined using communication.

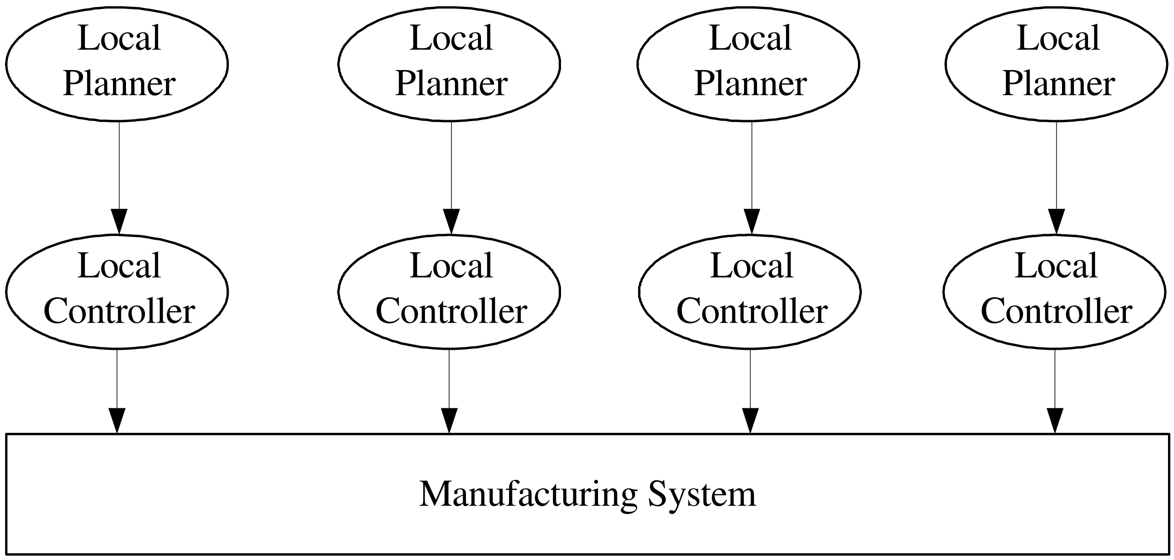


Figure 1.6: Heterarchical Manufacturing Architecture (adapted from [PRAB95a])

Entities in heterarchical architectures have a dual set of rules for operations. The first set of rules allows the entity to meet its the local objectives, giving the entity local autonomy [HATV85]. This set of local rules provides the entity with enough flexibility and intelligence to deal with disturbances. The second set of rules ensures overall system survival under most circumstances. Heterarchical architectures consist of entities that are cooperative and sacrifice their own local objectives on behalf of the overall performance of the system [DUFF95]. Entities in heterarchical architectures are willing to trade local performance to improve global objectives; they also share resources and contend continuously for these resources, making the locals goals interdependent.

When designing heterarchical architectures these basic guidelines apply:

1) No master planner: This principle removes the need for global information and makes the system more flexible.

2) Local control: Each entity contains a controller, allowing them to decide based on local information.

3) Minimum communication: There should be communication among entities only by request.

4) Entities should tend to cooperate.

5) Entities should not retain information of other entities (global information): The architecture then is more flexible and easier to configure; also, an entity makes decisions based on local information.

6) Entities should not make assumptions about the system status: This principle increases fault tolerance, allowing entities to react to unexpected events in real-time.

Heterarchical architectures tend to reduce complexity, improving the ability to react in real-time and increasing configurability. The need for the heterarchical architecture and its relationship to Production Planning and Control (PPC) is discussed in the next section.

1.5.1 Need for Heterarchical and Dynamic PPC Systems

There is an opportunity to distribute traditionally centralized planning tools such as MRP in heterarchical architectures. Decisions tools that are based on heterarchical architectures could provide the results needed by production managers to make decisions in real-time, while reducing complexity and improving reliability by localizing information and control, improving modifiability by improving modularity and self-configurability. Such heterarchical production planning control systems would help production managers to process work orders on time while controlling capacity and inventory levels and make the system robust to introduction of new products or new processes, variation in demand, machine failures and interruption in the flow of work orders.

Heterarchical architectures distribute decision making in one level and spread decision making over a set of autonomous but cooperating controllers [HATV85]. The levels of management in the hierarchical architecture do not exist in heterarchical architectures, improving flexibility and agility. However, high distribution and autonomy in heterarchical architectures makes it difficult to achieve global consistency and decision-making effectiveness because algorithms that improve global performance almost always need synchronization among entities. This conflicts with principles of local autonomy and minimal global information [NAID92].

Nevertheless, there is a need to integrate different levels of decision making in order to make decisions in real time in a distributed system. There is also an opportunity to use control theory in modeling and designing a distributed system that combines the decisions made at different of levels of management in a shop floor, including planning and scheduling.

1.6 Goal and Objectives of Current Research

The overall goal of this research was to develop and analyze heterarchical systems in which high-level production planning and control is integrated with low-level scheduling. The following specific research objectives were identified:

1. Develop a distributed production planning and control (PPC) system, consisting of a distributed multi-rate controller that controls input rate and capacity by sampling inventory and backlog, making decisions based on local information;
2. Use control-theoretic approaches to construct dynamic models of Production Planning and Control (PPC) systems, relating properties such as time constant, bandwidth and stability to physical parameters of the system.
3. Integrate the high-level production planning with low-level scheduling by modifying an Arrival Time Control (ATC) concept to incorporate the decisions generated by the distributed PPC system.
4. Use discrete event simulations to study the effects of capacity adjustments on WIP levels and order release times.
5. Develop a control theoretic model for control of capacity while regulating due date deviation with an adaptive controller, and study the dynamic behavior of the system.

1.7 Organization of the Dissertation

In this chapter, a review of manufacturing production control systems has been presented. Past research in the different types of production control systems and current research on appreciation of control theory in manufacturing systems was reviewed, and previous research done at UW-Madison was highlighted. Different types of manufacturing decision making architectures were discussed along with their properties. Decision making and planning architectures such as Closed loop MRP, MRP II and ERP were discussed. Heterarchical systems were discussed along with the need to investigate the integration of high level production planning and low-level scheduling using this architecture. Finally the goals and objectives of this work were presented.

A detailed description of a distributed production planning and control system that is used to control inventory and capacity is presented in Chapter 2. A control theory approach is presented for modeling the dynamic system using multirate z-transform analysis and the system transfer functions are obtained. An analysis of the dynamics of the characteristic equation is performed in order to study fundamental dynamics of the system. Also, the responses of the system are studied.

The Arrival Time Controller (ATC) concept is discussed in Chapter 3. The distributed arrival-time controller is the low-level scheduling system that will be integrated later with high-level planning decisions. The distributed, ATC architecture and the dynamic model that describes the trajectory of the order arrival times are presented in detail. Also, the different dynamic regions of response are explained.

The integrated heterarchical production planning controller and arrival time scheduling system is described in Chapter 4. The interactions between both subsystems, PPC and ATC, are described in detail and the need for such a heterarchical system is described. Industrial data is used in discrete event simulations, and the parameters and the assumptions of the simulation are defined. The results of the simulation are presented for both fixed capacity and by adjusting capacity and the differences of the responses is discussed.

In Chapter 5 a concept is presented for controlling due date deviation (DDD) and order release times in a system with PPC integrated with a scheduler. Simulations are used to illustrate the relationships between capacity and order DDD. The system transfer functions are obtained and control gains are theoretically derived. A discrete event simulation of DDD regulation driven by industrial data is described, and results obtained are used to illustrate the dynamic behavior of DDD regulation. Finally, conclusions are presented regarding the efficacy of combining scheduling and DDD regulation with adjustable capacity, and the resulting tradeoffs between DDD and capacity.

In Chapter 6, conclusions are drawn from this work and recommendations for future work are made.

An analysis of the dynamics of the PPC system shown in Figure 2.1 that integrates closed-loop control both of capacity and Work In Progress (WIP) is presented in this chapter. In the sections that follow, a control-theoretic dynamic model of the system is developed with the objective of both enabling analysis of the fundamental dynamic behavior of the system and enabling the design of control laws for capacity and WIP. The discrete nature of the system and the presence of multi-rate samplers motivate the use of sampler decomposition and modified z-transformations in the analysis; the result is a set of transfer equations that relate key system variables such as backlog and WIP to planned capacity and planned WIP, and also to unplanned disturbances in capacity and WIP due to equipment failures, rush orders, job cancellations, etc. The transfer equations developed are used to help choose the control laws necessary to achieve desired system performance and to understand the dynamic response of the system.

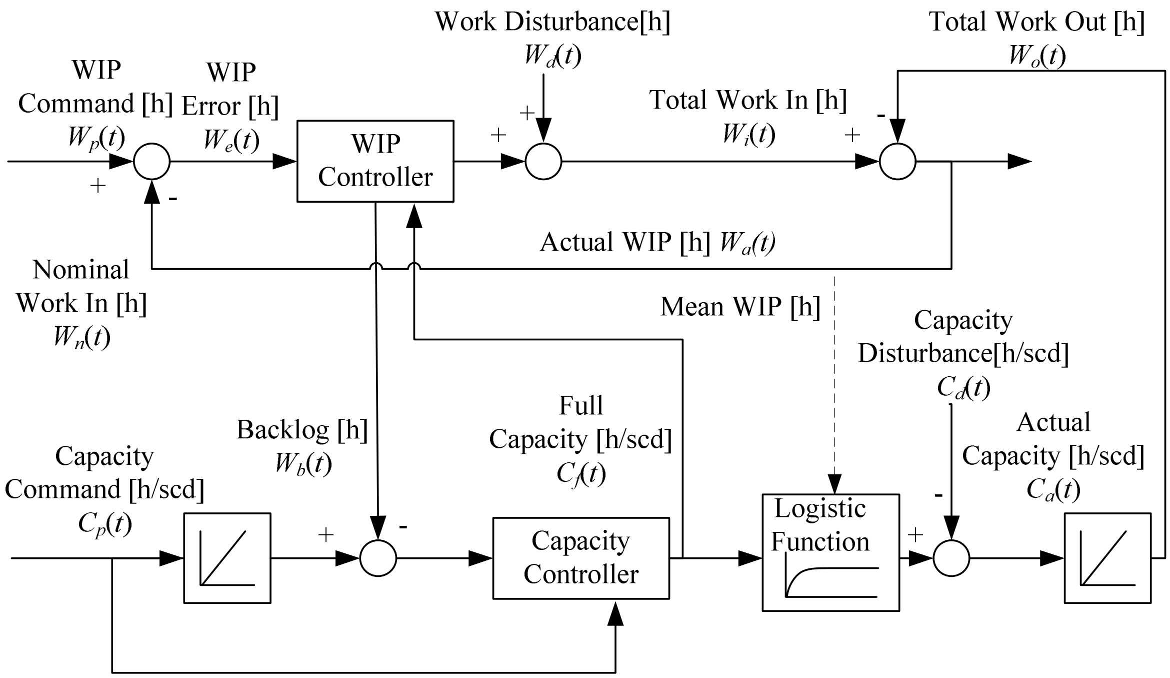


Figure 2.1: Closed-Loop Production Planning and Control System

2.1 Discrete System Model

There is a relationship between the actual capacity $C_a(t)$ of the system full capacity $C_f(t)$ and the actual WIP $W_a(t)$ that can be described by a logistic operating curve [NYHU94]:

$$C_a(t) = f_{LC}\left(C_f(t), W_a(t)\right) \tag{2.1}$$

The structure of the system is adapted from simulations studies performed by Wiendahl and Breithaupt [WIEN97]. The dynamics of the system can be analyzed at different operating points in the logistic operating curve using the approximation.

$$C_a(t) = C_c + \underbrace{\left.\frac{\partial f_{LC}}{\partial C_f}\right|_{OP}}_{K_{Cap}} \cdot C_f + \underbrace{\left.\frac{\partial f_{LC}}{\partial WIP_a}\right|_{OP}}_{K_{WIP}} \cdot W_a \tag{2.2}$$

where K_{cap} is the capacity related operating parameter and K_{wip} (scd^{-1}) is the WIP operating related parameter and C_c (h/scd) is the bias operating point linearization.

Assuming that physical limits on WIP, input rate and capacity are not exceeded and actual capacity is not affected by lack of WIP, the system in Figure 2.1 can be represented using the block diagram in Figure 2.2. The system consists of two loops that are sampled at different rates. The lower loop is the capacity controller; this controller adjusts capacity levels based on the backlog which is sampled with a period T. The upper loop is the WIP controller; this controller adjusts the input rate based on deviations of the actual WIP in the system from the planned WIP. The WIP is sampled at a faster rate than backlog, and the sampling period for this loop is T/N, the modified z transform is used to obtain the transfer functions and analyze this system.

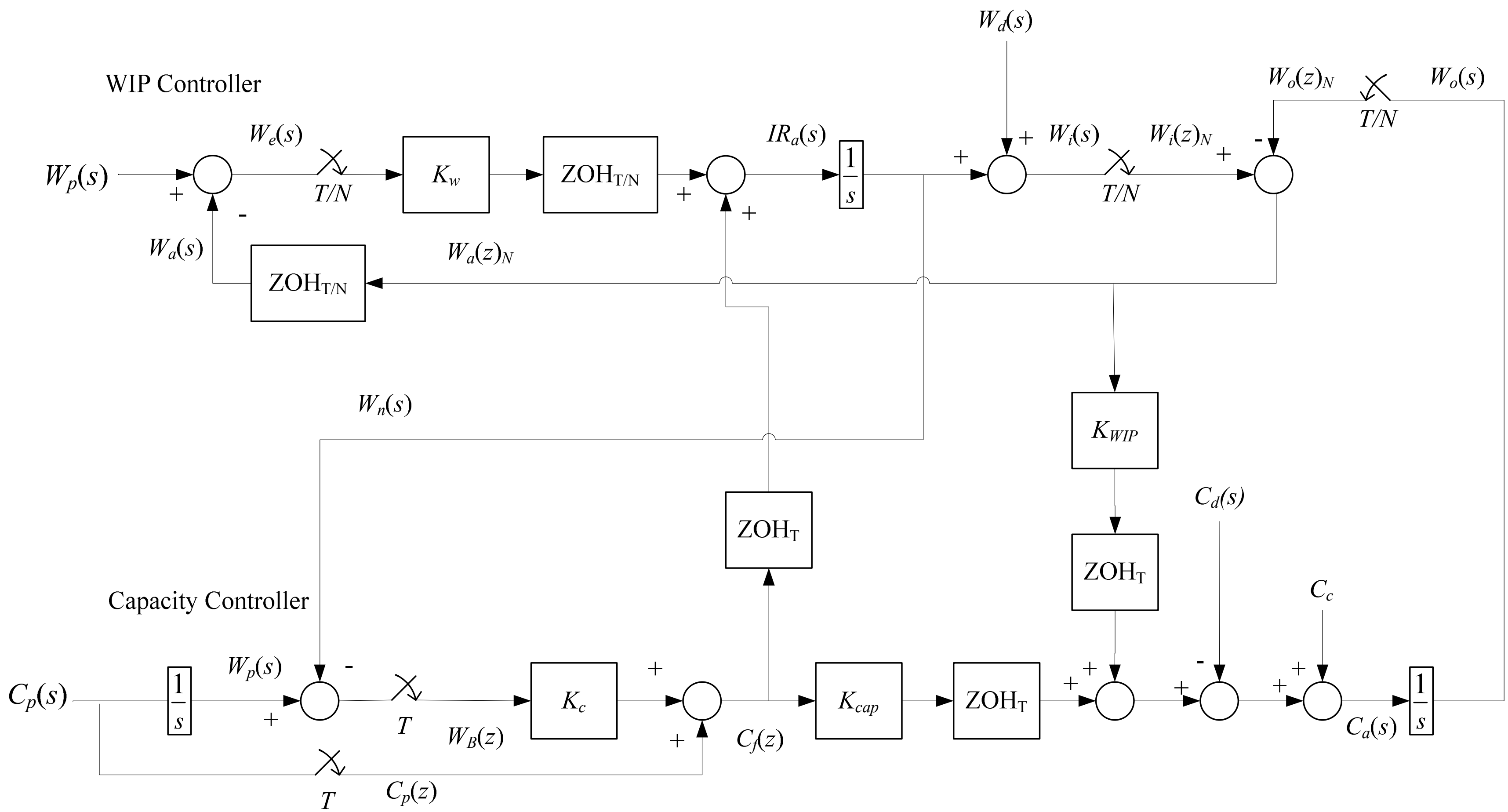


Figure 2.2: Production Planning Multi-Rate Control System

The backlog of the system is determined by the difference between the planned work $W_p(s)$ and the work that enters the system $W_n(s)$, exclusive of work disturbances $W_d(s)$. The backlog measures how would the system is able to keep with the demand.

$$W_b(z_N) = \mathbb{Z}\left[\frac{C_p(s)}{s}\right] - IR_a(z_N)_N \frac{T}{N\left(z_N^N - 1\right)} \tag{2.3}$$

It is assumed that the rate at which work is released into the system, exclusive of disturbances such as rush orders, can be instantaneously adjusted at time intervals *T/N*, where *N* is a positive integer. Then, a straightforward control law for adjusting the rate of work input is

$$IR_a(z_N)_N = K_w\left(\mathbb{Z}\left[W_p(s)\right]_N - W_a(z_N)_N\right) + C_f(z_N)\sum_{i=0}^{N-1}\left(\frac{iT}{N} + \frac{T}{z_N^N - 1}\right) z_N^{\left(\frac{-i}{N}\right)} \tag{2.4}$$

where K_w is an adjustable control gain.

Once adjusted, it is assumed that this input rate is held constant over the interval *T/N*. The work that is actually is in the system $W_i(s)$ is the sum of the work that entered the system $W_n(s)$ plus any unexpected rush orders $W_d(s)$. This value is used to determine the amount of WIP in the system.

$$W_i(z_N)_N = IR_a(z_N)_N \frac{1}{\left(z_N^{\left(\frac{1}{N}\right)} - 1\right)} + \sum_{i=0}^{N-1}\mathbb{Z}\left(\frac{W_d(s)}{s} e^{\left(\frac{isT}{N}\right)}\right) \tag{2.5}$$

It is assumed that backlog is evaluated and capacity is adjusted at time intervals *T*, weekly for example. A straightforward control law for adjusting system capacity as a function of backlog is

$$C_f(z_N) = \mathbb{Z}\left[C_p(s)\right] + K_c W_b(z_N) \tag{2.6}$$

The total work done in the system is the accumulation of the daily production. The daily production is a function of the work done due to the contributions of the capacity controller and the WIP controller. These contributions are a function of the parameter values K_{cap} and K_{WIP}, respectively. Any capacity disturbances in the system due to worker illness, equipment failures, etc. are subtracted from the actual capacity available for production.

$$\begin{aligned} W_o(z_N)_N &= \left(C_f(z_N)K_{cap} + C_c\right)\sum_{i=0}^{N-1}\left(\frac{iT}{N} + \frac{T}{z_N^N - 1}\right) z_N^{\left(\frac{-i}{N}\right)} \\ &+ \sum_{i=0}^{N-1}\left(\frac{C_d(s)}{s} e^{\left(\frac{isT}{N}\right)}\right) + \left(W_i(z_N)_N - W_o(z_N)_N\right)\frac{K_{wip}T}{N\left(z_N^{\left(\frac{i}{N}\right)} - 1\right)} \end{aligned} \tag{2.7}$$

The actual WIP of the system is the difference between work entering the system and the work done. The actual WIP is sampled with period *T/N*, daily for example:

$$W_a(z_N)_N = W_i(z_N)_N - W_o(z_N)_N \tag{2.8}$$

2.2 Transfer Function Analysis for $W_a >> W_{Ideal}$

Here it is assumed that the system actual WIP W_a is larger than the ideal WIP W_{ideal}. At this operating point the system is able to run at full utilization because most of the time there will be an order available in the system waiting for production, and an increase in WIP does not translate into an increase in utilization. This operating point is the flat region in logistic curve. Figure 2.3 shows the block diagram for the PPC system in this region, which is obtained from Figure 2.2 with the following parameters for the linearized logistic operating curve : $K_{wip} = 0$ scd^{-1}, $K_{cap} = 1$, $C_c = 0$, and $C_a(s) \approx C_f(s) - C_d(s)$.

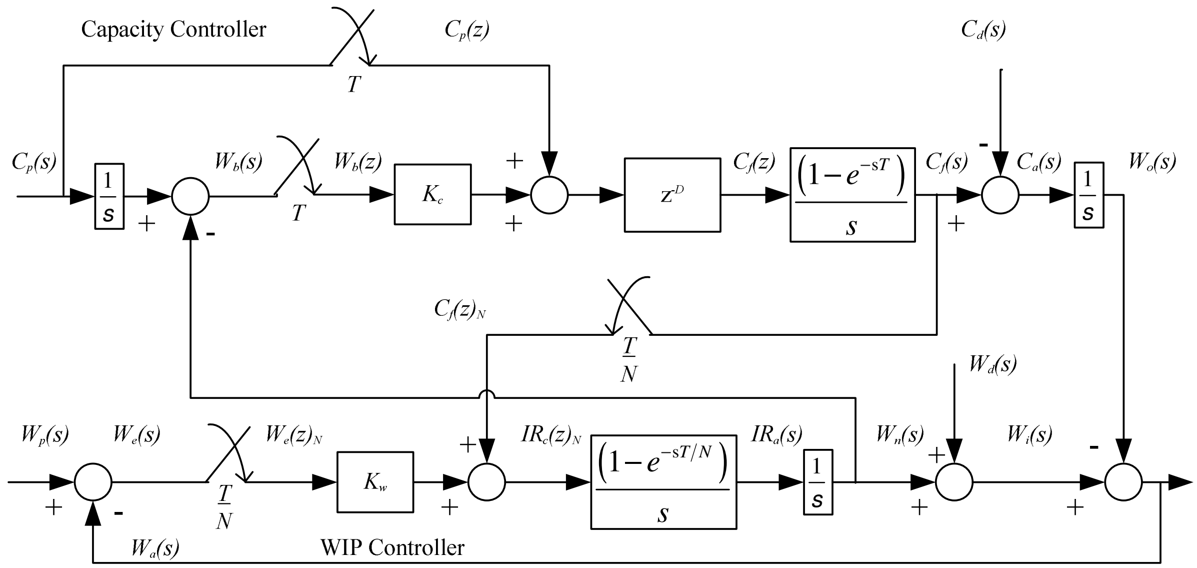


Figure 2.3: Production Planning Multi-Rate Controller (W_a>>W_{Ideal})

As an example of analysis using the dynamic model the transfer functions that describe the response of the change in inventory and backlog due to an unexpected rush order are [FALU01]:

$$\frac{\Delta W_a(z)_N}{W_d(z)_N} = \frac{z_N - 1}{z_N - \left(1 - \frac{K_w T}{N}\right)} \tag{2.9}$$

$$W_b(z) = \frac{(z-1) K_w \frac{T}{N} \sum_{i=0}^{N-1} \left(\left(1 - K_w \frac{T}{N}\right)^i \mathbb{Z}\left(W_d(s) e^{isT/N}\right) \right)}{\left[z - \left(1 - K_c T z^{-D}\right)\right] \left[z - \left(1 - K_w \frac{T}{N}\right)^N \right]} \tag{2.10}$$

The characteristic equation of Equation (2.9) has one pole at ($1 - K_w T/N$). WIP control gain K_w affects the time constant for the response of the change in inventory with respect to a rush order. The WIP responds with an exponential characteristic, when $K_w < N/T$,with equivalent time constant.

$$\tau_w = \frac{-T/N}{ln\left(1 - \frac{K_w T}{N}\right)} \tag{2.11}$$

The response tends to zero in one time interval *T/N* when $K_w = N/T$. The gain for the capacity controller K_c, does not affect the dynamics of this transfer function.

As an illustration of the dynamic behavior of the system, consider the response of WIP, input rate, backlog and capacity to an unexpected demand or rush order that occurs at time 0. The new demand of this WIP disturbance has a direct impact because, when the new work arrives, the capacity of the system is dedicated to the rush order. Backlog builds up because the system is not doing planned work and falls behind in schedule. More capacity is therefore needed to eliminate the backlog. The following figures shows the change in WIP ΔW_a, change in backlog ΔW_b, change in input rate ΔIR_a, change in work in ΔW_i, change in work out ΔW_o, change in capacity, ΔC_f, and change in actual capacity, ΔC_a, in response to a rush order of one hour of work for a case where $T = 5$ scd, $T/N = 1$ scd, and $D = 0$; the values for the gain of the capacity and WIP controller (K_c, K_w) are varied.

Figure 2.4 shows two cases where $K_c T = 1$ and the gain of the WIP controller changes. In one case, the gain $K_w = N/T$; the WIP level is corrected in one period. For the second case the gain $K_w < N/T$ or $K_w = 0.2$ scd^{-1}, in this case the WIP deviation decays exponentially to zero at approximately the 20th period. The backlog also responds exponentially, with values at instant separated by *T/N* when $N = 5$ are calculated using

$$W_b(z) = \frac{(z-1) K_w \sum_{i=0}^{4} \left((1-K_w)^i \, \mathbb{Z}\left(W_d(s) e^{is} \right) \right)}{\left[z - (1 - K_c T) \right] \left[z - (1-K_w)^5 \right]} \tag{2.12}$$

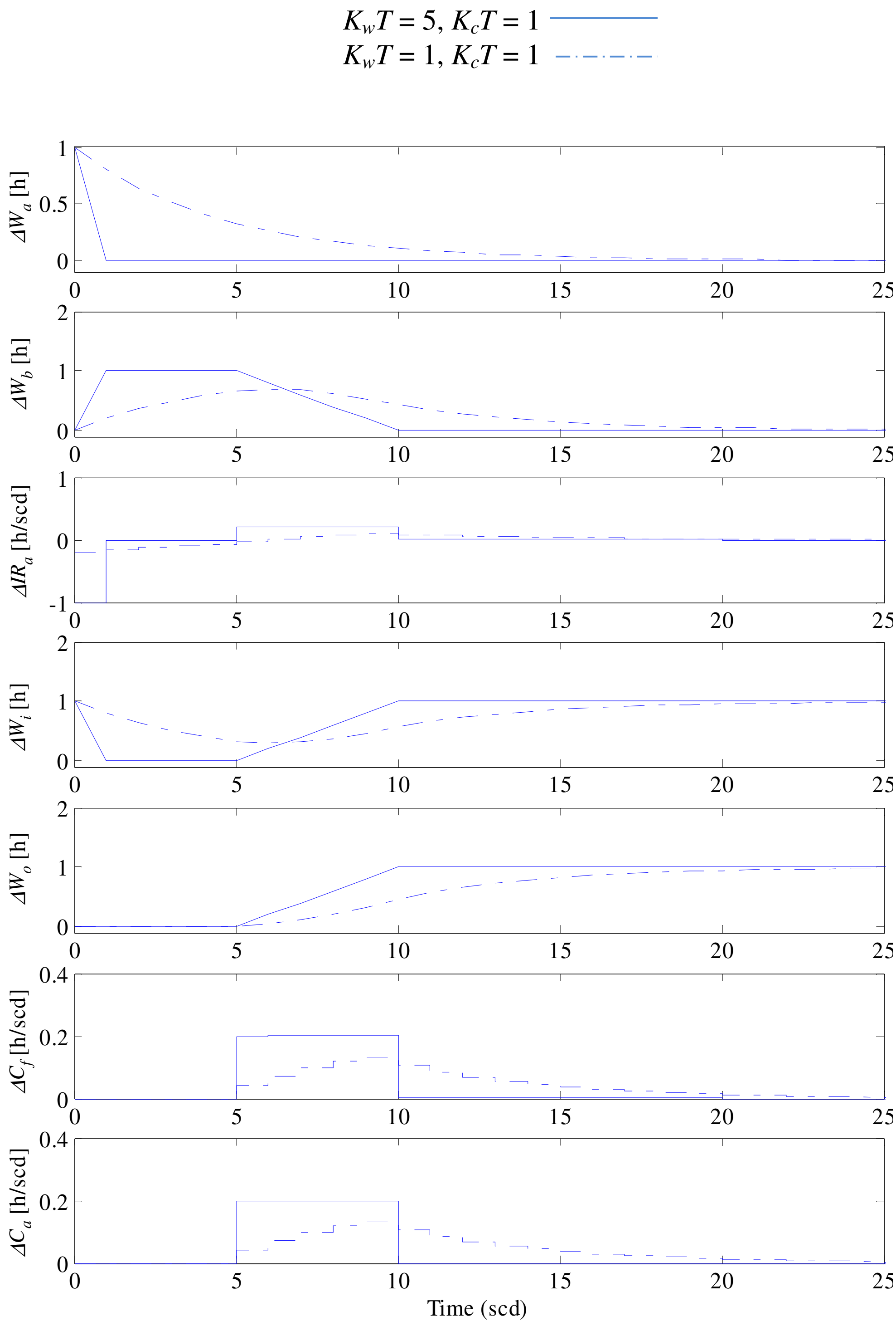


Figure 2.4: Time response for rush order when W_a>>W_{Ideal}

Figure 2.5 shows the response of the PPC system to a rush order with $K_w T$ = 5 and the gain of the capacity controller K_c changes. For both cases the figure shows that the WIP is corrected in one period, this is because $K_w = N/T$; however the response is affected for different values for K_c. When $K_c T$ = 1, the inventory increases at time 0 and immediately reduces the rate of input of planned work. This is desirable because the current inventory level exceeds the planned inventory levels. Between day 0 and day 1, the backlog W_b increases by one hour, the magnitude of the disturbance introduced, because of the decrease of the rate of input of planned work. The capacity controller samples the backlog every five days, and the increased backlog is detected on day 5 and eliminated by day 10. There is no steady-state error in either backlog or WIP. When the $K_c T$ = 0.5, the backlog deviation decays exponentially, and is eliminated at approximately the 25th period.

Figure 2.6 shows a case where the gain of the capacity controller K_c is *2/T*. This creates an oscillation in capacity, and the system is not stable. Figure 2.7 shows the response for the case where there is a delay of five days in adjusting the capacity. Such delay maybe necessary due to the logistics of making changes in overtime, temporary workers, number of work shifts, additional equipment, etc. The best response in this case is obtained replacing capacity control law $G_c(z) = K_c$ with a modified capacity control law

$$G_c(z) = \frac{K_c z}{z+1} \tag{2.13}$$

where $K_c = 0.2\ \text{scd}^{-1}$.

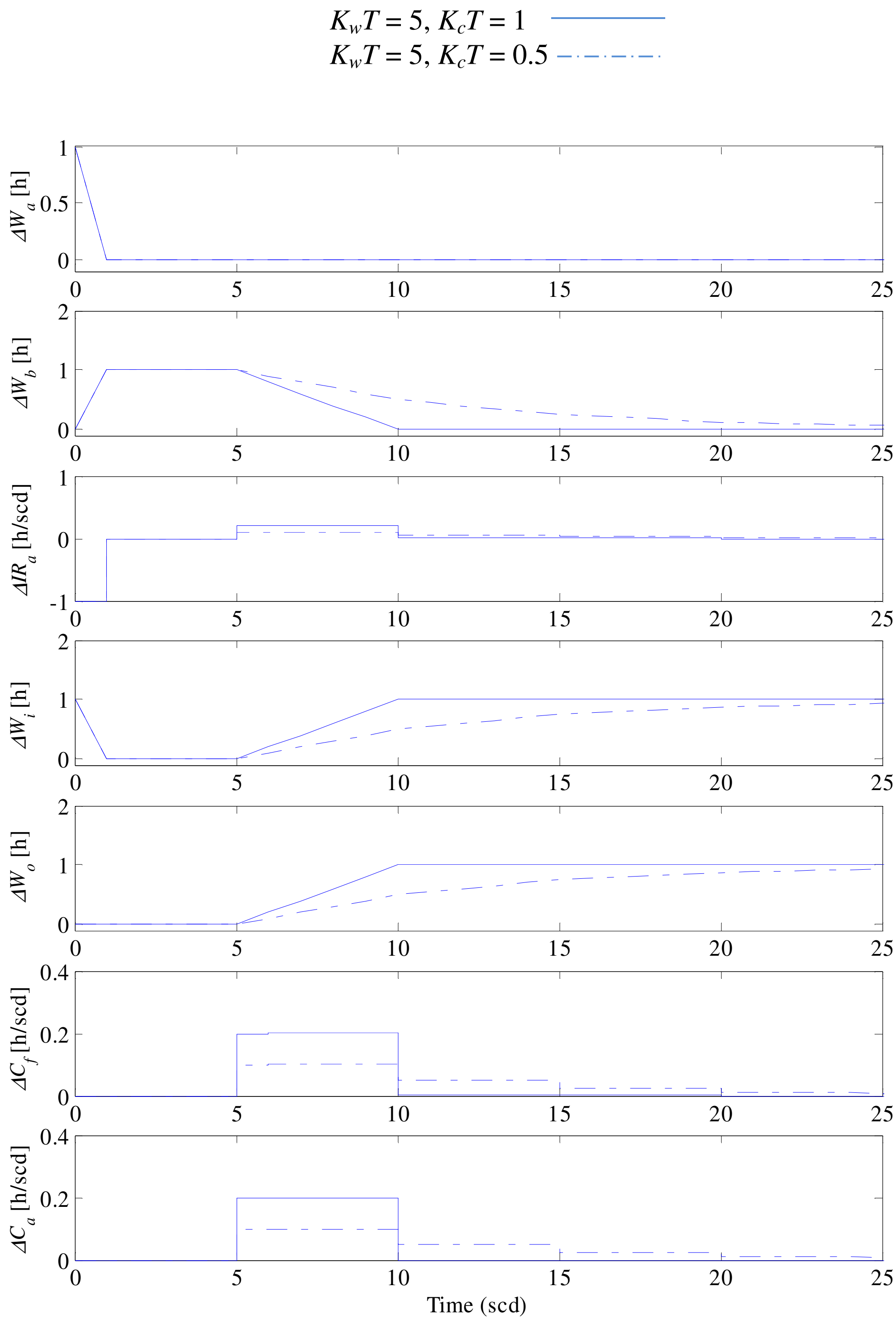


Figure 2.5: Time response of rush order when W_a>>W_{Ideal}

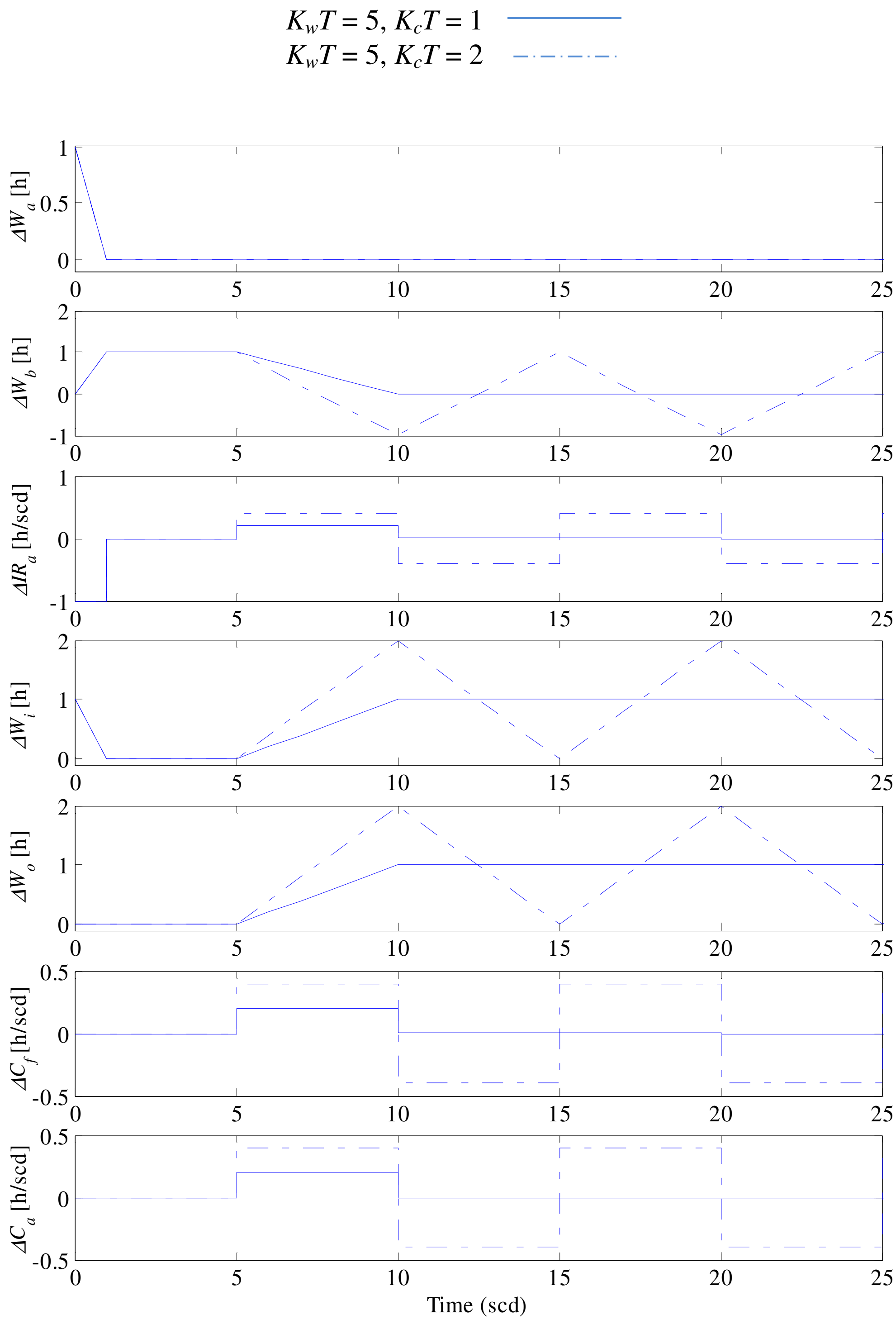


Figure 2.6: Time response of rush order when W_a>>W_{Ideal}

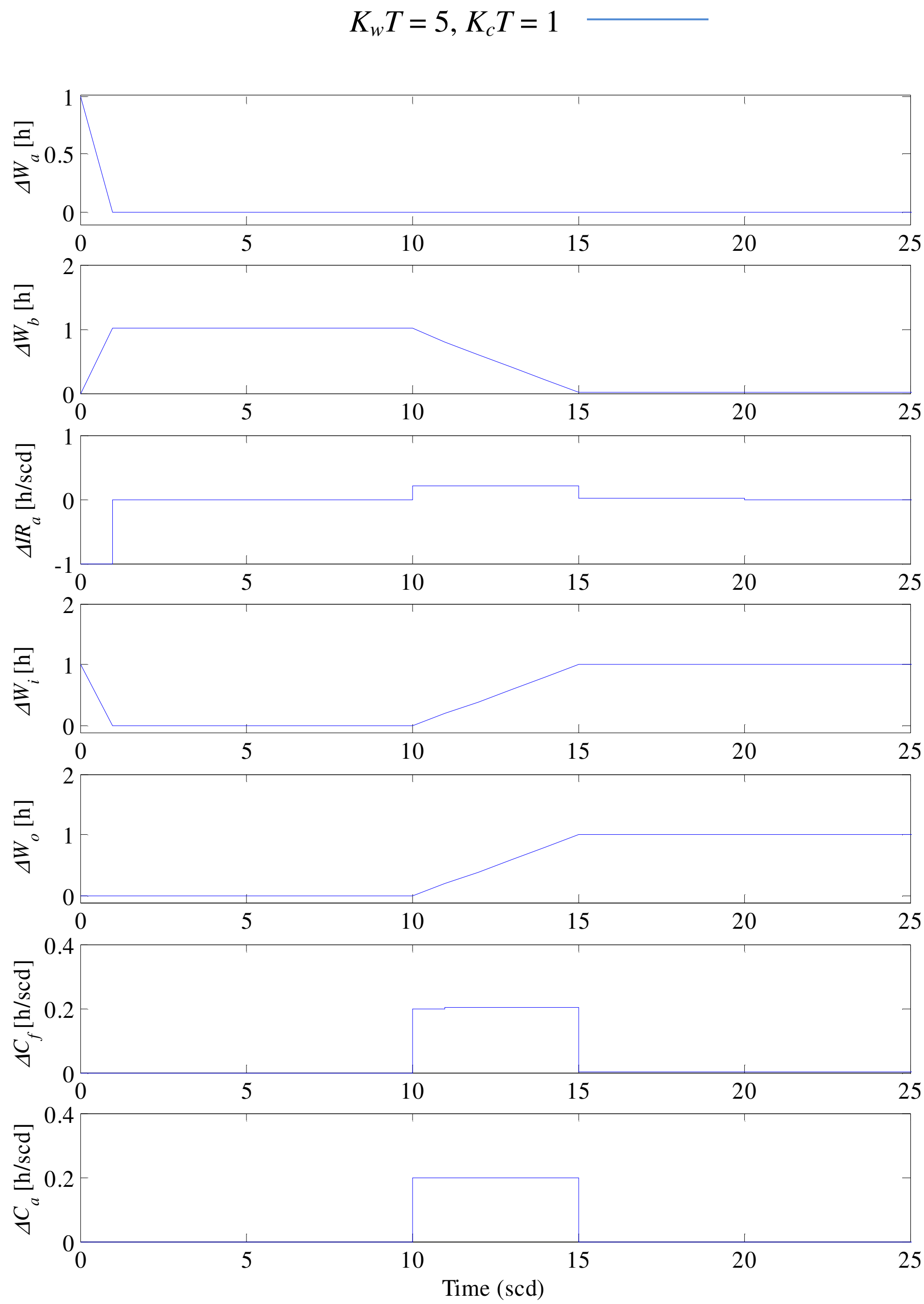


Figure 2.7: Time response of rush order when delay DT = 5scd for W_a>>W_{Ideal}

2.3 Closure

In this chapter, the structure of a closed-loop production planning and control system has been presented that includes control laws that adjust capacity in response to the backlog of work in the system and adjust work input as a function of desired work-in-progress. A control-theoretic dynamic model of the system has been developed that includes disturbances in capacity and work input that result from equipment failures, rush orders, etc. Transfer function analysis methods were used to obtain a dynamic model of the system that can be used to design the control laws necessary to achieve desired system performance, and to calculate the dynamic response of the system to planned and unplanned inputs without using simulation. Control-theoretic analysis also can be used to characterize stability, steady-state behavior and sensitivity to changes in system parameters.

In this chapter the modified-z transform method was used to derive the transfer equations for the multi-rate PPC system. The transfer equations and responses could be derived for different operating points in the logistic operating curve but the analysis presented was for the most common case of $W_a >> W_{Ideal}$. The next chapter reviews the distributed arrival time controller; the concept is introduced and its functionality is discussed. In Chapters 4 and 5 systems that integrate scheduling using the arrival time controller and WIP and due date deviation regulation, respectively, is presented.

Arrival Time Control (ATC) is reviewed in this chapter. The concept is adapted from the work of Prabhu [PRAB95a], and is largely unchanged except for the introduction of variable capacity and a variable mix of orders. The algorithm for arrival time control is based on integral control of individual order arrival times, which in this work are the times individual orders are released into the workstation queue.

The release time of an order to the workstation determines the sequence of order processing [DUFF96]. An arrival time controller can be embedded in each order entity that has the goal of meeting the order's due date by continuously adjusting its release time to the workstation. While other scheduling algorithms could have been used to determine the sequence and times of order releases, ATC was chosen because of its ability to continuously evolve and adapt release times in real time as capacity and hence order processing times are varied, and the mix of orders being scheduled continuously changes with time. The ATC algorithm is described here and will be used in the concepts for integrated capacity and release time adjustment presented in Chapters 4 and 5.

3.1 Arrival Time Control Algorithm

Figure 3.1 shows a simulated workstation linked to a real workstation. The simulation time scale is at least an order of magnitude faster than real time. In the simulated workstation, the status of the real workstation is used to initialize each time step of the simulation, and the adjustments made to order arrival times are used as the schedule in the real workstation. A controller is constructed for each order to control its arrival time, and predict resulting completion times, local performance and global performance. The objective of adjusting the arrival time is to complete the order as close as possible to its due date. However the orders must cooperate to improve the global performance even if this results in poorer individual performance of the order itself. In this heterarchical system, no order controls another, making the decisions distributed, and global information is reduced because the orders make decisions on based on their due date information.

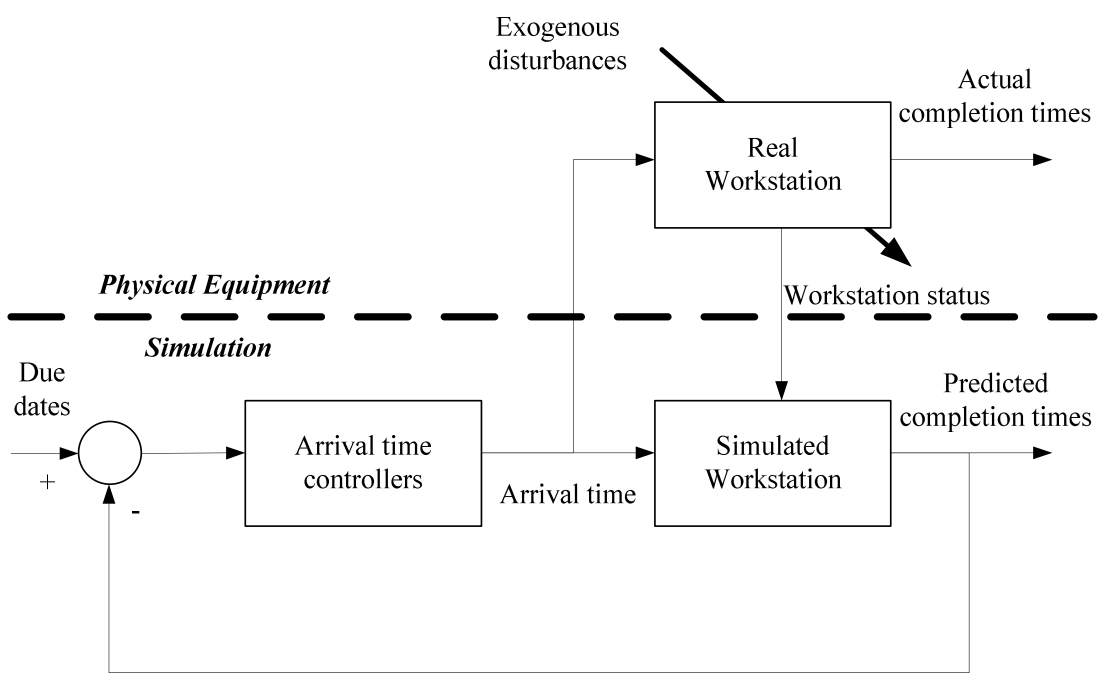


Figure 3.1: Closed loop arrival time control for workstation. (adapted from [PRAB95a])

For a system with n orders to be processed, Figure 3.2 shows the resulting n-dimensional multivariable control system. Due date is defined as the promised date for order completion, the due-date deviation is the difference between the due-date and the predicted completion time, the arrival time (or release time) is the time at which the order is released to the FCFS workstation queue, and the predicted completion time is the time at which the order is expected to be completed.

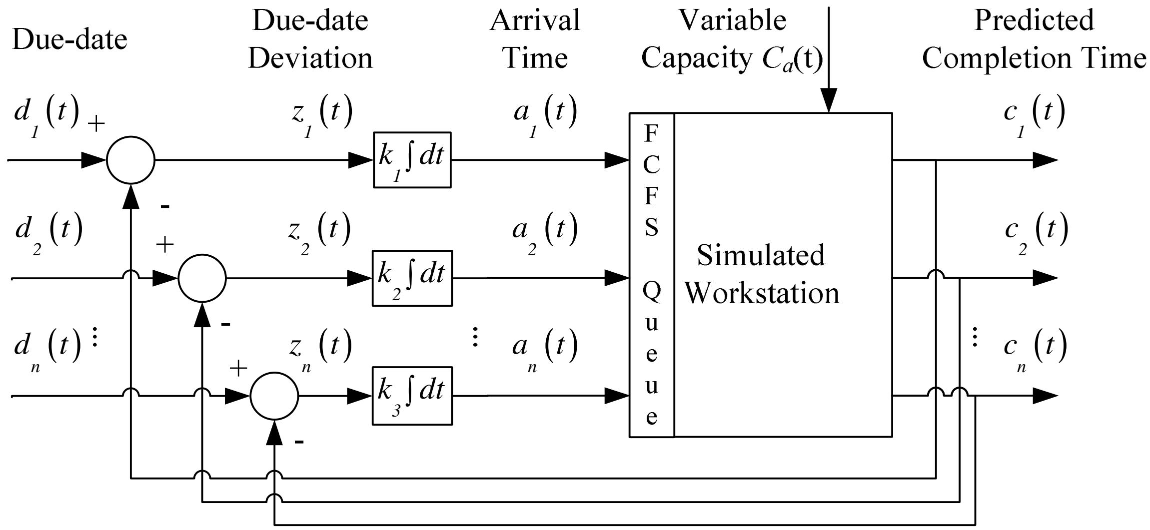


Figure 3.2: Arrival time controllers for n-order entities (adapted from [DUFF96])

The arrival times can change with each simulation, because the sequence in which orders are processed is determined by their position in the simulated queue. If there is contention for completion times then the orders entities will continuously adjust their arrival times to attempt to eliminate due-date deviation. The algorithm uses the best schedule found to release the orders to the workstation. The best scheduled is the schedule that provides the lowest average absolute due date deviation DDD_a, determined by the following formula:

$$DDD_a = \frac{\sum_{i=1}^{n} \left| d_i - c_i(t) \right|}{n} \tag{3.1}$$

where d_i is the order due date, $c_i(t)$ is the order completion time and n is the number of orders.

3.2 Arrival Time Control Dynamics

In this section an overview of dynamics the arrival time control is presented. Assumptions made in order to facilitate the analysis of arrival time control are:

- A First-Come-First-Served (FCFS) queuing discipline is used at the workstation.
- The workstation is available continuously for order being processed.
- Set up times and transportation times are not included.
- Due dates are known and constant.

Orders are processed in the sequence in which they are released to the workstation. If the arrival times of orders at the queue are not spaced appart according to their processing and completion times then the orders will interact at the queue.

The orders' processing sequence is determined by their arrival times at the queue. The first order to arrive does not incur waiting time; however, any subsequent orders may incur waiting time if the first order is still in the queue. The queue could have several fragments; however, this analysis focuses on one queue fragment.

Figure 3.3 shows the arrival time $a_{qi}(t)$, waiting time $q_{qi}(t)$, processing time $p_{qi}(t)$ and completion time $c_{qi}(t)$ of the i^{th} part in the queue. The completion time for the i^{th} part in the queue is expressed as

$$c_{qi}(t) = a_{qi}(t) + q_{qi}(t) + \frac{p_{qi}(t)}{C_a(t)} \tag{3.2}$$

where $C_a(t)$ is the capacity of the workstation, which can be adjusted by adjusting its numbers of workers, equipment, working hours, etc.

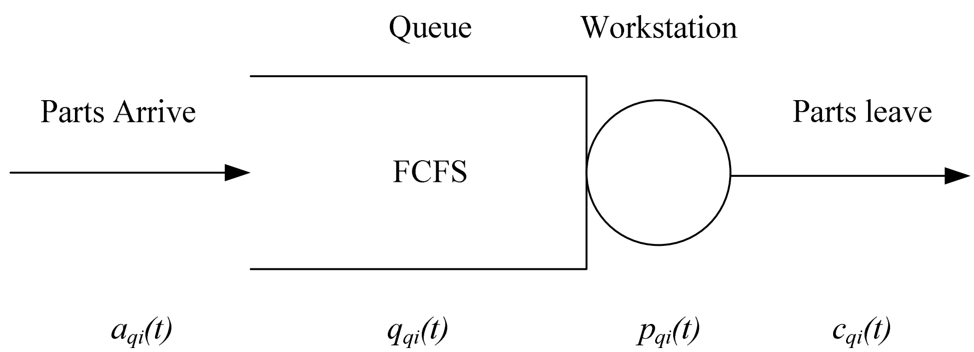


Figure 3.3: Parts interact via queuing (adapted from [PRAB95a])

The dynamic behavior of the ATC can be divided into three regions: decoupled, dead-zone and discontinuous. In the decoupled region, M_c, there is no interaction between the orders, waiting time in the queue is zero and due-date deviations are zero. This means that orders are completed at their respective due-dates. In the dead-zone region, M_z, two or more orders interact and at least one of the orders incurs waiting time. The partial derivative of the completion time of a waiting order with respect to its own arrival time is zero; this means that the completion of the order is not a function of its own arrival time but a function of the orders that are released earlier. In the discontinuity region, M_s, two or more orders have theoretically equal arrival times.

Figure 3.4 shows the different regions for a two-order one-workstation system. The line where $a_1 = a_2$ is the discontinuity region M_s, above this line $a_1 < a_2$ and the processing sequence is <1, 2>, below this line the processing sequence reverses. In the dead-zone region, the orders interact and the completion time of the second order is a function of the arrival time of the first order. In the decoupled region the orders do not interact because the second order is released after the first order is completed.

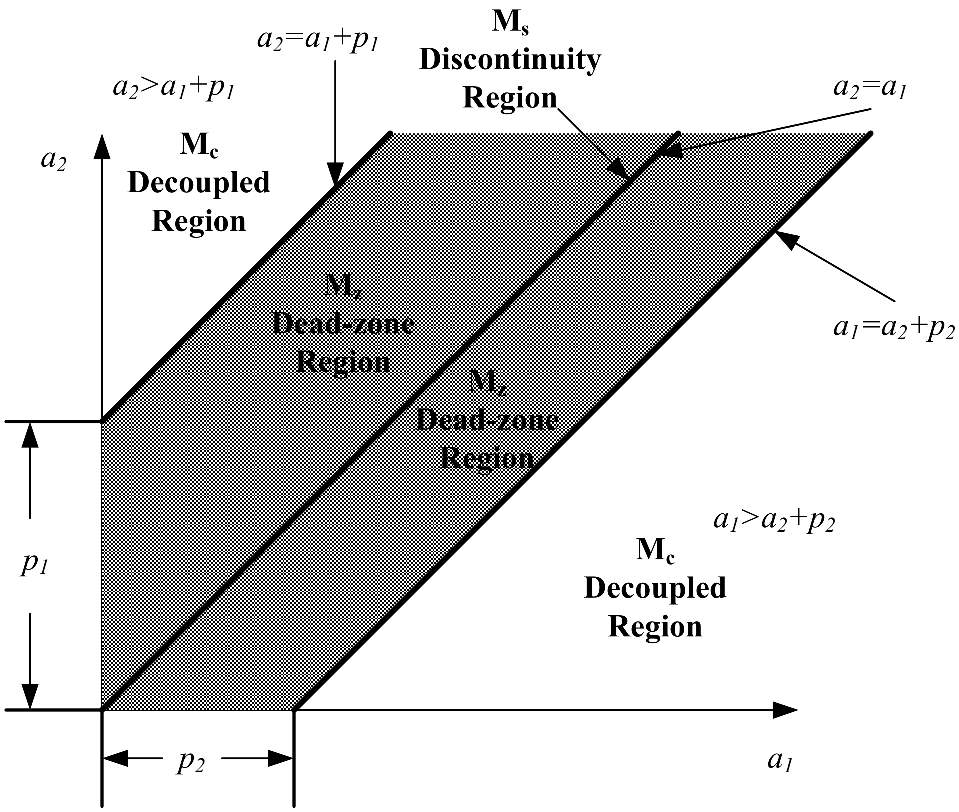


Figure 3.4: Illustration of various arrival time regions (adapted from [PRAB95a])

3.3 Integral control of arrival time

An integral control law is used in the ATC, and it is well known that for a constant disturbance input, error will asymptotically become zero [BOLL88].

$$a_j(t) = k_j \int_0^t \left(d_j(\tau) - c_j(\tau)\right) d\tau + a_j(0) \tag{3.3}$$

where k_j is the gain for the arrival time controller for the j^{th} order in the system and $a_j(0)$ is the initial arrival time. As shown in Figure 3.2, the closed-loop feedback from the simulated workstation provides the information necessary, in the form of the completion time, to adjust the manipulated variable, arrival time. When there is enough capacity to process all the orders on time the error will converge to zero at the steady state. However, when the capacity is not sufficient, the control implicitly adjusts the arrival time to equal, theoretically, the arrival time of other contending orders [Prab95a]. In this case, the common arrival time is a function of all the processing times and due dates, and infinitesimal deviations in arrival time determine the orders of part in the queue. When implemented in discrete rather than continuous form on a computer, the arrival times differ by finite but small deviations.

In the decoupled region the due-date deviations for constant due dates, processing times and workstation capacity are

$$z_1(t) = d_1 - a_1(t) - \frac{p_1}{C_a(t)} \tag{3.4}$$

$$z_2(t) = d_2 - a_2(t) - \frac{p_2}{C_a(t)} \tag{3.5}$$

$$z_j(t) = d_j - a_j(t) - \frac{p_j}{C_a(t)} \tag{3.6}$$

Substituting Equation (3.3) yields

$$z_1(t) = d_1 - k_1 \int_0^t z_1(\tau) d\tau - a_1(0) - \frac{p_1}{C_a(t)} \tag{3.7}$$

$$z_2(t) = d_2 - k_2 \int_0^t z_2(\tau) d\tau - a_2(0) - \frac{p_2}{C_a(t)} \tag{3.8}$$

$$z_j(t) = d_j - k_j \int_0^t z_j(\tau) d\tau - a_j(0) - \frac{p_j}{C_a(t)} \tag{3.9}$$

If the arrival times stay in the decoupled region

$$z_1(t)=\left(d_1-a_1(0)-\frac{p_1}{C_a(t)}\right)e^{-k_1 t} \tag{3.10}$$

$$z_2(t)=\left(d_2-a_2(0)-\frac{p_2}{C_a(t)}\right)e^{-k_2 t} \tag{3.11}$$

$$z_j(t)=\left(d_j-a_j(0)-\frac{p_j}{C_a(t)}\right)e^{-k_j t} \tag{3.12}$$

when $C_a(t)$ is constant. The responses are stable if $k_j > 0$ and the due-date deviation converges to zero as $t\rightarrow\infty$.

In the dead zone region, the due-deviations are

$$z_{q1}(t)=d_{q1}-k_{q1}\int_0^t z_{q1}(\tau)d\tau-a_{q1}(0)-\frac{p_{q1}}{C_a(t)} \tag{3.13}$$

$$z_{q2}(t)=d_{q2}-k_{q1}\int_0^t z_{q1}(\tau)d\tau-a_{q1}(0)-\frac{(p_{q1}+p_{q2})}{C_a(t)} \tag{3.14}$$

$$z_{qj}(t)=d_{qk}-k_{q1}\int_0^t z_{q1}(\tau)d\tau-a_{q1}(0)-\frac{(p_{q1}+p_{q2}+\ldots+p_{qi})}{C_a(t)} \tag{3.15}$$

This set of equations is valid for a processing sequence <1,2,…,j,…>, as long as the arrival times stay in the dead zone region

$$z_1(t)=\left(d_1-a_1(0)-\frac{p_1}{C_a(t)}\right)e^{-k_1 t} \tag{3.16}$$

$$z_2(t)=\left(d_2-a_1(0)-\frac{(p_1+p_2)}{C_a(t)}\right)e^{-k_1 t} \tag{3.17}$$

$$z_j(t) = \left(d_j - a_1(0) - \frac{(p_1 + p_2 + ... + p_j)}{C_a(t)} \right) e^{-k_1 t} \tag{3.18}$$

when $C_a(t)$ is constant. Note that infinitesimal differences in arrival time changes the order of parts in the queue and hence generate different schedules that a merit evaluator can choose from. In the discontinuous region, the arrival times of two or more orders are equal. The arrival time for the orders in the discontinuity region is:

$$a_j(t)_\infty = \alpha\left(1 - e^{-kjt}\right) + a_j(0)e^{-kjt} \tag{3.19}$$

This set of equations is valid for a processing sequence <1,2,…,j,…> and α is:

$$\alpha = \frac{\frac{p_1 z_1(t)}{C_a(t)} + \frac{p_2 z_2(t)}{C_a(t)} + ... \frac{p_j z_j(t)}{C_a(t)}}{\frac{(p_1 + p_2 + ... p_j)}{C_a(t)}} \tag{3.20}$$

when $C_a(t)$ is constant.

3.4 Closure

The Arrival Time Control (ATC) scheduling algorithm was reviewed in this chapter. Controllers in the ATC adjust order release times to improve the global performance, sacrificing local performance if necessary. By treating arrival time as a continuous variable, the dynamic behavior of discrete parts in the system can be modeled using differential equations for each of these regions of dynamic behavior: decoupled, dead zone and discontinuity. The exponential response behavior of the ATC will be observed in the next chapter where it is coupled to WIP regulation.

The arrival time controller adjusts arrival times to control the release of orders for production at a low level. These decisions are made at the local controller; however, the entities cooperate to improve the global performance of the system. The decisions made at this lower level do not incorporate planning decisions; decisions such as capacity, inventory and input rate. It will be shown in later chapters that these decisions, particularly adjustments in capacity, significantly affect the dynamics of the release of orders.

The production planning and control system described in Chapter 2 regulates WIP by controlling capacity, but does not address the scheduling of individual parts for production on a workstation. On the other hand, the arrival time control (ATC) described in Chapter 3 is a low-level scheduler that controls release time and the order of production of individual parts, but does not consider capacity.

The integration of the Production Planning and Control (PPC) system with the ATC system presents an opportunity to connect medium-level planning decisions with scheduling decisions made at a lower level. In this chapter, the integrated control system is presented; and its anticipated operation will be illustrated using data derived from a supplier for the automotive industry. The data is used in a discrete event simulation performed in Matblab®. The simulation illustrates the behavior of a system, with one processing step and one workstation, that integrates capacity and order release time controllers. A controller that adjusts capacity based on WIP levels is presented, and the effects of capacity adjustments on WIP levels and orders release times are investigated.

4.1 Integrated Production Planning Control System Topology.

In this section, the proposed topology for the integrated system is discussed and the modified arrival time controller is described, along with the information exchanged between mid-level management (i.e., the production department) and low-level scheduling (i.e., the shop floor). Figure 4.1 shows the structure of the proposed integrated distributed production control system; this model applies to any workstation in this system. At the planning level (mid-level management), capacity-related decisions are made. At the lower scheduling level, the arrival time controller uses the capacity levels provided by the planning system to determine the time that orders are released to the workstation buffer. Release time is defined as the time than an order leaves the ATC, and is placed in the buffer's (queue) workstation for production.

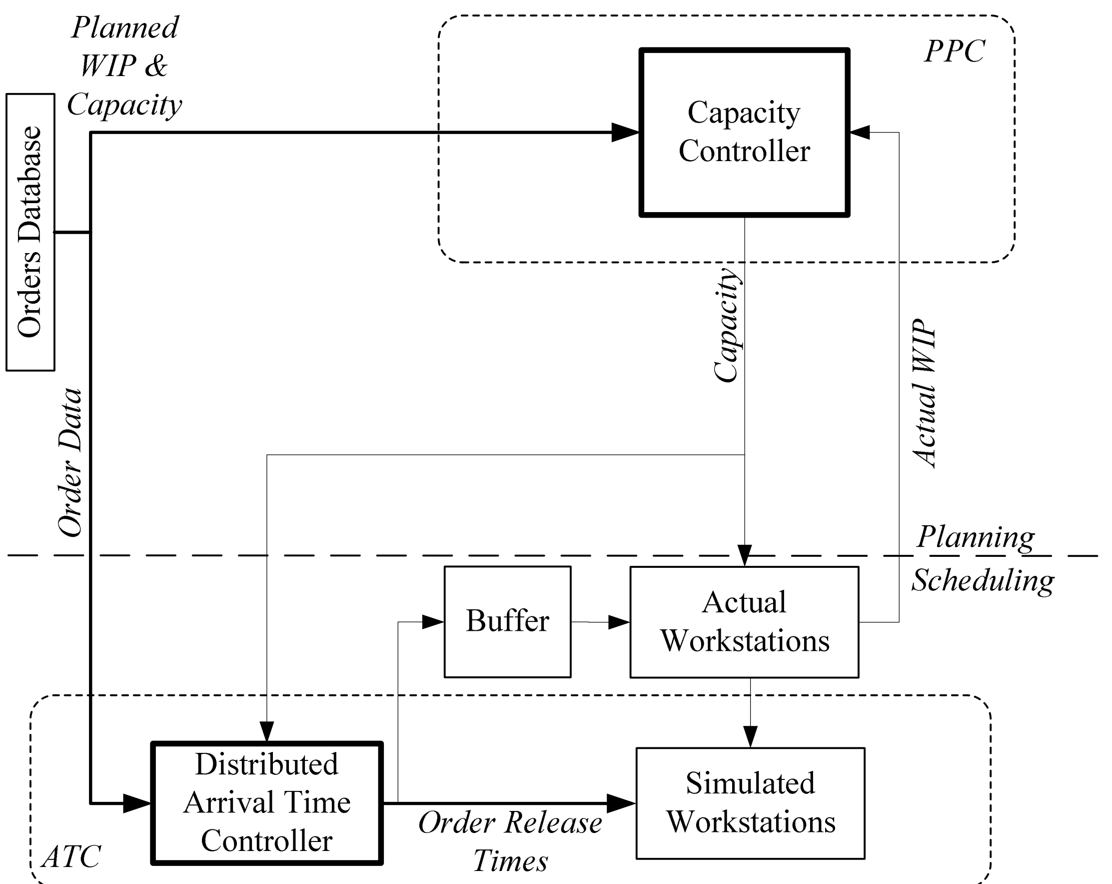


Figure 4.1: Integrated production planning control system

The database contains information on the set of incoming orders, as well as specifications about routing and processing times. This information is generated by other planning functions that are not shown and are outside the scope of this work. The database also contains the planned workstation WIP and capacity. This information is used by the PPC system to manipulate actual capacity.

The PPC passes the capacity needed for production to the ATC; and this value is then used by the ATC to determine the orders' release and expected completion times. The relationship between expected completion time and capacity is an important property deriving from the integration of these two systems. The PPC system adjusts actual capacity based on the actual WIP level in the workstation buffer. The orders that are not released for production remain in the ATC.

4.1.1 Discrete-Event Simulation for Workstation 2061

The results from the discrete-event simulation -- for which Matlab® was used -- of a production planning and control system integrated with an arrival time control are described in this section. The behavior of the integrated system was investigated by first simulating the system without capacity adjustments, and then with capacity adjustments based on WIP levels. Real data from an automotive production facility was used to run both simulations. Production data from a forging company that supplies components to the automotive industry were used to illustrate the behavior of capacity and WIP in one of the processing steps. The production data, listed in Appendix A, includes all the information needed to schedule the orders that go through the workstation. The parameters used in the simulation are: *Order Number*, *Order Start Date, Operation Sequence Due Date and Order Time Actual*, which are referred to here and in the simulation as order number, initial order release time, order due date and order processing time, respectively.

Production data for the workstation was chosen because it is the first workstation in the processing sequence of all orders that visit it, and the dynamics of this workstation are independent of dynamics of others workstations. Each initial order release time (to be modified later by the ATC), processing time, and due date was known in advance, as specified in the production data. Figure 4.2 shows a Gantt Chart based on the production data (see the Appendix). The chart is arranged by the orders' due dates; there are several instances during the production when the orders will contend for the workstation. This makes the schedule unfeasible, and the orders' release times will need to be modified in order to complete the orders as close to their respective due dates as possible. For example, Figure 4.3 shows a more in-depth view of days 160-170 where many of the orders have the same due date.

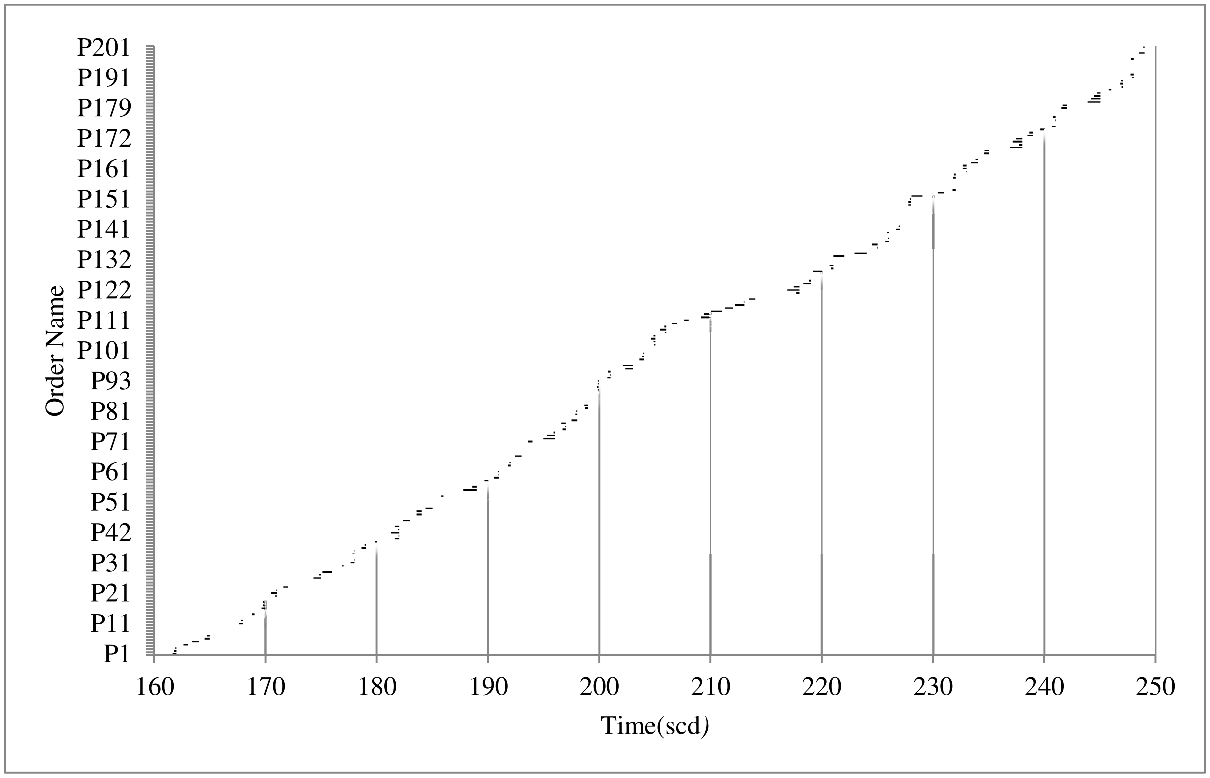


Figure 4.2: Order due dates and processing times

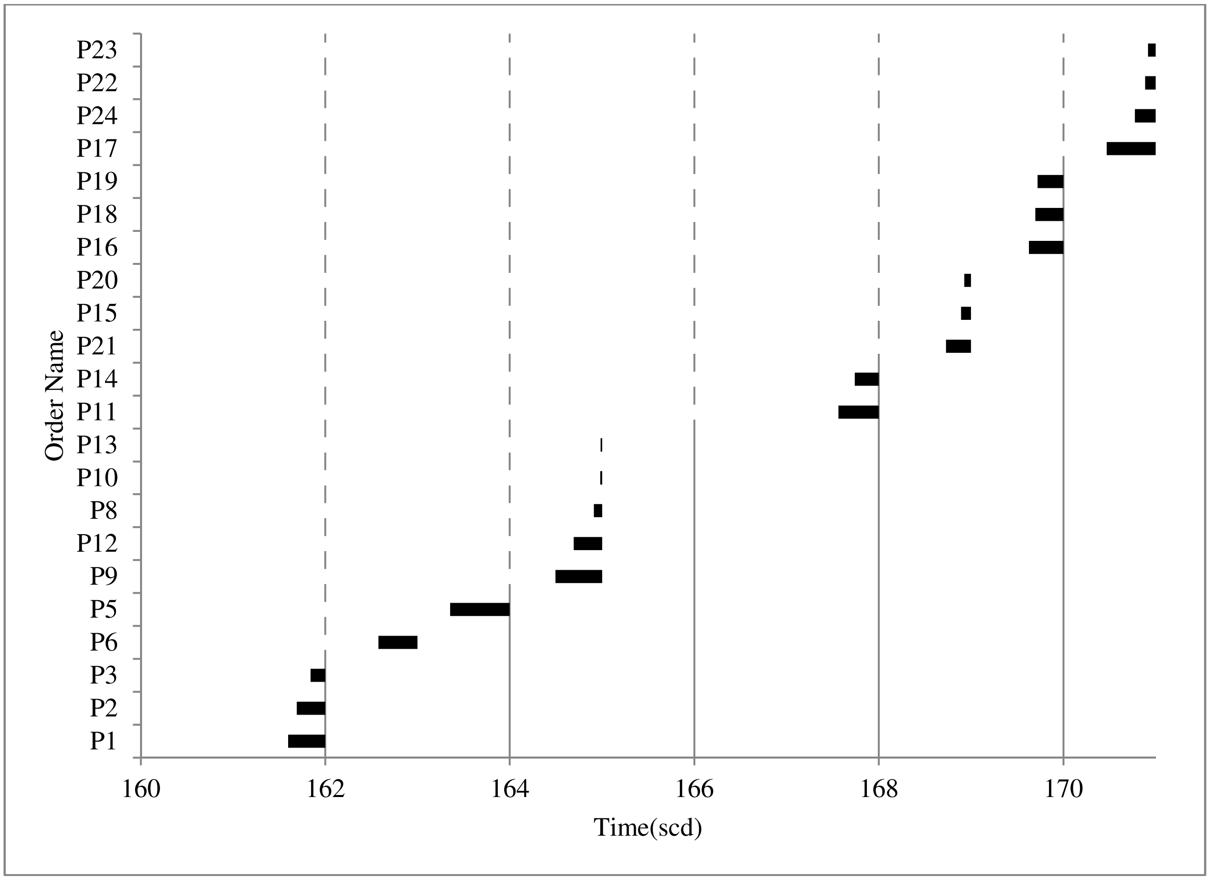


Figure 4.3: Order due dates and processing times, for days 160-170

Figure 4.4 shows the actual WIP based on the orders' due dates in the production data. Due to the contention of orders in the system, some of them are required to wait in the queue for the resource to become available. The data shows several instances where the WIP exceeds 40 hours of work.

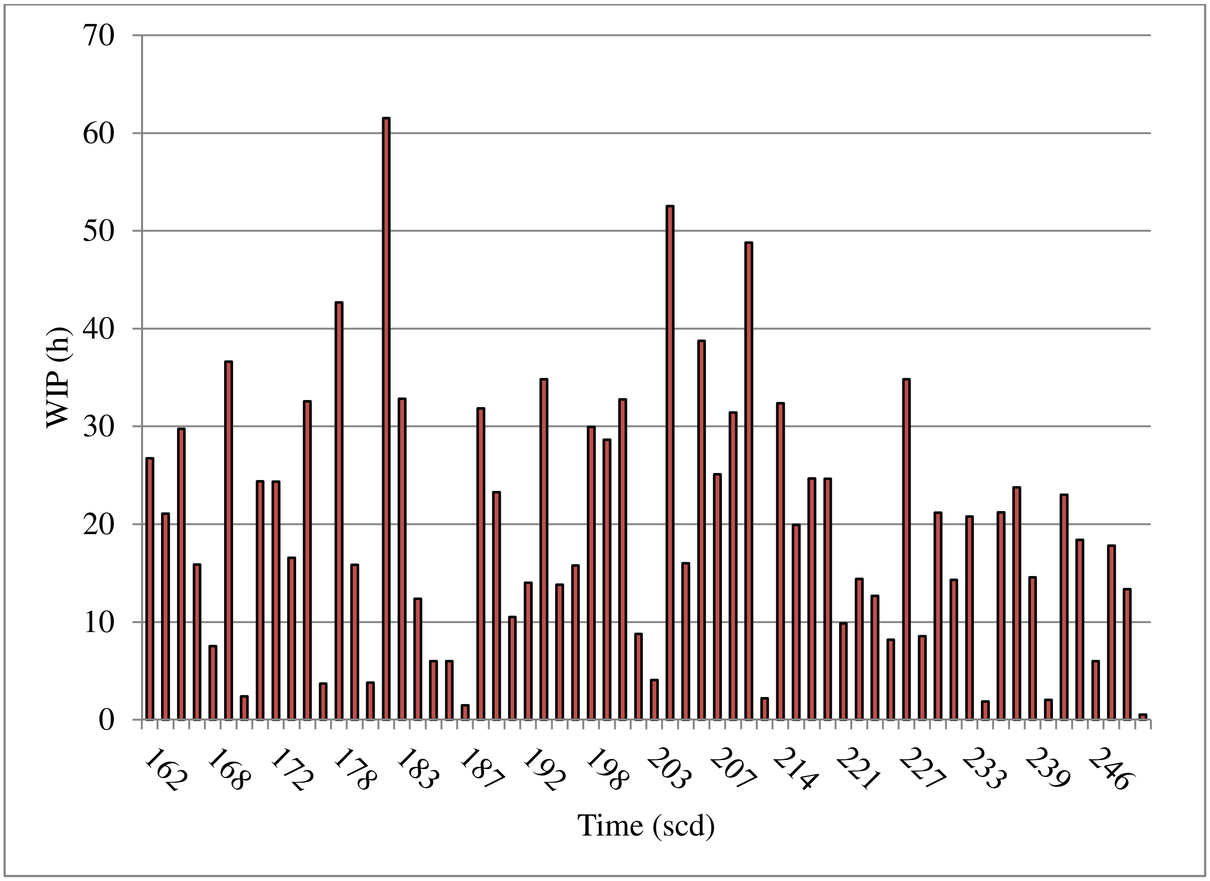


Figure 4.4: WIP in Workstation 2061

Table 4.1 shows a summary of the data for Workstation 2061. The average capacity was calculated as the average of the amount of work done each calendar day using the order processing times and days in production.

Table 4.1: Summary of data for Workstation 2061

Orders Completed	221
Average Capacity (h/scd)	18.22
Average WIP (h)	19.93

The parameter values listed in Table 4.2 were used in the simulation and the following assumptions were made:

- Orders have one processing step. Orders can be partially completed in a day, and work resumes, at the beginning of the next shop calendar day.
- Setup and transportation times are not considered.
- Capacity can be added without limits.
- Capacity is adjusted at the beginning of each work period.
- The initial WIP is zero.
- Order due dates and processing times are constant.
- Rush orders are handled as soon as the workstation becomes available and the order being worked on is completed.

Table 4.2: Parameters used in the simulation.

	Parameter	Value
WIP Disturbance	W_d	0 [h]
Capacity Disturbance	C_d	0 [h/scd]
Delay	d	1 [scd]
WIP regulation Sampling Rate	T	1 [scd]
ATC Rate	$T/100$	0.01 [scd]
ATC Gain	K_i	0.1

4.1.2 Regulation of WIP using fixed planned capacity

Figure 4.5 shows the control-theoretic topology of the integrated production system, which shows the relationships between the variables in the PPC (planning) and the ATC (scheduling). There are two main portions: planning and scheduling. The top half of the figure represents planning, where capacity calculations and adjustments, at a sample rate of *T*, are done. The bottom half of the figure represents scheduling, where the ATC resides and works continuously by adjusting the release time of the orders in order to complete them as close to their due dates as possible. The ATC provides the planning portion with the actual WIP, $W_a(kT)$.

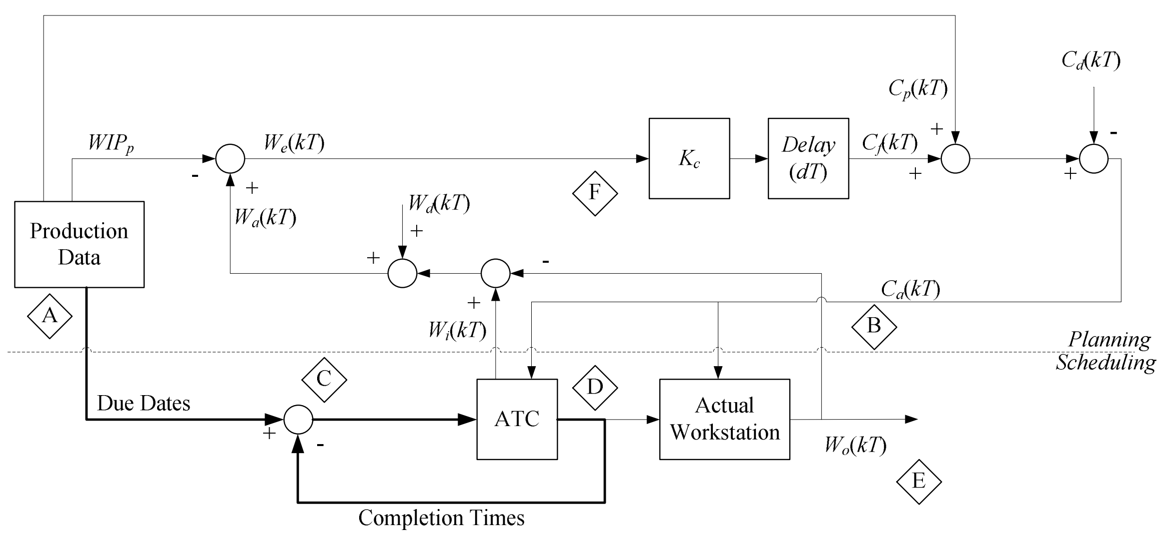


Figure 4.5: Topology for WIP regulation using fixed planned capacity

Marker A

The production data contains all the information used by the capacity controller and the ATC. This includes the planned capacity, WIP_p, as well as the orders that need to be produced at the workstation. The orders that are placed in the ATC are selected according to their due dates, with the orders selected having the order due dates within the next ten working days.

Marker B

The capacity is adjusted according to the error in WIP $W_e(kT)$ (see marker F). A proportional controller with gain K_c was used, and the adjusted capacity was calculated using:

$$C_a(kT) = C_p(kT) + K_c W_e(kT - dT) - C_d(kT) \tag{4.1}$$

where $C_p(kT)$ is the planned capacity in (h/scd) and $C_d(kT)$ is any capacity disturbance such as workstation failure, the gain K_c is chosen using the following equation [DUFF10]:

$$K_c = \frac{d^d}{T(d+1)^{(d+1)}} \tag{4.2}$$

where d determines the delay in adjusting capacity (delay=dT, where d is a non-negative integer).

Marker C

The production data contains order due dates; these are used to calculate the due date deviation as discussed in Chapter 3. The ATC uses this information to adjust order release times.

Marker D

The schedule is continuously determined in the ATC using the work content of the orders in the database and the adjusted capacity $C_a(kT)$. Once the release time of the order is reached in real time, the order is released for production and placed in the workstation queue. The actual WIP, $W_a(kT)$, is

$$W_a(kT) = W_i(kT) - W_o(kT) + W_d(kT) \tag{4.3}$$

where $W_o(kT)$ is the total work that has been done by the workstation, $W_d(kT)$ is any external disturbance in WIP and $W_i(kT)$ the total work in is

$$W_i(kT) = \sum_{i=1}^{m_i} p_i \tag{4.4}$$

where m_i, orders have been placed in the queue, and p_i is the processing time of the i^{th} order placed in the queue.

Marker E

Every time an order is completed the actual work output $W_o(kT)$ increases by the magnitude of the completed order's processing time, p_i. The total work done by the workstation up to time kT

$$W_o(kT) = \sum_{i=1}^{m_o} p_i \tag{4.5}$$

where m_o orders have been completed by the workstation.

Marker F

The error in WIP, $W_e(kT)$ is used to adjust capacity $C_a(kT)$ in the workstation (see Equation (4.1)).

$$W_e(kT) = W_a(kT) - WIP_p \tag{4.6}$$

where WIP_p is the planned WIP

4.2 Results with Capacity Fixed at Planned Capacity C_p

The behavior of the workstation without capacity adjustments was investigated first. In this case, the capacity was fixed at $C_a(kT)$ = 18.22 (h/scd) and the ATC scheduled the release times of orders using this fixed capacity. Figure 4.6 shows the release times for the orders that were processed. At the beginning of each work week, orders were placed in the ATC, and once this is done, the release times were adjusted to reduce their due date deviation as explained in Chapter 3. Marker A, identifies one of the orders that was initially planned to be released some 20 scd earlier than its due date.

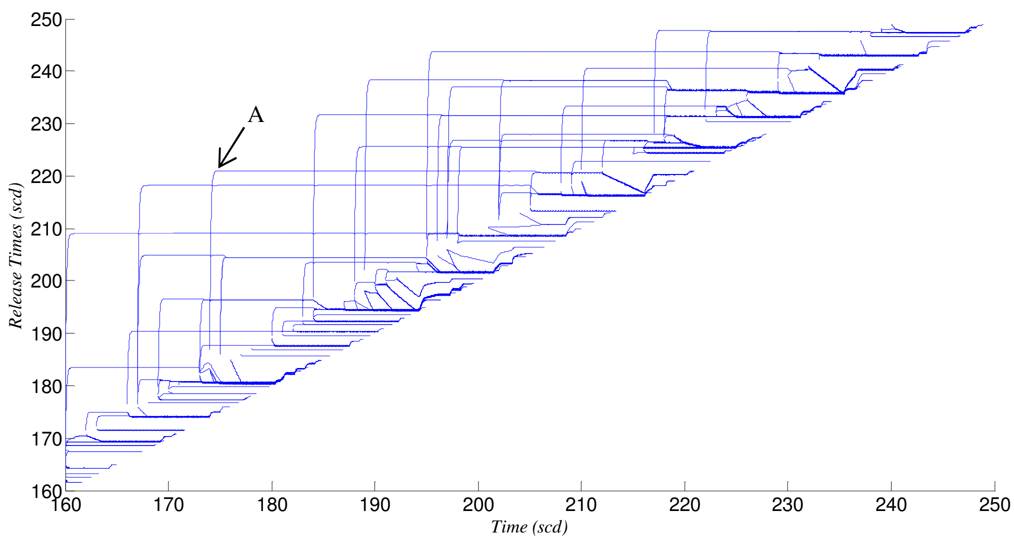


Figure 4.6: Order release time with fixed capacity

Figure 4.7 more clearly shows the dynamic behavior of order release times for the period 190 to 195 scd. At marker B, two orders contend for resources in the ATC. Their release times converge and their subsequent trajectories are in a discontinuous state because of the unfeasibility of their due-dates. At marker C, there is an order that is in a decoupled state; its due date does not conflict with any other order in the system and it is released at the proper release time. At marker D, there are multiple orders contending for resources in the ATC; these orders have unfeasible due-dates. As production progresses, one of these orders is placed in the workstation queue at approximately 194.4 scd, and this creates some relaxation in the contention of the orders and the remaining orders converge to a later release time; however, it can be observed there is still contention between the orders.

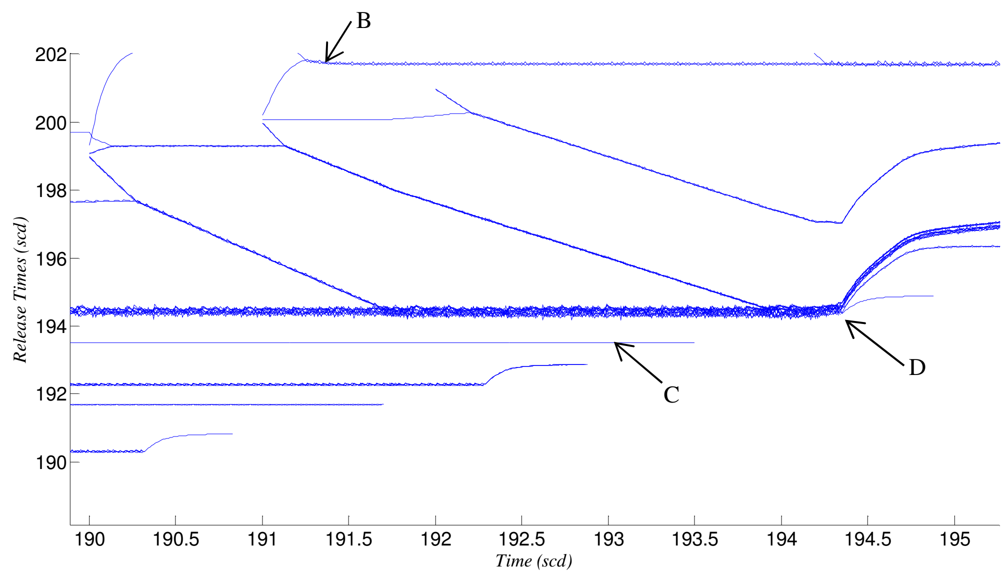


Figure 4.7: Order release time with fixed capacity

Figure 4.8 shows a plot of the actual capacity, $C_a(kT)$, which is the actual work done by the workstation during the day. There is no production in the first 16 periods because processing of orders is initially inhibited until WIP in the workstation reached 160 h. The workstation works at full capacity, 18.22 (h/scd), at all times, as long as there are orders in the workstation queue.

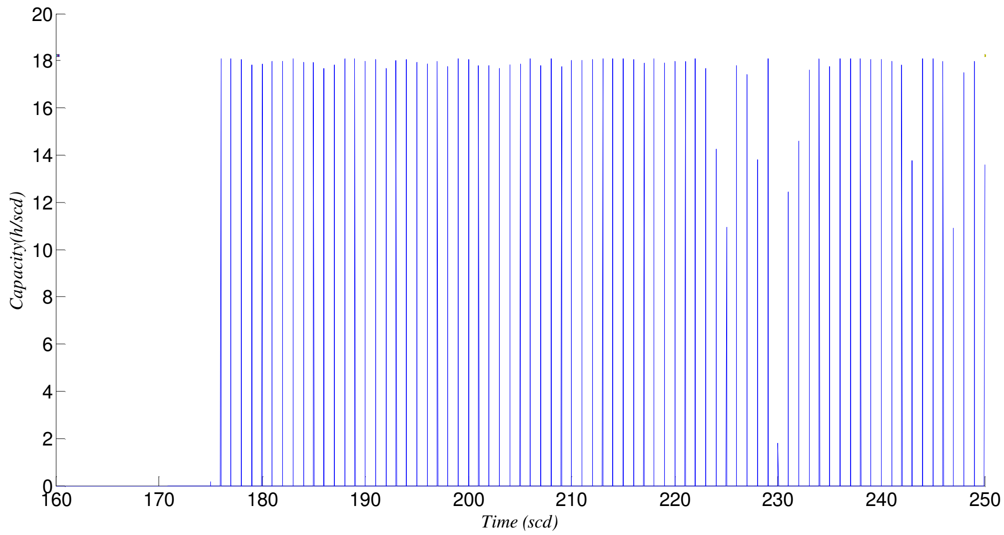


Figure 4.8: Capacity vs. time with fixed capacity

Figure 4.9, shows WIP as a function of time, in the first 16 periods, order processing is inhibited while WIP builds to 160 h. After order processing starts, WIP is slowly depleted because there is no capacity control to reduce production in the workstation. Figure 4.10 is a plot of the lead time, which is calculated in the discrete event simulation using the following formula:

$$LT(kT) = \frac{W_a(kT)}{C_a(kT)} \tag{4.7}$$

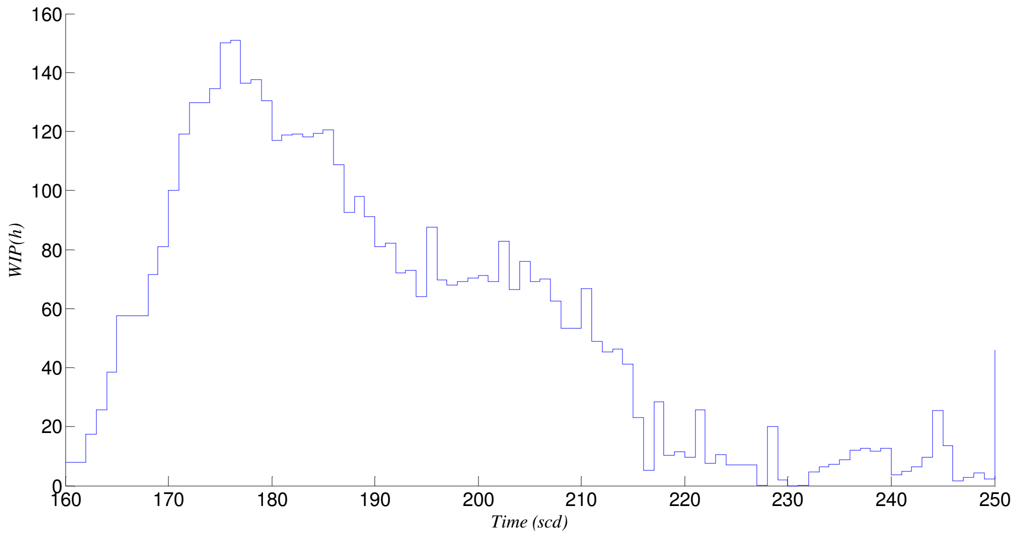


Figure 4.9: WIP with fixed capacity

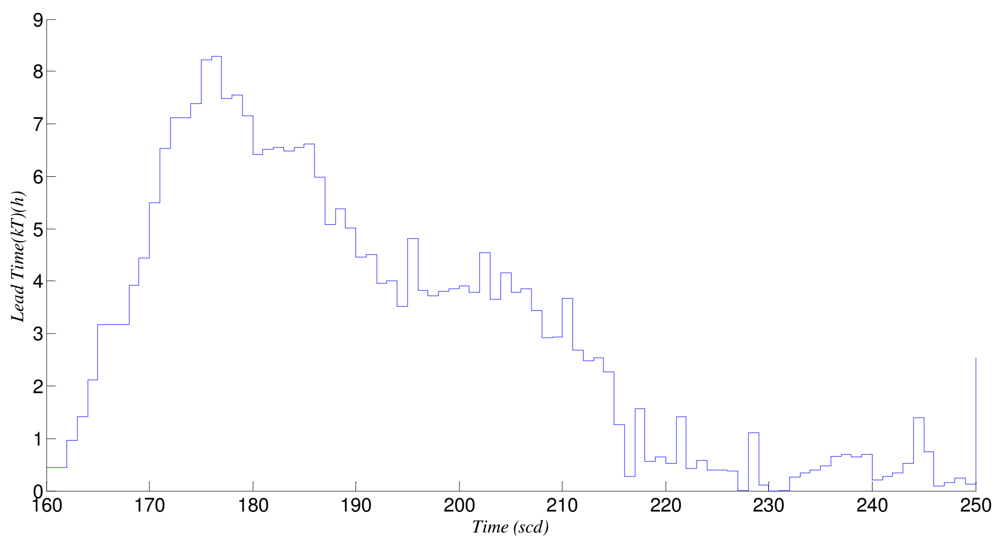
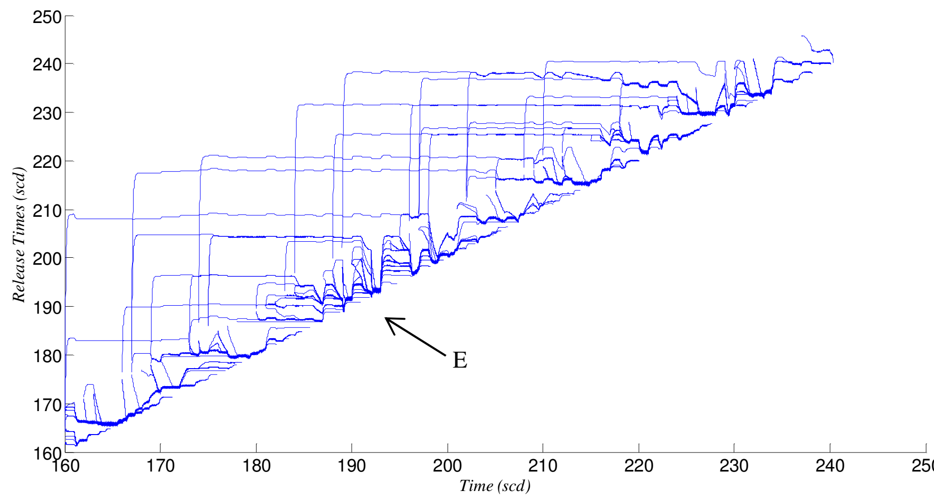


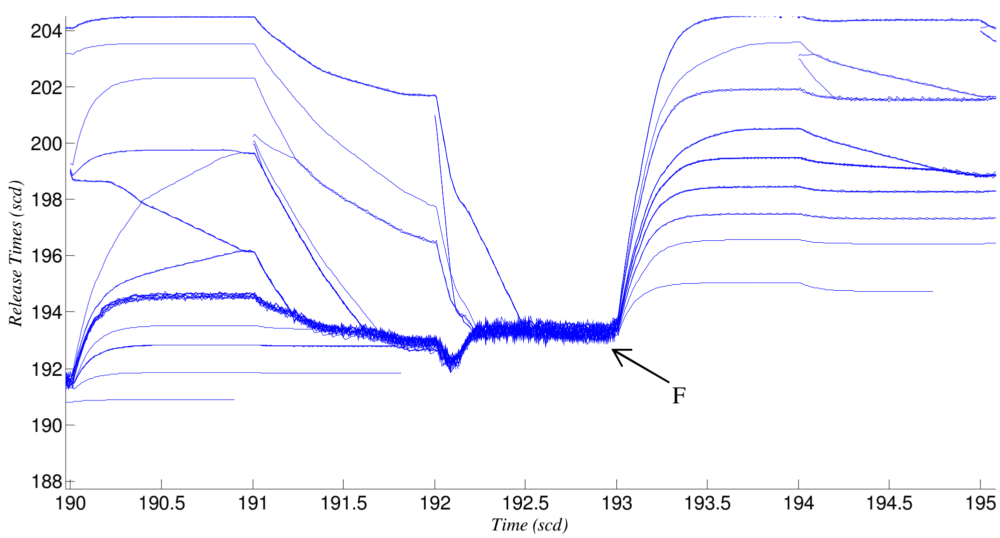
Figure 4.10: Lead time with fixed capacity.

4.3 Results with WIP Regulated by Adjusting Capacity

Marker E in Figure 4.11a an example the effects of capacity adjustments on the trajectory for the order release time, which can be seen more clearly in Figure 4.11b; these fluctuations in the trajectory in Figure 4.11a are not present in Figure 4.6, because in the latter case the capacity is constant. As the capacity decreases, the order release times tend to become more discontinuous and converge to a lower value of arrival time, placing some orders in the workstation queue at an earlier time as shown in Marker F in Figure 4.11b. This causes an increase in WIP, causing an increase in capacity in order to adjust for the deviation from planned WIP. There is an increase in contention when comparing Figure 4.11a with Figure 4.6. Figure 4.12 shows the variation in workstation capacity with time. The average system capacity is 16.8 h/scd, which is less than $C_p(kt)$ = 18.22 h/scd. Figures 4.13 and 4.14, shows variation in WIP and lead time vs. time, respectively. Average WIP is 136.13 h, which is less than planned because the average capacity required is slightly less than planned.



(a)



(b)

Figure 4.11: Order release time (delay, d=1)

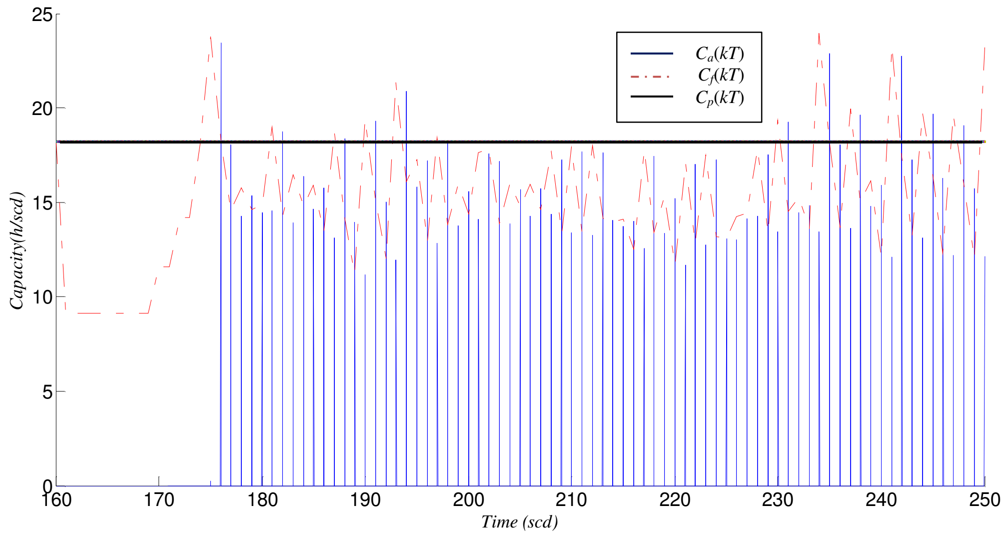


Figure 4.12: Capacity (*delay, d = 1*)

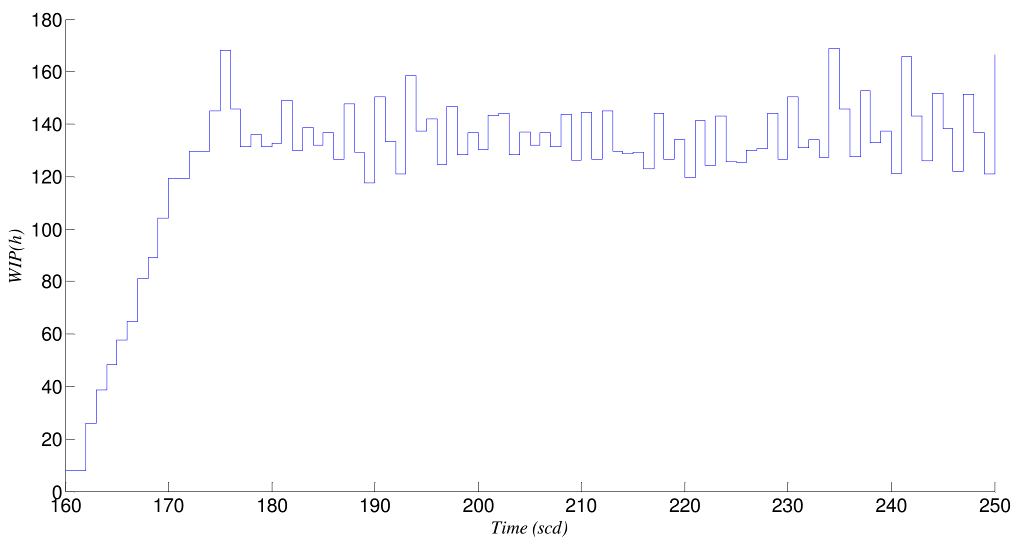


Figure 4.13: WIP (*delay, d = 1*)

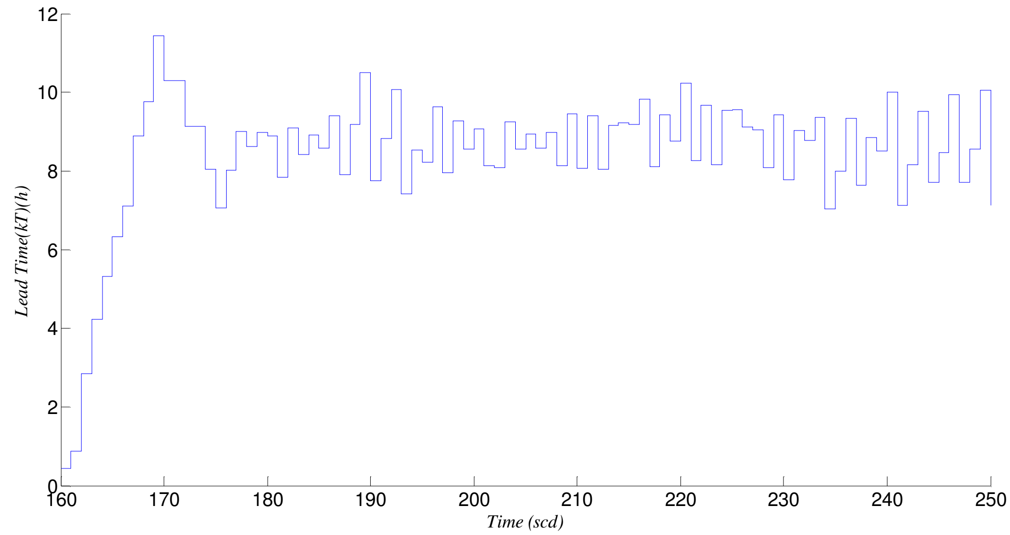


Figure 4.14: Lead Time (*delay, d = 1*)

4.4 Closure

A method was presented in this chapter for extending the arrival time controller to accommodate variable capacity and linking it to a higher level planning controller, effectively integrating planning with scheduling. The behavior of the integrated system was illustrated using a discrete-event simulation with one workstation and one processing step. Table 4.3 and Table 4.4 summarize the overall results obtained with and without WIP regulation using capacity adjustment.

The system without WIP regulation runs at a higher capacity, which tends to drive the ATC to a decoupled state. If contention is minimized the orders are released at the right time for production. The system with WIP regulation manages the resources better while controlling lead time and inventory but, by decreasing the capacity, the contention of the order release times increases thus increasing the average absolute due date deviation. This leads to consideration of a different architecture based on due date deviation regulation, which will be investigated in the next chapter.

Table 4.3: Averages with and without WIP regulation

WIP regulation	DDD_a(scd)	Lead Time (scd)	$C_f(kT)$(h)	$C_a(kT)$(h/scd)	$W_a(kT)$(h)
With	7.21	8.75	15.81	15.50	136.13
Without	0.33	2.42	18.22	17.16	44.17

Table 4.4: Variances with and without WIP regulation

WIP regulation	DDD_a (scd)	Lead Time (scd)	$C_f(kT)$(h)	$C_a(kT)$(h/scd)	$W_a(kT)$(h)
With	2.31	0.63	8.11	6.75	129.77
Without	0.04	4.53	0.00	6.17	1505.16

In the previous chapter a control architecture that integrates low-level distributed scheduling of orders and higher level production planning decisions was presented. The system was illustrated using a discrete event simulation, in Matlab®, with one machine and one processing step using real data derived from a supplier of the automotive industry, system capacity was controlled by regulating inventory. It was shown that the ATC is able to provide a schedule with lower due date deviation by completing the orders as close as possible to their due-dates; however, the controller makes adjustment based solely on WIP deviations, and not by considering the due date deviations in capacity adjustments.

In this chapter a control-theoretic order due date deviation regulation topology is presented for workstations that dynamically adjust their capacity and order release times. The relationship between average absolute due date deviation and workstation capacity is shown to be nonlinear and time varying, and a method is presented for characterizing the relationship quantitatively in real time. This information then is used in adaptive capacity adjustment control laws that maintain favorable dynamic behavior with the presence of the nonlinearities. The goal is to ensure quick yet stable response in real time in the presence of time-varying demand and order contention. Control theoretic analyses are included in the paper for predicting and illustrating the dynamic behavior of average absolute due date deviation and workstation capacity.

First, a discrete system model is presented along with the equations used to regulate due date deviation (DDD) and adjust capacity. Then, the relationship between capacity and average absolute due date deviation is investigated, and control theoretic analysis is used to provide guidance for setting parameters in DDD regulation. A discrete event simulation of DDD regulation driven by industrial data is described, and results obtained are used to illustrate the dynamic behavior of DDD regulation.

5.1 Discrete System Model with DDD regulation

In this section a control theoretic topology is presented for adjusting the release time of orders to a workstation by adjusting capacity while considering due date deviation. Figure 5.1 shows a block diagram for due date deviation regulation. In the diagram, the database contains incoming order information including name, due date and processing time. This information is sent to the scheduler where an appropriate algorithm is used to determine the release time for each order into the actual workstation's first-in-first-out queue and hence the order processing sequence.

A model of the workstation within the scheduler is used, for a given set of order release times, to compute the predicted completion time $c_i(kT)$ for each order, the due date deviation for each order, and the actual average absolute due date deviation $DDD_a(kT)$ for all orders currently being scheduled, which is then used as the feedback for making capacity adjustments:

$$DDD_a(kT) = \frac{\sum_{i=1}^{m} \left| d_i - c_i(kT) \right|}{m} \tag{5.1}$$

where d_i is the due date for order i, m is the total number of orders being scheduled, T is time period between capacity adjustments and k =0,1,2,3,…. Average absolute value of due date deviation is used as a straightforward measure of contention of orders for the workstation resource, where work has units of shop calendar days, scd. If $DDD_a(kT)$ is greater than the planned average absolute due date deviation DDD_p, it is desirable to increase capacity in order to complete orders closer to their due dates. On the other hand, if $DDD_a(kT)$ is less than the planned average absolute due date deviation DDD_p, it is desirable to decrease capacity in order to increase average absolute due date deviation. While obtaining zero average absolute due date deviation would be ideal, this is not possible if due dates are identical, and requires unrealistically large capacities depending upon the mix of processing times and due dates when no due dates are identical. Therefore, a reasonable $DDD_p>0$ is selected.

The workstation's production capacity $C_a(kT)$ is adjusted using the following equation, which has an integrating effect:

$$C_f(kT) = C_f((k-1)T) + K_c(kT)\left(DDD_p((k-d)T) - DDD_a((k-d)T)\right) \tag{5.2}$$

$$C_a(kT) = C_f(kT) - C_d(kT) \tag{5.3}$$

where $K_c(kT)$ is an adjustable due date regulation gain, dT is a time delay in adjusting capacity (d is assumed to be a positive integer) and $C_d(kT)$ is any unexpected capacity disturbance such as equipment failure or worker absenteeism.

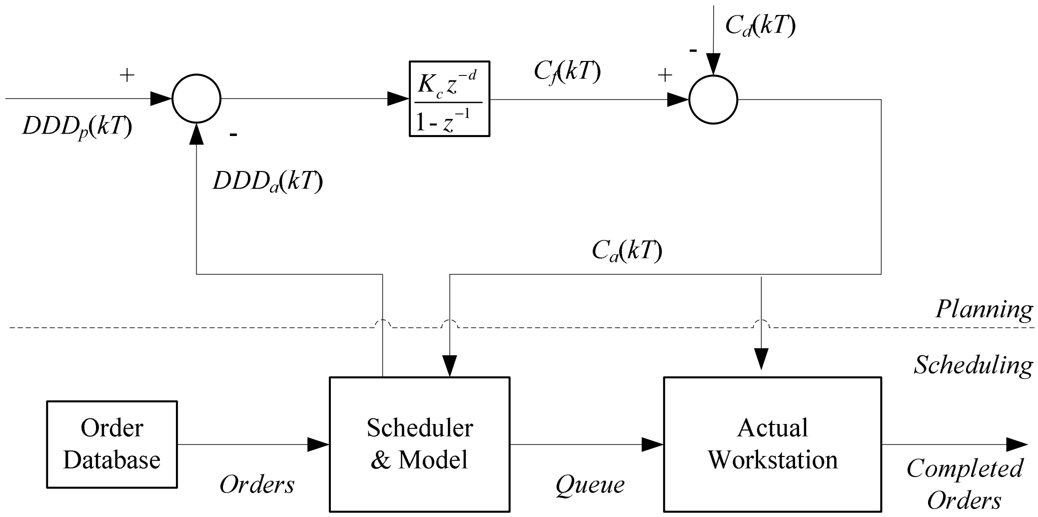


Figure 5.1: Dynamic model for due date deviation regulation for a given K_c

Figure 5.2 is a representation of the model used to process orders. The orders come from a database and they are placed in a scheduler. Once an order is scheduled for production, the order is placed in the workstation queue. The actual average absolute due date deviation of all the orders can be obtained in the scheduler using Equation (5.1). The difference between planned absolute due date deviation and actual average absolute due date deviation is integrated over time, thus eliminating error by driving the system to the needed capacity. The actual average absolute due date deviation a function of the capacity of the system; with low capacity, orders take longer to complete, increasing due date deviations on the other hand with high capacity orders are completed closer to their due date, decreasing average absolute due date deviation.

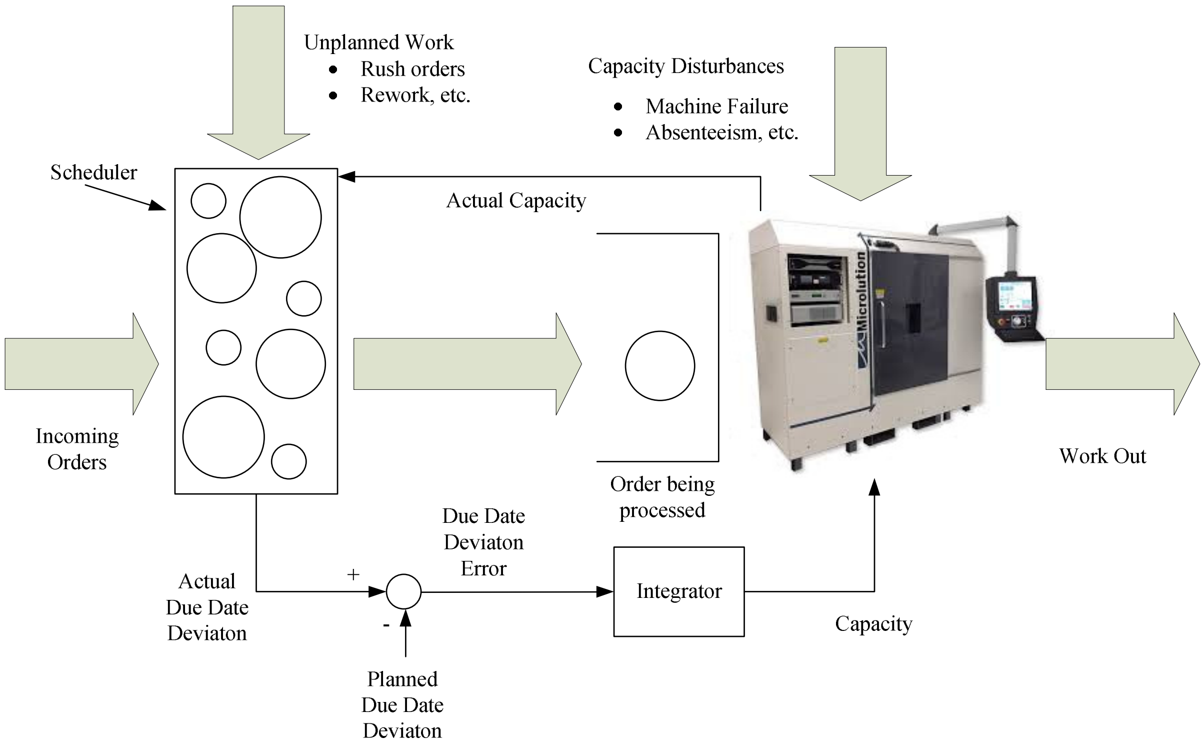


Figure 5.2: Model of a single workstation with a scheduler

5.1.1 Three order production example

Listed in Table 5.1 is the processing information for an example of three orders contending for the same resource. The information that the order carries is an example of the order name (O_i), initial release time (a_i), due date (d_i) and processing time (p_i). The ATC, as described in Section 3.1, works to adjust the release times in order to provide sequences that improve the average absolute due date deviation in the system. Initial capacity, $C_a(0)$, is 5 h/scd and this is not enough capacity to complete the orders on time, causing the release time to converge.

Table 5.1: Three orders production data.

Order Name	Initial Release Time (a_i) (scd)	Due Date (d_i) (scd)	Processing Time (p_i) (h)
O_1	140	161	20
O_2	145	162	20
O_3	165	163	30

For the three orders in Table 5.1, Table 5.2 shows the results of calculations for the first three iterations of the ATC. It is shown in Table 5.2, how the average absolute due date deviation decreases with time. The expected completion time is calculated and used to obtain the due date deviation. Order release time is adjusted to complete the orders as close as possible to their due dates.

As the ATC works to improve the average absolute due date deviation, the orders' release times converges because a capacity of 5 h/scd is not enough to process all the orders in time since the due dates are close to each other. The following equation determines the final theoretical release time for the three orders.

$$a_{123}(kT)_\infty = \frac{\dfrac{p_1 z_1(kT)}{C_a(kT)} + \dfrac{p_2 z_2(kT)}{C_a(kT)} + \dfrac{p_3 z_3(kT)}{C_a(kT)}}{\dfrac{(p_1 + p_2 + p_3)}{C_a(kT)}} \tag{5.4}$$

where:

$$z_1(kT) = d_1 - \frac{p_1}{C_a(kT)} \tag{5.4a}$$

$$z_2(kT) = d_2 - \frac{p_1 + p_2}{C_a(kT)} \tag{5.4b}$$

$$z_3(kT) = d_3 - \frac{p_1 + p_2 + p_3}{C_a(kT)} \tag{5.4c}$$

Table 5.2: Three order release time example

Iteration 1

Part Name	Initial Release Time (scd)	Processing Time (h/scd)	Due Date (scd)	Completion Time(scd)	DDD (scd)	DDD_a
2015541	140.00	20.00	161.00	141.33	19.67	19.67
2015601	145.00	20.00	162.00	146.33	15.67	15.67
2015609	165.00	30.00	163.00	167.00	-4.00	4.00
					average	13.11

Iteration 2

Part Name	Initial Release Time (scd)	Processing Time (h/scd)	Due Date (scd)	Completion Time(scd)	DDD (scd)	DDDa
2015541	141.97	20.00	161.00	143.30	17.70	17.70
2015601	146.57	20.00	162.00	147.90	14.10	14.10
2015609	164.60	30.00	163.00	166.60	-3.60	3.60
					average	11.80

Iteration 3

Part Name	Initial Release Time (scd)	Processing Time (h/scd)	Due Date (scd)	Completion Time(scd)	DDD (scd)	DDD_a
2015541	143.74	20.00	161.00	145.07	15.93	15.93
2015601	147.98	20.00	162.00	149.31	12.69	12.69
2015609	164.24	30.00	163.00	166.24	-3.24	3.24
					average	10.62

In the discontinuous region the ATC visits all the possible sequences and the average absolute due deviation is calculated for each one of these sequences. The sequence that produces the lowest average absolute due date deviation is the one used for production. For a production sequence of orders $<O_1, O_2, O_3>$ the average absolute due date deviation is:

$$DDD_a(kT) = \frac{\left|d_1 - a_1(kT) - \frac{p_1}{C_a(kT)}\right| + \left|d_2 - a_1(kT) - \frac{p_1 + p_2}{C_a(kT)}\right| + \left|d_3 - a_1(kT) - \frac{p_1 + p_2 + p_3}{C_a(kT)}\right|}{3} \quad (5.5)$$

For sequence <O_1, O_3, O_2>, the average absolute due date deviation is:

$$DDD_a(kT) = \frac{\left|d_1 - a_1(kT) - \frac{p_1}{C_a(kT)}\right| + \left|d_2 - a_1(kT) - \frac{p_1 + p_2 + p_3}{C_a(kT)}\right| + \left|d_3 - a_1(kT) - \frac{p_3 + p_2}{C_a(kT)}\right|}{3} \quad (5.6)$$

Table 5.3, shows the average absolute due date deviation for all six sequences in the discontinuous region, for $a_{123}(kT)_\infty$ = 152.71 scd and $C_a(kT)$, 5 h/scd.

Table 5.3: Average absolute due date deviation for 3 order example and $C_a(kT)$ = 5 h/scd

Sequence	$DDD_a(kT)$ (scd)
<O_1, O_2, O_3>	3.09
<O_1, O_3, O_2>	3.76
<O_2, O_1, O_3>	3.09
<O_2, O_3, O_1>	3.76
<O_3, O_1, O_2>	3.56
<O_3, O_2, O_1>	3.56

As capacity increases, orders that have feasible dues date leave the discontinuous region, decreasing contention. In the previous example, when the first order due date becomes feasible, the only two orders remaining in contention are O_2 and O_3. At this point the due date for the first order, d_1, is the release time for either O_2 or O_3.

$$a_{23}\left(kT\right)_{\infty} = d_1 = \frac{\frac{p_2}{C_a\left(kT\right)}\left(z_2\left(kT\right)\right) + \frac{p_3}{C_a\left(kT\right)}\left(z_3\left(kT\right)\right)}{\frac{\left(p_2 + p_3\right)}{C_a\left(kT\right)}} \tag{5.7}$$

where:

$$z_2\left(kT\right) = d_2 - \frac{p_2}{C_a\left(kT\right)} \tag{5.7a}$$

$$z_3\left(kT\right) = d_3 - \frac{p_2 + p_3}{C_a\left(kT\right)} \tag{5.7b}$$

Solving for the capacity required to decouple O_1 leads to $C_a(kT)$ = 23.75 h/scd. The average absolute due date deviation for sequence <O_1, O_2, O_3> is, (there is no deviation for O_1):

$$DDD_a(kT) = \frac{\left|d_2 - a_{23}(kT)_{\infty} - \frac{p_2}{C_a(kT)}\right| + \left|d_3 - a_{23}(kT)_{\infty} - \frac{p_2 + p_3}{C_a(kT)}\right|}{3} \tag{5.8}$$

and for sequence <O_1, O_3, O_2>, the average absolute due deviation is:

$$DDD_a(kT) = \frac{\left| d_2 - a_{23}(kT)_\infty - \frac{p_3 + p_2}{C_a(kT)} \right| + \left| d_3 - a_{23}(kT)_\infty - \frac{p_3}{C_a(kT)} \right|}{3} \tag{5.9}$$

The theoretical average absolute due date deviation for these sequences and the example in Table 5.3 are 0.0877 scd and 0.6795 scd, respectively. As capacity increases further the amount of contention between order O_2 and O_3 decreases and the orders enter in a decoupled state where all the due dates are feasible. In this state the average absolute due date deviation $DDD_a(kT)$ = 0 scd. When O_3, enters the decoupled state in this example then capacity is defined by:

$$C_a(kT) = \frac{p_3}{d_3 - a_3(kT)} \tag{5.10}$$

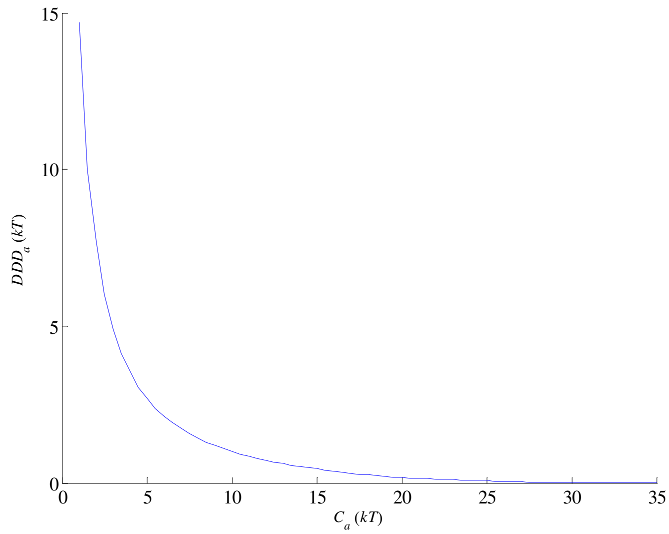
And the release times are:

$$a_1(kT)_\infty = d_1 - \frac{p_1}{C_a(kT)} \tag{5.10a}$$

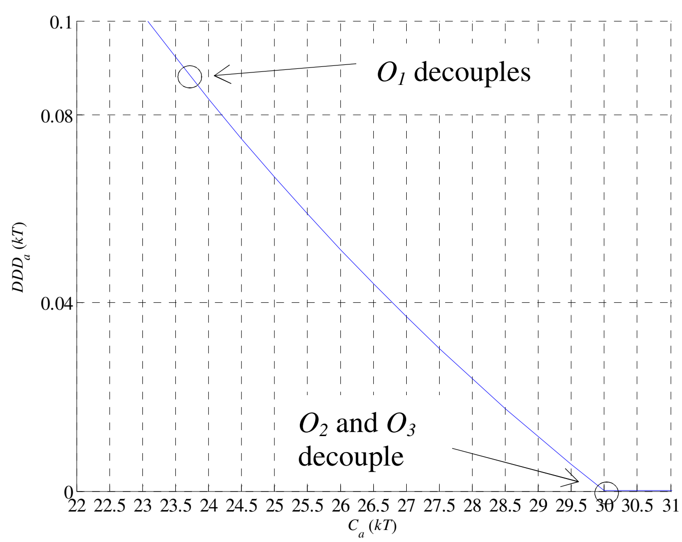
$$a_2(kT)_\infty = d_2 - \frac{p_2}{C_a(kT)} \tag{5.10b}$$

$$a_3(kT)_\infty = d_3 - \frac{p_3}{C_a(kT)} \tag{5.10c}$$

For the example in Table 5.3, the capacity where all the orders become decoupled is 30 h/scd and the release time of orders O_1, O_2, and O_3 are 160.33 scd, 161.33 scd and 162 scd, respectively. For a range of capacities $C_a(kT)$, Figure 5.3(a) shows the resulting average absolute due date deviation for capacities greater than 30 h/scd, DDD_a is zero, because the three orders are feasible.



(a)



(b)

Figure 5.3: DDD_a vs. Ca trajectory for 3 order example

5.2 Integral Control Adaptability

Figure 5.4, shows the relationship between average absolute due date deviation $DDD_a(kT)$ and capacity $C_a(kT)$ for the two sets of orders listed in Tables 5.4 and 5.5. There is an inverse relationship between capacity and due date because, unless there is no contention for the workstation resource, the average absolute due date deviation decreases as capacity is increased. However, in general, increasing capacity beyond some value will not yield practical improvements in the average absolute due date deviation.

Table 5.4: Production schedule for scd 160 - 165

Part Name	Initial Planned Release Time (scd)	Due Date (scd)	Processing Time (h)
2015541	161.58	162.00	8.00
2015674	161.68	162.00	6.17
2015694	161.83	162.00	3.27
2015777	162.56	163.00	8.38
2015601	163.34	164.00	12.7
2015654	164.90	165.00	1.93
2015770	164.48	165.00	9.96
2015669	164.97	165.00	0.57
2015776	164.68	165.00	6.14
2015812	164.97	165.00	0.53

The fundamental dynamic properties of the system with the topology shown in Figure 5.1 are difficult to analyze using control theory because of the nonlinearities in the sequencing of orders in the scheduler. Due to the changing relationship between average absolute due date deviation and capacity there is a need to recalculate the relationship between the two variables in order to maintain constant system dynamic properties.

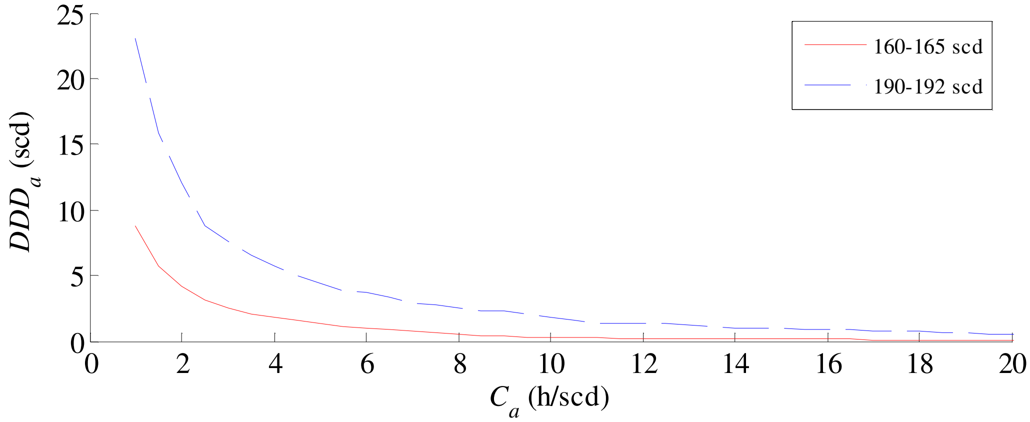


Figure 5.4: Examples of the relationship between average absolute due date deviation and workstation capacity

Table 5.5: Production schedule for scd 190 - 192

Part Name	Initial Planned Release Time (scd)	Due Date (scd)	Processing Time (h)
2016225	189.73	190.00	5.15
2016224	189.79	190.00	4.09
2016251	189.88	190.00	2.23
2016221	189.80	190.00	3.80
2016276	189.80	190.00	3.86
2016232	190.64	191.00	6.88
2016250	190.86	191.00	2.77
2016310	190.69	191.00	6.00
2016258	190.31	191.00	13.22
2016236	190.05	191.00	18.23
2016314	190.93	191.00	1.42
2016153	191.52	192.00	9.10
2016331	191.86	192.00	2.65
2016235	191.73	192.00	5.14
2016246	191.96	192.00	0.83
2016315	191.93	192.00	1.41

For a given capacity $C_a(kT)$, this relationship can be approximated using

$$DDD_a(kT) \approx K_s(kT)C_a(kT) + DDD_s(kT) \tag{5.11}$$

where $DDD_s(kT)$ is the vertical axis intercept and slope $K_s(kT)$ can be approximated using

$$K_s(kT) \approx \frac{DDD_a\left(C_a(kT)+\Delta C_a\right) - DDD_a\left(C_a(kT)-\Delta C_a\right)}{2\Delta C_a} \tag{5.12}$$

where the production model in the scheduler is used to obtain average absolute due date deviation at two capacities separated from $C_a(kT)$ by an incremental change in capacity ΔC_a. In the next section, system characteristic equations are derived using these approximations.

5.3 Discrete Control Model

The model presented in Figure 5.1 can be simplified by replacing the scheduler and the workstation with a constant gain, K_s, which is the slope of the curve at $C_a(kT)$ as shown in Figure 5.5.

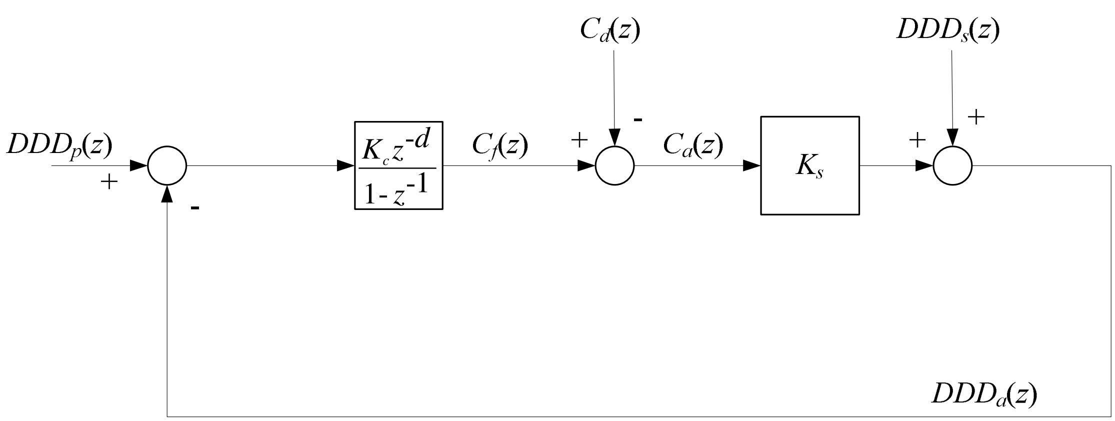


Figure 5.5: Simplified DDD regulation topology

The system transfer function with delay $d = 0$ and given values of K_s and K_c is:

$$\frac{DDD_a(z)}{DDD_p(z)} = \frac{K_c K_s}{z - \left(1 - K_c K_s\right)} \tag{5.13}$$

The characteristic equation of this discrete first order system is:

$$z - \left(1 - K_c K_s\right) = 0 \tag{5.14}$$

Time constant τ (scd), represents the time it takes a continuous first order system to reach 63.2% of its final value in response to a step input. In this discrete first order system with capacity adjustment period T (scd) and $\tau \geq T$, the control gain K_c can be set as follows to approximate time constant τ:

$$K_c = \frac{\left(1 - e^{\left(-T/\tau\right)}\right)}{K_s} \tag{5.15}$$

On the other hand, to obtain complete response in one period T, the control gain should be:

$$K_c = \frac{1}{K_s T} \tag{5.16}$$

There are occasions in the production floor, when adjustments in capacity cannot be implemented on the same calendar day, for example, when using temporary workers who might be hired directly by the company or dispatched from an external provider [KIM05]. If there is a 1-day delay, $d = 1$, in capacity adjustment, then system transfer function is the following:

$$\frac{DDD_a(z)}{DDD_p(z)} = \frac{K_c K_s z}{z^2 - z + K_c K_s} \tag{5.17}$$

and the characteristic equation is:

$$\left(z-\left(\frac{1+\sqrt{1-4K_cK_s}}{2}\right)\right)\left(z-\left(\frac{1-\sqrt{1-4K_cK_s}}{2}\right)\right)=\left(z-(a+bi)\right)\left(z-(a-bi)\right)=0 \tag{5.18}$$

The real part of the root is always a = 0.5, while the imaginary portion, b, depends on the product K_cK_s and $\sqrt{a^2+b^2}<1$ is required for stability. For equal roots, the system is critically damped ($\zeta = 1$), b =0, K_cK_s = 0.25 and the workstation response can be approximately characterized by time constant τ = 1.44T. In a critically damped system the system response reaches steady state value as quickly as possible without oscillating. For a stable underdamped system ($\zeta < 1$), the response of the system oscillates but gradually converges at its steady state value. As the damping ratio gets smaller, the system response is more oscillatory. For an underdamped second order system the characteristic equation is:

$$z^2-2e^{(-\zeta\omega_nT)}\cos\left(\omega_dT\right)z+e^{(-2\zeta\omega_nT)}=0 \tag{5.19}$$

where $\omega_d=\omega_n\sqrt{1-\zeta^2}$. For example, for ζ = 0.2, ω_n = 0.94/T rad/s, K_cK_s = 0.686 and the approximate time constant is:

$$\tau=\frac{1}{\zeta\omega_n}=\frac{1}{0.2\left(0.941/T\right)}=5.31T \tag{5.20}$$

Overdamped systems, $\zeta > 1$, also can be obtained.

5.4 Integral Control Gain Adaptation Algorithm

As shown in Figure 5.4, the relationship between average absolute due date deviation $DDD_a(kT)$ and capacity $C_a(kT)$ is not constant. The orders in the scheduler change with time as orders are released to the workstation or new work comes in. To maintain the constant dynamic behavior in the system, the gain for the integral controller needs to adapt to changes in gain in the ATC. The following is a description of the procedure.

1. Use Equation (5.12) to estimate $K_s(kT)$.
2. Use $K_s(kT)$ to calculate $K_c(kT)$, for example, Equations (5.15), (5.16) or Equations (5.18) and (5.19).
3. Use Equation (5.2), to adjust the full capacity $C_f(kT)$.

5.4.1 Response to sudden change in order mix

To illustrate adaptation, of control gain $K_c(kT)$ and also adaptation limitation, the integrated due date deviation regulation and scheduling system was simulated with given order mixes. No orders were released, and hence no production. Figure 5.6 shows the capacity response of the system when using different batches of orders as listed in Tables 5.4 and 5.5, T = 1 scd, d = 0 and DDD_p = 1.5 scd. At the beginning of the simulation the scheduler contains the orders in Table 5.4, capacity is adjusted while regulating due date deviation. The system converges to approximately $C_a(kT)$ = 3.2 h/scd, $DDD_a(kT)$ = 1.5 scd, $K_s(kT)$ = -1.3 scd^2/h and $K_c(kT)$ = -0.8 h/scd^2.

At the 190th shop calendar day the orders in Table 5.4 are replaced by the orders in Table 5.5 with the resulting changes in capacity and average absolute due date deviation shown in Figures 5.6 and 5.7, respectively. The relationship between average absolute due date deviation and capacity suddenly changes as reflected in the change in $K_s(kT)$ shown in Fig. 5.8 and the resulting change in K_c shown in Fig. 5.9. The system converges to approximately $C_a(kT)$ = 6.0 h/scd, $DDD_a(kT)$ = 1.5 scd, $K_s(kT)$ = -0.5 scd^2/h and $K_c(kT)$ = -2.0 h/scd^2.

The responses in Figures 5.8 and 5.9 differ from the theoretial responses that would be expected with constant gains K_c and K_s. For example, for $K_c(kT)K_s(kT)$=1, capacity would be expected to rise in one step to its new value at time 190 scd, and average absolute due date deviation would be expected, theoretically with constant gains, to deviate from DDD_p for only one period T at time 190 scd. Instead, the response is prolonged due to overestimation of gain $K_s(kT)$ as capacity increases.

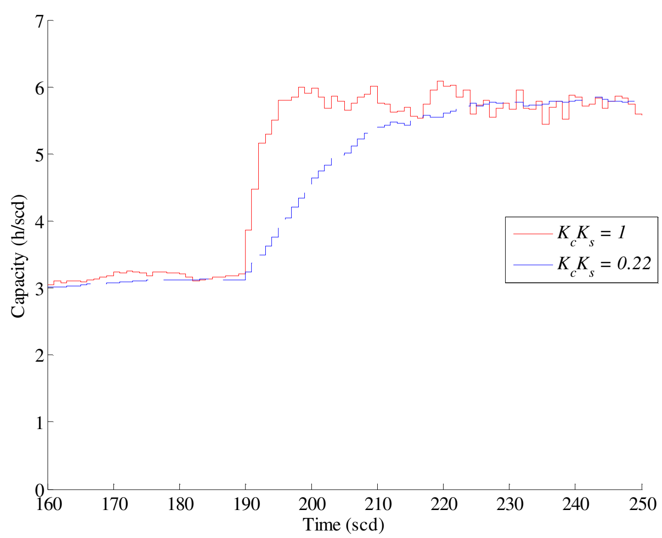


Figure 5.6: Response of capacity C_a (kT)

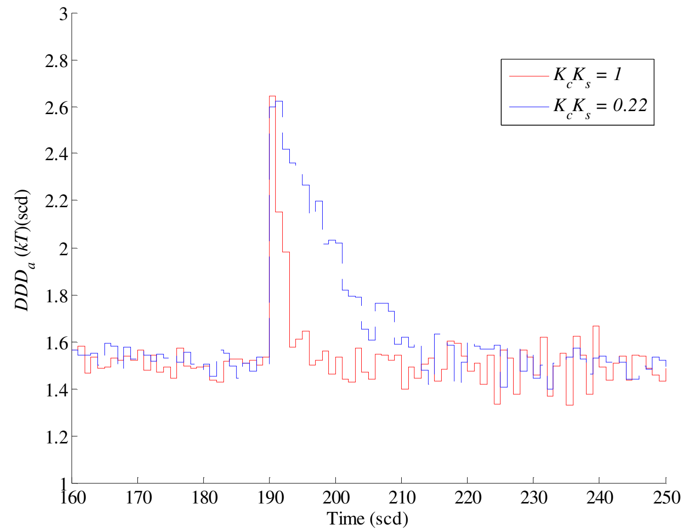


Figure 5.7: Response of average absolute due date deviation DDD_a (kT)

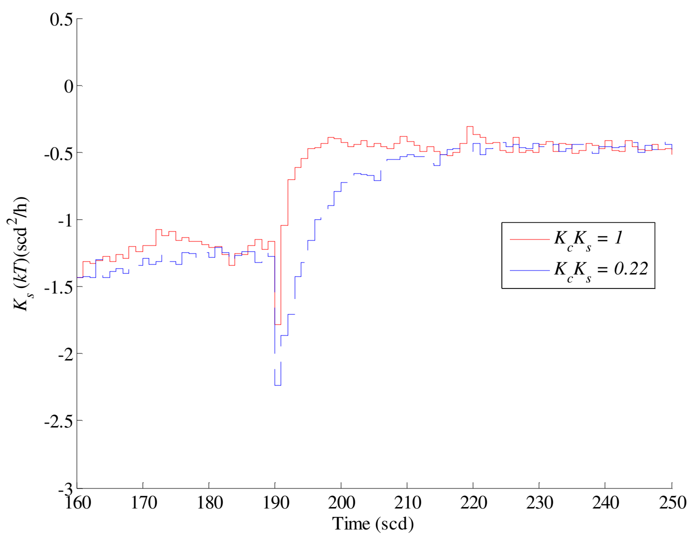


Figure 5.8: Response of average absolute due date deviation capacity gain K_s (kT)

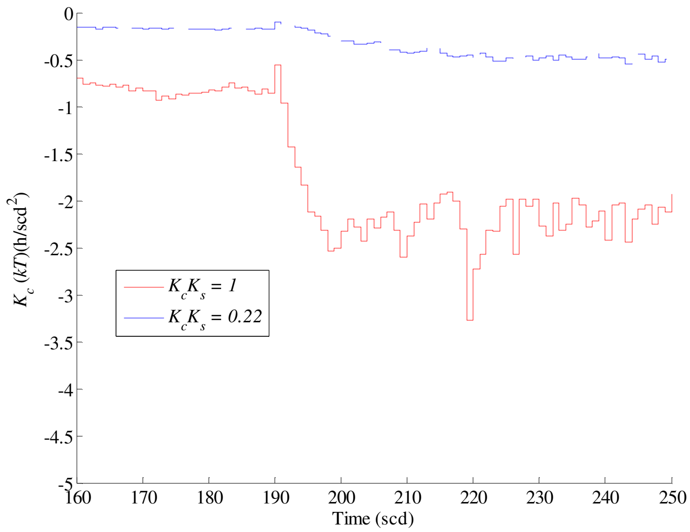


Figure 5.9: Response of integral control gain K_c (kT)

On the other hand, Figures 5.10 through 5.13 shows the response when the orders listed in Table 5.5 initially are in the scheduler, but are replaced on day 190 with the orders in Table 5.4. As expected, capacity decreases as the demand for capacity lowers. In the case of $K_c(kT)K_s(kT) = 1$ capacity is adjusted as expected approximately in one day period, which is reflected in the control gain K_c. In both Figures 5.9 and 5.13 the relatively high value of capacity causes the adapted control gain $K_c(kT)$ to be relatively noisy.

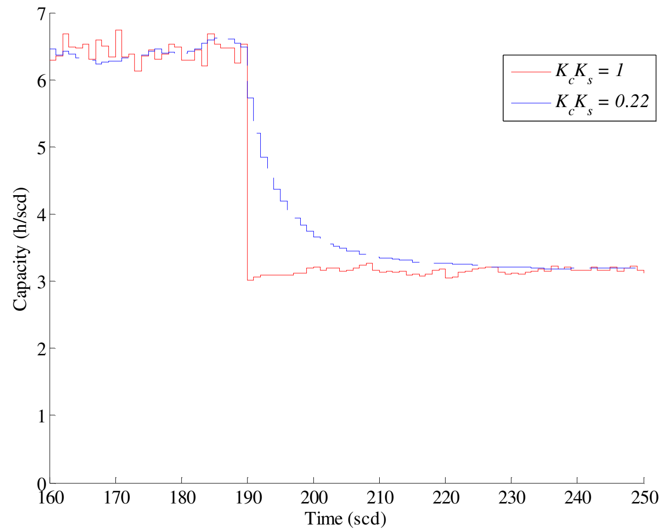


Figure 5.10: Response of capacity $C_a\,(kT)$

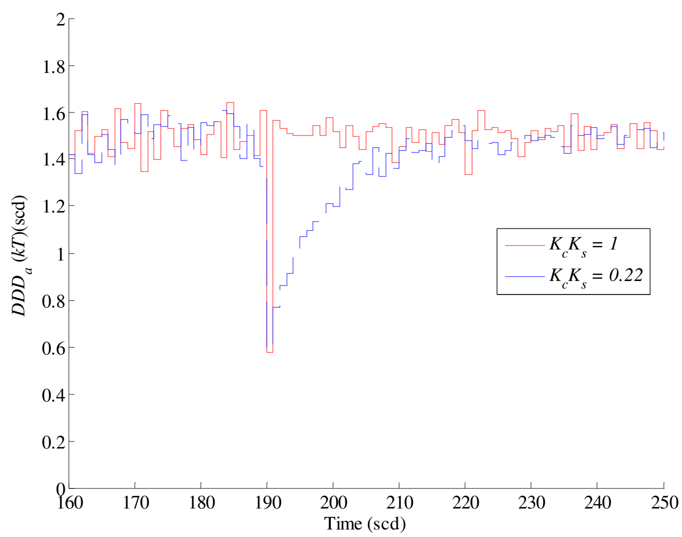


Figure 5.11: Response of average absolute due date deviation $DDD_a\,(kT)$

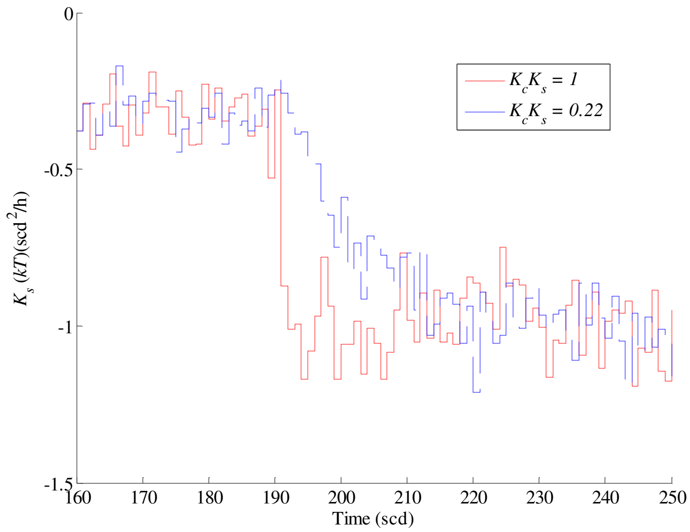


Figure 5.12: Response of average absolute due date deviation capacity gain K_s (kT)

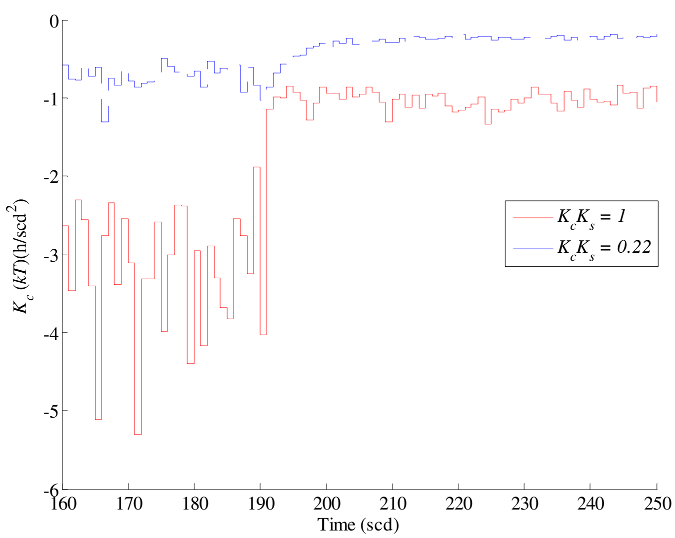


Figure 5.13: Response of integral control gain K_c (kT)

5.5 Discrete event simulation of Workstation 2061

The discrete event simulation described in Section 4.2 was modified to replace WIP regulation with due date deviation regulation, and the production data in the Appendix was again used as the input to Workstation 2061. Figure 5.14 shows the total amount of work in orders that are added each day for consideration by the scheduler (input to the scheduler), as well as the total amount of work in orders that are due each day.

Assumptions used in this production model included:

- Orders had one processing step.
- Orders could be partially completed during a day; in this case, work on the order resumes at the beginning of the next day.
- Setup and transportation times are not considered.
- Capacity could be added without an upper limit.
- Capacity was adjusted at the beginning of each work day (T=1 scd).
- Order due dates and processing times are constant.
- The release time of each order into the queue at the workstation was determined by the scheduler, and orders were assumed to be processed in the order in which they were released.
- The initial capacity was $C_a(0)$ = 20 h/scd, and capacity disturbances $C_a(kT)$ were assumed to be zero.
- The planned average absolute due date deviation was DDD_p=1 scd and remained constant.
- Orders began to be considered by the scheduler 10 days in advance of their planned release time.

- The scheduler determined the actual order release time of orders to the queue of the workstation.

- The release time of an order continued to be (re)scheduled until its release time was reached; a released order was no longer considered in the scheduler.

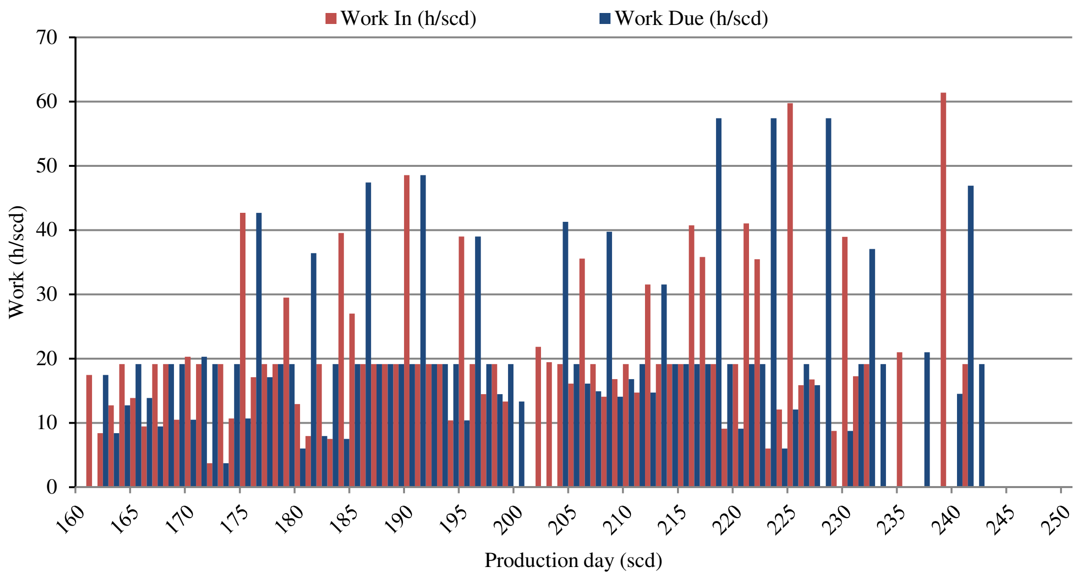


Figure 5.14: Work In and Work Due vs. time for Station 2061

Figure 5.15, is a flowchart that describes the order of events for the main processes for the discrete event simulation.

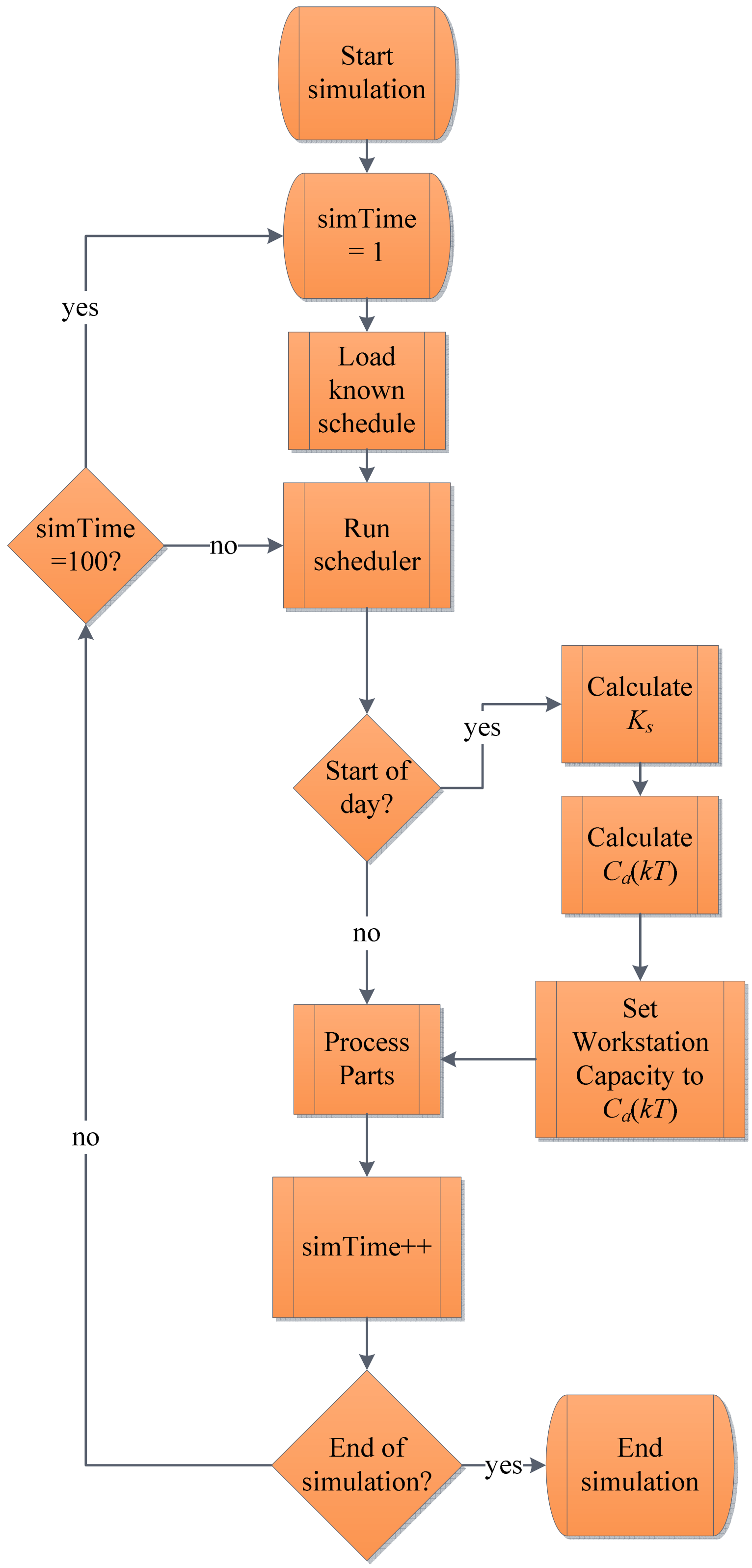


Figure 5.15: Discrete event simulation flowchart

5.5.1 Results of Due Date Deviation Regulation with d = 0

For *d*=0, Figs. 5.16 and 5.17 show the capacity and average absolute due date deviation simulation results, respectively, for K_cK_s = 1 and K_cK_s = 0.22, and Table 5.6 lists the corresponding statistical results. As expected, due date deviation is lower with the higher K_cK_s product, but the standard deviation of capacity is increased, reflecting the larger day-to-day adjustments in capacity.

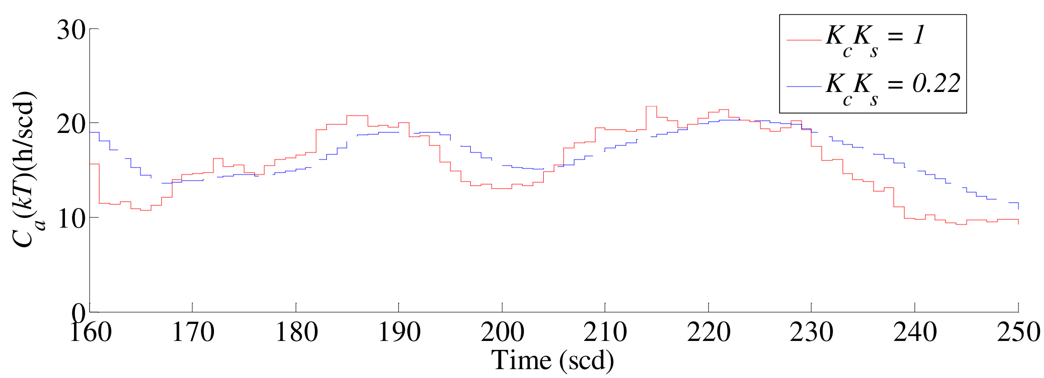


Figure 5.16: Work system capacity with delay *d*=0

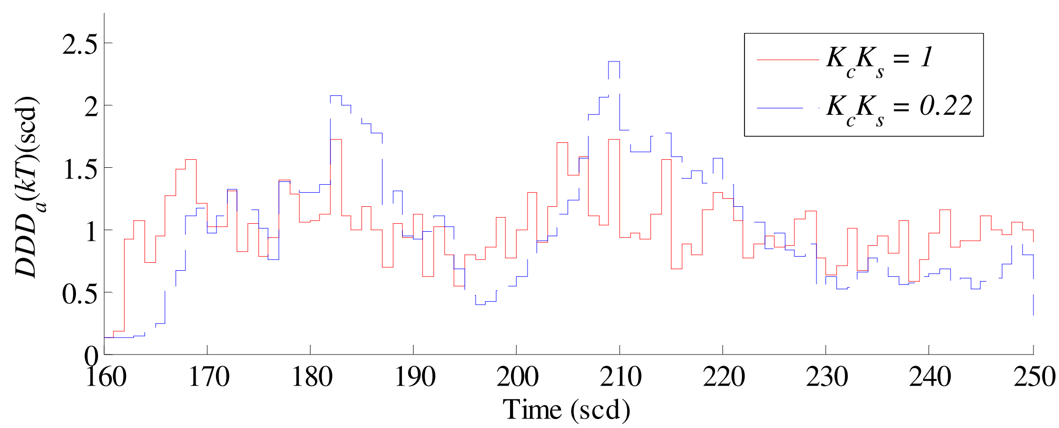


Figure 5.17: Average absolute due date deviation with delay *d*=0

Table 5.6: Due date deviation regulation results for ATC scheduling and *d*=0

K_cK_s	Average $C_a(kt)$(h/scd)	Std. Dev. $C_a(kt)$(h/scd)	Average Absolute $DDD_a(kt)$(h)	Std. Dev. $DDD_a(kt)$(h)
1.00	17.66	2.63	1.05	0.26
0.22	17.29	2.11	1.22	0.45

5.5.2 Results of Due Date Deviation Regulation with d = 1

For d=1, Figs. 5.18 and 5.19 show the capacity and average absolute due date deviation simulation results, respectively, for K_cK_s = 0.25 and K_cK_s = 0.686, and Table 5.7 lists the corresponding statistical results. As would be expected with the additional 1-day delay in capacity adjustment, due date regulation performance is decreased compared to Figures. 5.15 and 5.16 and Table 5.7. Furthermore, for K_cK_s = 0.686, the approximate damping ratio is 0.2, the workstation capacity is fundamentally oscillatory, and capacity deviates more significantly from the mean than is the case when K_cK_s = 0.25 and the system is critically damped and fundamentally non oscillatory.

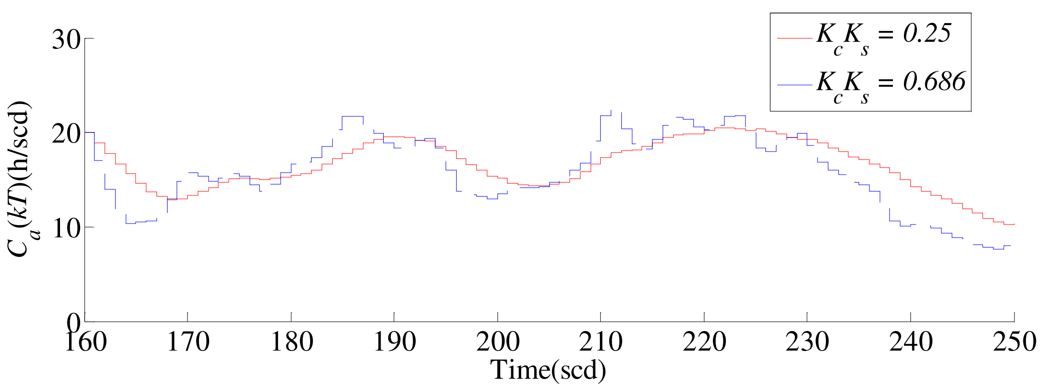


Figure 5.18: Work system capacity with delay *d*=1

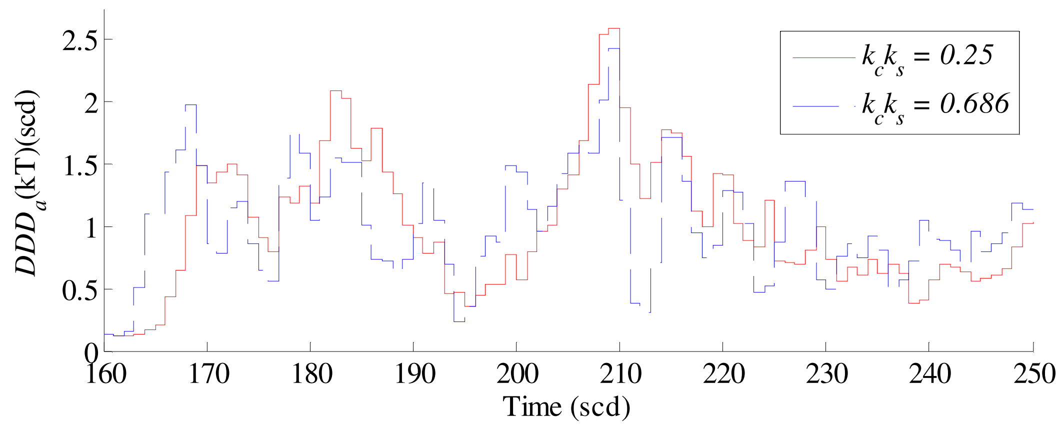


Figure 5.19: Average absolute due date deviation with delay *d*=1

Table 5.7: Capacity and average absolute due date deviation summary for *d* = 1

K_cK_s	Average $C_a(kt)$(h/scd)	Std. Dev. $C_a(kt)$(h/scd)	Average Absolute $DDD_a(kt)$(h)	Std. Dev. $DDD_a(kt)$(h)
0.25	17.25	2.25	1.22	0.50
0.686	17.66	2.81	1.10	0.45

5.6 Closure

In this chapter, results of discrete event simulations and control theoretic modeling have been presented for regulation of due date deviation by adjusting workstation capacity and order release times. It was observed that there is an inverse relationship between average absolute due date deviation and workstation capacity. This relationship was repeatedly measured (daily in the examples presented) using the results of scheduling with incremental changes in workstation capacity. The measured approximate relationship then was used to calculate the current due date regulation gain that was expected to produce desired fundamental dynamic properties. Hence, due date deviation regulation was adapted based on the operating conditions in the workstation and the mix of orders to be produced.

The results obtained from discrete event simulations were used to illustrate the dynamic behavior of average absolute due date deviation and capacity in a workstation with integrated scheduling, which makes order release time adjustments, and due date deviation regulation, which makes capacity adjustments. The responses were observed for systems with no delay d=0 and delay d=1, as well as for, different values of $K_c(kT)K_s(kT)$, which result in different damping ratios and time constants. The systems with larger values of $K_c(kT)K_s(kT)$ produced larger average capacities with more variation than lower values; however, with higher values, average absolute due date deviation was closer to plan. Hence, there is a tradeoff between capacity variation and due date deviation variation.

The results from the discrete event simulation show that with the developed algorithm, when the mix of orders in the scheduler changes, the slope of the $DDD_a(kT)$ vs $C_a(kT)$ curve changes resulting in a change of the control gain, thus maintaining desired fundamental dynamic behavior and adapting to varying operating conditions. This is made possible by control theoretic modeling. However, sudden significant changes in the mix of orders in the scheduler resulted in large adaptation in control gain and dynamic behavior that deviated from desired, designed behavior. Sudden, significant changes are unlikely to occur in practice unless significant disturbances such as large rush orders or large order cancelations occur.

The focus of this research was on modeling and understanding the dynamics of distributed manufacturing control systems, and particularly on integrating dynamic scheduling with production planning and control (PPC). First, control laws for a production planning and control system with two integrated controllers were developed: a capacity controller that controls backlog by adjusting capacity; and a WIP controller that controls the WIP by adjusting the input rate. These two controllers have different sampling rates, and modified z-transform theory was used to analyze the system. Characteristic equations obtained from the transfer functions were analyzed in order to understand the relationships between control parameters and dynamic properties such as time constants and response.

The concept of arrival time control then was reviewed. The arrival time controller adjusts the release time of orders to improve global performance while making tradeoffs between due date deviations of individual orders. The arrival time control concept was modified to accommodate adjustable workstation capacities. Differential equations were used to model the controller and describe the different dynamics regions; decoupled, dead-zone and discontinuity.

Next, the behavior of integrated PPC and dynamic scheduling was studied using a discrete event simulation with one workstation and one processing step; the results were presented for systems with and without WIP regulation. The effects of capacity adjustments in the trajectories of the order release times were shown. Then, the behavior of integrated PPC and dynamic scheduling was studied in which both capacity and order release times were adjusted with the goal of regulating average absolute due date deviation. It was observed that there is an inverse relationship between average absolute due date deviation and capacity. In order to keep the dynamic properties of the system constant, the control gain was varied continuously with time. System transfer functions were found for systems with and without delay in capacity adjustments, and control gain functions were selected to obtain various dynamic properties. Results from discrete event simulations were used to illustrate the efficacy of using DDD regulation in reducing average absolute due date deviation.

The most significant conclusions drawn from this work can be summarized as follows:

1. It was shown in Chapter 2 that transfer functions analysis methods can be used to obtain a dynamic model of a PPC system that integrates backlog and WIP control. Because the system was multirate, the sampler decomposition and modified z-transforms were needed in the analysis. The results were used to design the control laws necessary to achieve desired system performance and calculate the dynamic response to planned and unplanned inputs without using simulation.
2. It was shown in Chapter 3 that the arrival time control scheduling algorithm could be modified to accommodate varying system capacity. This allowed new schedules to be generated in real time that adapted order release times to changes in capacity.
3. It was shown in Section 4.2 that PPC could be integrated with an arrival time controller that performs dynamic scheduling. A control theoretic topology was presented, and this topology was used to derive the equations needed for a discrete event simulation that illustrated the effect of capacity adjustments on the trajectories

of order release times. Contention of order release times was found to be inversely related to capacity level.

4. It was shown in Section 4.3, that a system that combined arrival time control with WIP regulation managed resources better by running at an overall lower capacity than without WIP regulation. But lower capacity levels tend to increase due date deviation. This indicated that controllers that regulate due date deviation instead of WIP were needed.

5. It was shown in Section 5.2 that the relationship between average absolute due date deviation and workstation capacity is nonlinear, variable and dependent upon the mix of orders being scheduled. It was also shown that the slope of this deviation versus capacity function could be estimated for a given capacity using values calculated in the vicinity of the given capacity. Furthermore, this slope then could be used to adjust the due date deviation gain to adapt it to the varying deviation versus capacity function.

6. It was found in Section 5.3 that adaptation of the due date deviation regulation gain can be designed to maintain approximately constant regulation properties, such as approximately constant damping ratio, in the presence of time varying due date deviation versus capacity function.

7. In Section 5.4 it was shown that when the mix of orders being scheduled was changed suddenly and significantly, that the implemented adaptation method did not maintain constant dynamic behavior. However, such sudden changes may not occur in practice when there is a slow evolution of order mix as individual orders enter the scheduler and are eventually released.

6.1 Recommendations

Based on the results of this research, the following recommendations are made regarding future research:

1. The arrival time controller could be extended to incorporate other higher-level planning decisions. Decisions made in other department such as sales, purchasing or financing could be incorporated into arrival time control, through the PPC system. The extension could be made by investigating the effect of these decisions on either system capacity or order release times.

2. Systems where the order due date is not constant need to be studied in order to understand the relationships between varying order due dates and capacity and WIP. In many manufacturing systems it is not unusual for order due dates to change after the initial schedule is done. Control theoretic analysis, similar to Chapter 5, can be done to provide a better understanding of what physical parameters are affected by varying due dates in a production system.

3. Alternatives to the ATC scheduling algorithm for adjusting release times should be investigated. This would allow more traditional scheduling systems to be evaluated with regard to dynamic interactions in systems where capacity is regulated to adjust WIP or due date deviation. Many scheduling algorithms directly minimize a cost function in searching for optimal order release time. These may produce different relationships between capacity and average absolute due date deviation, and may be able to incorporate cost tradeoffs between them.

4. The adjustment of order release times in the ATC was based on an average absolute due date deviation merit function. Research is needed in incorporating other merit functions that can integrate logistic measures such as backlog or actual inventory. This type of merit system would provide a compromise between order contention and logistic response.

5. Further research is needed to more thoroughly characterize the behavior of due date regulation, especially the relationship between average absolute due date deviation and workstation capacity, due dates and processing times, as well as adaptive behavior as capacity varies quickly and significantly with time. More complete characterization in real-time of the average absolute due date deviation versus capacity function may be required. More complex due date regulation control laws may further reduce average absolute due date deviation, and measures of due date reliability other than Equation (5.1) could be considered.

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Operation Sequence Number: 10
Workstation: Maze: 2061
Workstation capacity: 19.13 (h/scd)

Order Number	Article number	Order Start Date	Order Start Date [shop calender day]	Operation Sequence Start Date	Operation Sequence Start Date [shop calender day]	Operation Sequence Due Date	Operation Sequence Due Date [shop calender day]	Order Time Target [min]	Order Time Actual [h]	Amount Target [item]	Amount Actual [item]	Lot-Size [item]
2015541	901116	02/01/01	162	02/01/01	162	02/01/01	162	417.29	8.00	5000	5000	5000
2015601	901108	03/01/01	163	03/01/01	163	04/01/01	164	693.02	12.70	8559	8559	8559
2015609	901062	04/01/01	164	04/01/01	164	19/02/01	210	1132.39	17.87	15655	15655	15655
2015654	901143	04/01/01	164	04/01/01	164	05/01/01	165	86.15	1.93	570	570	570
2015669	901104	05/01/01	165	05/01/01	165	05/01/01	165	72.44	0.57	431	431	431
2015674	901138	02/01/01	162	02/01/01	162	02/01/01	162	308.91	6.17	3300	3300	3300
2015693	901043	15/01/01	175	15/01/01	175	15/01/01	175	232.52	4.88	2600	2615	2600
2015694	901054	02/01/01	162	02/01/01	162	02/01/01	162	163.18	3.27	1720	1720	1720
2015696	901116	05/01/01	165	05/01/01	165	08/01/01	168	411.04	8.63	4508	4508	4508
2015770	901014	04/01/01	164	04/01/01	164	05/01/01	165	1086.34	9.96	15000	15001	15000
2015776	911405	05/01/01	165	05/01/01	165	05/01/01	165	432.77	6.14	4765	4765	4765
2015777	901027	03/01/01	163	03/01/01	163	03/01/01	163	472.42	8.38	5234	5234	5234
2015812	901011	05/01/01	165	05/01/01	165	05/01/01	165	70.22	0.53	520	520	520
2015829	910101	02/01/01	162	02/01/01	162	24/01/01	184	653.74	9.31	8052	8052	8052
2015830	901198	09/01/01	169	09/01/01	169	10/01/01	170	277.84	7.44	3200	3200	3200
2015838	910049	09/01/01	169	09/01/01	169	11/01/01	171	1300.71	10.41	16403	16403	16403
2015842	901112	08/01/01	168	08/01/01	168	08/01/01	168	256.78	5.22	2300	2300	2300
2015843	901052	12/01/01	172	12/01/01	172	12/01/01	172	511.50	8.35	6216	6216	6216
2015844	901180	09/01/01	169	09/01/01	169	10/01/01	170	214.37	6.09	2532	2619	2532

2015849	901195	08/01/01	168	08/01/01	168	09/01/01	169	120.39	2.32	1070	1070	1070
2015854	901144	18/01/01	178	18/01/01	178	18/01/01	178	231.55	2.74	2860	2863	2860
2015855	901144	18/01/01	178	18/01/01	178	22/01/01	182	882.18	8.88	12102	12102	12102
2015870	901199	11/01/01	171	11/01/01	171	11/01/01	171	218.54	1.80	2220	2231	2220
2015871	901195	09/01/01	169	09/01/01	169	10/01/01	170	273.41	5.59	2880	2880	2880
2015872	901195	10/01/01	170	10/01/01	170	11/01/01	171	216.76	2.39	2210	2210	2210
2015875	901161	19/01/01	179	19/01/01	179	20/01/01	180	299.30	4.42	3474	3477	3474
2015877	901094	11/01/01	171	11/01/01	171	11/01/01	171	533.73	4.53	6503	6503	6503
2015900	901104	09/01/01	169	09/01/01	169	09/01/01	169	111.74	1.63	1050	1056	1050
2015901	901143	09/01/01	169	09/01/01	169	09/01/01	169	73.31	5.47	560	560	560
2015902	910071	15/01/01	175	15/01/01	175	31/01/01	191	965.92	10.16	13291	13291	13291
2015903	901127	18/01/01	178	18/01/01	178	18/01/01	178	645.56	8.40	8742	8742	8742
2015909	901065	16/01/01	176	16/01/01	176	16/01/01	176	74.86	1.09	580	580	580
2015912	910071	15/01/01	175	15/01/01	175	15/01/01	175	46.20	1.53	231	231	231
2015929	901041	17/01/01	177	17/01/01	177	17/01/01	177	199.01	3.72	2000	2000	2000
2015931	901011	22/01/01	182	22/01/01	182	25/01/01	185	1003.45	13.15	12523	12566	12523
2015934	901149	18/01/01	178	18/01/01	178	06/02/01	197	1822.25	6.76	25451	25451	25451
2015949	901127	11/01/01	171	11/01/01	171	16/01/01	176	2599.15	18.04	36483	36483	36483
2015955	901198	18/01/01	178	18/01/01	178	18/01/01	178	292.01	4.86	3100	3100	3100
2015956	911405	02/02/01	193	02/02/01	193	13/03/01	232	1590.61	6.29	20145	20145	20145
2015957	901143	12/01/01	172	12/01/01	172	15/01/01	175	778.71	13.85	8857	8857	8857
2015960	911405	16/01/01	176	16/01/01	176	28/02/01	219	1154.60	14.28	14517	14517	14517
2015973	901057	12/01/01	172	12/01/01	172	12/01/01	172	68.66	2.15	550	550	550
2015978	910049	16/01/01	176	16/01/01	176	22/01/01	182	1316.83	14.53	16611	16611	16611
2015991	901094	16/01/01	176	16/01/01	176	14/02/01	205	379.08	2.65	4127	4130	4127
2015999	901096	20/01/01	180	20/01/01	180	22/01/01	182	403.66	3.81	4800	4824	4800
2016000	910081	19/02/01	210	19/02/01	210	21/02/01	212	725.02	14.48	8210	8222	8210
2016001	901019	19/01/01	179	19/01/01	179	22/01/01	182	893.52	8.67	12263	12263	12263
2016002	910061	19/01/01	179	19/01/01	179	19/01/01	179	199.01	2.75	2000	2000	2000
2016003	910061	18/01/01	178	18/01/01	178	18/01/01	178	92.49	2.59	740	740	740
2016004	910061	18/01/01	178	18/01/01	178	19/01/01	179	393.96	7.92	4306	4306	4306
2016005	901014	18/01/01	178	18/01/01	178	18/01/01	178	69.30	0.53	557	559	557

2016018	911405	31/01/01	191	31/01/01	191	31/01/01	191	115.15	2.07	1100	1100	1100
2016025	901026	25/01/01	185	25/01/01	185	25/01/01	185	116.31	1.52	1115	1115	1115
2016030	901043	30/01/01	190	30/01/01	190	30/01/01	190	422.48	7.92	5088	5067	5088
2016031	901043	01/02/01	192	01/02/01	192	25/04/01	273	986.17	20.73	12334	12343	12334
2016034	901054	23/01/01	183	23/01/01	183	24/01/01	184	675.00	9.82	9160	9160	9160
2016035	901025	23/01/01	183	23/01/01	183	23/01/01	183	115.70	1.88	1218	1218	1218
2016038	911405	24/01/01	184	24/01/01	184	14/02/01	205	1106.30	7.97	12732	12732	12732
2016071	910049	22/01/01	182	22/01/01	182	29/01/01	189	1311.56	23.52	16543	16543	16543
2016074	901142	22/01/01	182	22/01/01	182	23/01/01	183	732.14	13.20	9064	9064	9064
2016076	901143	24/01/01	184	24/01/01	184	14/02/01	205	626.62	4.40	7058	7058	7058
2016078	910081	21/02/01	212	21/02/01	212	21/04/01	269	699.92	14.50	8000	7925	8000
2016079	910100	29/01/01	189	29/01/01	189	29/01/01	189	520.18	8.92	6328	6328	6328
2016080	901039	25/01/01	185	25/01/01	185	25/01/01	185	107.25	2.07	998	998	998
2016090	901104	27/01/01	187	27/01/01	187	27/01/01	187	105.97	1.48	771	771	771
2016091	910049	23/01/01	183	23/01/01	183	23/01/01	183	73.16	2.00	558	558	558
2016092	901054	22/01/01	182	22/01/01	182	22/01/01	182	178.60	2.36	1900	1919	1900
2016096	901199	31/01/01	191	31/01/01	191	31/01/01	191	368.77	3.68	4008	4008	4008
2016097	901198	31/01/01	191	31/01/01	191	01/02/01	192	192.62	4.77	2100	2100	2100
2016098	910101	30/01/01	190	30/01/01	190	31/01/01	191	270.87	3.23	3110	3110	3110
2016100	901014	29/01/01	189	29/01/01	189	05/02/01	196	1481.83	20.42	20589	20617	20589
2016101	901191	29/01/01	189	29/01/01	189	29/01/01	189	103.87	2.50	1050	1050	1050
2016110	901127	30/01/01	190	30/01/01	190	02/02/01	193	2495.49	12.13	35011	35011	35011
2016114	910101	23/01/01	183	23/01/01	183	03/03/01	222	1118.11	19.13	14016	14046	14016
2016115	901149	22/01/01	182	22/01/01	182	06/02/01	197	2291.35	9.31	29190	29190	29190
2016116	901021	26/01/01	186	26/01/01	186	26/01/01	186	372.89	5.98	4870	4870	4870
2016119	901039	25/01/01	185	25/01/01	185	25/01/01	185	242.90	2.40	2749	2749	2749
2016120	901198	01/02/01	192	01/02/01	192	01/02/01	192	177.13	2.72	1900	1900	1900
2016121	901023	02/02/01	193	02/02/01	193	05/02/01	196	1169.37	14.56	16180	16180	16180
2016153	910049	01/02/01	192	01/02/01	192	13/02/01	204	1292.34	9.10	16295	16295	16295
2016177	910092	06/02/01	197	06/02/01	197	07/03/01	226	1796.06	7.57	25079	25079	25079
2016180	901011	05/02/01	196	05/02/01	196	05/02/01	196	260.02	3.28	2970	2970	2970
2016189	901038	02/02/01	193	02/02/01	193	02/02/01	193	262.50	1.23	3002	3002	3002

2016190	910101	02/02/01	193	02/02/01	193	02/02/01	193	111.28	0.46	1050	1050	1050
2016193	910049	13/02/01	204	13/02/01	204	20/02/01	211	1209.76	19.13	15225	15229	15225
2016195	901014	06/02/01	197	06/02/01	197	06/02/01	197	911.48	3.05	12518	12518	12518
2016209	911926	08/02/01	199	08/02/01	199	08/02/01	199	911.13	7.14	12513	12513	12513
2016211	910063	02/02/01	193	02/02/01	193	02/02/01	193	150.17	1.14	1313	1313	1313
2016221	901094	09/02/01	200	09/02/01	200	09/02/01	200	366.70	3.80	4347	4347	4347
2016222	901027	13/02/01	204	13/02/01	204	14/02/01	205	508.01	4.11	5655	5655	5655
2016223	910101	07/02/01	198	07/02/01	198	08/02/01	199	962.31	8.21	12035	12035	12035
2016224	910101	08/02/01	199	08/02/01	199	09/02/01	200	417.68	4.09	5005	5005	5005
2016225	901195	06/02/01	197	06/02/01	197	09/02/01	200	461.43	5.15	5104	5104	5104
2016226	912422	01/02/01	192	01/02/01	192	02/02/01	193	374.68	2.18	4450	4450	4450
2016229	901020	07/02/01	198	07/02/01	198	07/02/01	198	316.27	3.11	4066	4066	4066
2016230	901020	07/02/01	198	07/02/01	198	07/02/01	198	72.54	1.37	550	550	550
2016231	901143	05/02/01	196	05/02/01	196	07/02/01	198	878.80	10.52	10041	10041	10041
2016232	901199	09/02/01	200	09/02/01	200	10/02/01	201	385.00	6.88	4200	4200	4200
2016235	911927	13/02/01	204	13/02/01	204	13/02/01	204	804.86	5.14	11000	11004	11000
2016236	911927	09/02/01	200	09/02/01	200	12/02/01	203	982.89	18.23	13532	13532	13532
2016237	910100	07/02/01	198	07/02/01	198	08/02/01	199	249.86	1.83	3123	3123	3123
2016238	911284	07/02/01	198	07/02/01	198	07/02/01	198	68.59	4.14	549	549	549
2016241	901138	02/02/01	193	02/02/01	193	02/02/01	193	351.27	1.98	3801	3801	3801
2016243	901057	08/02/01	199	08/02/01	199	30/04/01	278	821.69	12.90	11378	11243	11378
2016244	901038	08/02/01	199	08/02/01	199	08/02/01	199	84.16	1.03	700	700	700
2016245	901054	08/02/01	199	08/02/01	199	08/02/01	199	71.76	0.92	540	540	540
2016246	910121	13/02/01	204	13/02/01	204	13/02/01	204	114.72	0.83	1200	1204	1200
2016250	901040	10/02/01	201	10/02/01	201	10/02/01	201	99.65	2.77	900	900	900
2016251	901112	08/02/01	199	08/02/01	199	09/02/01	200	168.03	2.23	1508	1508	1508
2016252	901199	27/02/01	218	27/02/01	218	28/02/01	219	297.08	4.04	3160	3160	3160
2016253	910071	02/02/01	193	02/02/01	193	03/02/01	194	548.14	9.15	6689	6689	6689
2016256	901014	14/02/01	205	14/02/01	205	15/02/01	206	919.37	11.61	12630	12630	12630
2016258	901197	08/02/01	199	08/02/01	199	12/02/01	203	504.53	13.22	6126	6126	6126
2016275	901108	22/02/01	213	22/02/01	213	09/04/01	259	840.76	17.25	10466	10466	10466
2016276	911426	09/02/01	200	09/02/01	200	09/02/01	200	395.91	3.86	4724	4724	4724

2016289	901145	07/02/01	198	07/02/01	198	20/03/01	239	2094.03	11.30	26643	26643	26643
2016297	910049	14/02/01	205	14/02/01	205	13/03/01	232	1126.86	4.39	14159	14159	14159
2016298	901202	15/02/01	206	15/02/01	206	15/02/01	206	174.33	3.00	1700	1708	1700
2016310	901048	10/02/01	201	10/02/01	201	10/02/01	201	334.37	6.00	3893	4323	3893
2016314	901011	12/02/01	203	12/02/01	203	12/02/01	203	114.47	1.42	1000	1000	1000
2016315	901038	13/02/01	204	13/02/01	204	13/02/01	204	170.39	1.41	1800	1813	1800
2016329	910092	14/02/01	205	14/02/01	205	09/04/01	259	1163.38	19.82	16088	16095	16088
2016331	901142	12/02/01	203	12/02/01	203	13/02/01	204	328.87	2.65	3536	3536	3536
2016333	910075	16/02/01	207	16/02/01	207	17/02/01	208	558.10	8.75	7500	7500	7500
2016334	901014	15/02/01	206	15/02/01	206	16/02/01	207	664.37	10.37	9009	9009	9009
2016335	911405	13/02/01	204	13/02/01	204	26/03/01	245	1208.09	21.92	13936	13936	13936
2016336	901094	15/02/01	206	15/02/01	206	19/03/01	238	1016.86	17.13	11668	11674	11668
2016353	901041	15/02/01	206	15/02/01	206	15/02/01	206	277.69	4.51	2575	2512	2575
2016370	901116	23/02/01	214	23/02/01	214	02/03/01	221	433.78	7.28	4777	4777	4777
2016371	901142	15/02/01	206	15/02/01	206	08/03/01	227	1096.49	3.74	13790	13767	13790
2016373	911405	21/02/01	212	21/02/01	212	10/04/01	260	1478.05	19.13	18692	18692	18692
2016389	901143	16/02/01	207	16/02/01	207	07/03/01	226	673.12	3.97	7608	7608	7608
2016390	901062	19/02/01	210	19/02/01	210	04/07/01	339	1167.89	19.58	19261	16159	19261
2016395	901127	19/02/01	210	19/02/01	210	22/02/01	213	1752.39	16.93	24447	24459	24447
2016396	910101	08/03/01	227	08/03/01	227	08/03/01	227	118.25	0.34	1140	1140	1140
2016405	901014	20/02/01	211	20/02/01	211	20/03/01	239	1683.52	7.83	23481	23481	23481
2016407	901011	16/02/01	207	16/02/01	207	19/02/01	210	610.97	12.37	7500	7500	7500
2016411	901054	23/02/01	214	23/02/01	214	23/02/01	214	575.14	12.27	7600	7742	7600
2016412	901096	23/02/01	214	23/02/01	214	27/02/01	218	721.84	11.77	8931	8931	8931
2016413	901052	05/03/01	224	05/03/01	224	07/03/01	226	804.73	3.63	10001	10001	10001
2016414	901197	22/02/01	213	22/02/01	213	22/02/01	213	249.23	2.20	3114	3114	3114
2016416	910049	20/02/01	211	20/02/01	211	27/02/01	218	1318.53	21.83	16609	16633	16609
2016432	912569	23/02/01	214	23/02/01	214	23/02/01	214	91.34	1.05	872	872	872
2016437	910071	20/02/01	211	20/02/01	211	10/03/01	229	1662.11	19.13	23177	23177	23177
2016449	901145	23/02/01	214	23/02/01	214	18/04/01	266	1180.56	20.98	16339	16339	16339
2016470	901043	13/03/01	232	13/03/01	232	13/03/01	232	139.94	0.46	1487	1420	1487
2016491	901144	28/02/01	219	28/02/01	219	01/03/01	220	1028.31	16.12	14175	14177	14175

2016495	901144	26/02/01	217	26/02/01	217	15/03/01	234	2739.72	12.26	38479	38479	38479
2016512	910049	27/02/01	218	27/02/01	218	05/03/01	224	1188.14	20.63	14950	14950	14950
2016513	911405	28/02/01	219	28/02/01	219	09/05/01	286	1237.34	21.77	15616	15585	15616
2016516	901021	26/02/01	217	26/02/01	217	27/02/01	218	455.07	7.68	6037	6037	6037
2016517	911926	02/03/01	221	02/03/01	221	02/03/01	221	103.52	0.85	1045	1045	1045
2016522	910100	02/03/01	221	02/03/01	221	02/03/01	221	466.55	5.08	6200	6200	6200
2016535	910071	28/02/01	219	28/02/01	219	22/03/01	241	1376.56	7.74	17377	17382	17377
2016549	901112	08/03/01	227	08/03/01	227	09/03/01	228	266.94	6.17	2400	2403	2400
2016552	910101	07/03/01	226	07/03/01	226	29/03/01	248	468.66	4.15	5663	5663	5663
2016553	910086	28/02/01	219	28/02/01	219	28/02/01	219	70.28	0.40	573	573	573
2016557	901038	06/03/01	225	06/03/01	225	07/03/01	226	326.18	1.62	3700	3824	3700
2016578	901023	08/03/01	227	08/03/01	227	13/03/01	232	1779.30	5.72	24841	24841	24841
2016591	910086	28/02/01	219	28/02/01	219	28/02/01	219	70.07	0.40	570	570	570
2016610	901010	12/03/01	231	12/03/01	231	29/03/01	248	748.73	7.09	10523	10207	10523
2016611	910006	02/03/01	221	02/03/01	221	08/03/01	227	673.26	2.22	8300	8304	8300
2016617	901021	02/03/01	221	02/03/01	221	02/03/01	221	143.31	1.71	1610	1610	1610
2016633	901127	06/03/01	225	06/03/01	225	08/03/01	227	2502.18	7.78	35106	35106	35106
2016635	910086	08/03/01	227	08/03/01	227	08/03/01	227	149.65	0.37	1700	1700	1700
2016636	910049	08/03/01	227	08/03/01	227	19/03/01	238	1334.49	21.59	16804	16839	16804
2016637	901145	05/03/01	224	05/03/01	224	06/03/01	225	595.00	10.78	8000	8024	8000
2016638	910071	07/03/01	226	07/03/01	226	08/03/01	227	528.87	1.64	7085	7085	7085
2016639	901031	06/03/01	225	06/03/01	225	06/03/01	225	54.95	0.67	323	323	323
2016640	901198	13/03/01	232	13/03/01	232	14/03/01	233	510.72	8.25	6206	6206	6206
2016641	901198	12/03/01	231	12/03/01	231	13/03/01	232	502.90	1.68	6105	6105	6105
2016653	901143	07/03/01	226	07/03/01	226	08/03/01	227	638.37	2.41	7197	7197	7197
2016656	901026	09/03/01	228	09/03/01	228	09/03/01	228	403.42	6.07	4753	4821	4753
2016658	901014	16/03/01	235	16/03/01	235	16/03/01	235	1017.04	9.24	14017	14017	14017
2016661	910121	06/03/01	225	06/03/01	225	06/03/01	225	49.65	2.60	280	280	280
2016669	910086	08/03/01	227	08/03/01	227	08/03/01	227	177.82	0.65	2100	2100	2100
2016673	910101	19/03/01	238	19/03/01	238	19/03/01	238	361.43	6.69	4279	4279	4279
2016676	910049	13/03/01	232	13/03/01	232	15/03/01	234	998.88	5.01	12462	12507	12462
2016678	901021	13/03/01	232	13/03/01	232	13/03/01	232	133.87	0.59	1476	1476	1476

2016689	901112	09/03/01	228	09/03/01	228	09/03/01	228	172.51	2.47	1590	1557	1590
2016691	901167	12/03/01	231	12/03/01	231	12/03/01	231	756.23	12.42	9375	9375	9375
2016695	901195	20/03/01	239	20/03/01	239	05/04/01	255	632.71	5.48	7130	7130	7130
2016731	901094	14/03/01	233	14/03/01	233	14/03/01	233	545.12	7.89	6650	6650	6650
2016749	901040	14/03/01	233	14/03/01	233	14/03/01	233	131.03	2.99	1300	1305	1300
2016750	910049	19/03/01	238	19/03/01	238	26/03/01	245	1253.22	17.07	15790	15790	15790
2016751	901198	15/03/01	234	15/03/01	234	15/03/01	234	332.07	1.87	3900	3900	3900
2016753	910049	20/03/01	239	20/03/01	239	21/03/01	240	496.24	9.10	6000	6019	6000
2016769	901197	22/03/01	241	22/03/01	241	23/03/01	242	752.54	8.65	10408	10261	10408
2016774	901011	14/03/01	233	14/03/01	233	16/03/01	235	982.30	9.89	12293	12293	12293
2016775	901027	23/03/01	242	23/03/01	242	26/03/01	245	483.07	6.26	5360	5360	5360
2016782	911426	21/03/01	240	21/03/01	240	22/03/01	241	395.45	2.04	4718	4718	4718
2016811	901142	16/03/01	235	16/03/01	235	19/03/01	238	715.89	11.97	8114	8114	8114
2016832	901143	28/03/01	247	28/03/01	247	29/03/01	248	679.96	5.73	7689	7689	7689
2016833	912499	22/03/01	241	22/03/01	241	22/03/01	241	198.82	0.88	2257	2180	2257
2016834	901054	22/03/01	241	22/03/01	241	22/03/01	241	163.10	0.64	1700	1719	1700
2016835	910071	22/03/01	241	22/03/01	241	23/03/01	242	735.99	10.48	10026	10026	10026
2016836	901019	20/03/01	239	20/03/01	239	22/03/01	241	1044.58	5.47	14216	14408	14216
2016838	901014	23/03/01	242	23/03/01	242	26/03/01	245	948.66	12.14	13046	13046	13046
2016850	911405	21/03/01	240	21/03/01	240	01/06/01	308	1216.63	23.43	14226	14037	14226
2016857	901199	22/03/01	241	22/03/01	241	22/03/01	241	401.91	2.36	4400	4400	4400
2016859	910101	23/03/01	242	23/03/01	242	26/04/01	274	910.10	3.95	11361	11361	11361
2016863	901054	28/03/01	247	28/03/01	247	28/03/01	247	264.67	3.92	3000	3030	3000
2016875	901127	29/03/01	248	29/03/01	248	02/04/01	252	2499.37	40.63	35066	35066	35066
2016893	911927	29/03/01	248	29/03/01	248	30/03/01	249	717.11	11.20	9758	9758	9758
2016896	901041	28/03/01	247	28/03/01	247	28/03/01	247	108.18	3.33	1000	1010	1000
2016898	901020	28/03/01	247	28/03/01	247	21/06/01	326	969.58	20.32	13403	13343	13403
2016899	901054	27/03/01	246	27/03/01	246	27/03/01	246	270.09	6.00	3100	3100	3100
2016911	901144	26/03/01	245	26/03/01	245	05/04/01	255	2410.99	13.65	33811	33811	33811
2016912	910100	29/03/01	248	29/03/01	248	29/03/01	248	121.83	0.95	1300	1305	1300
2016929	910049	27/03/01	246	27/03/01	246	26/04/01	274	2431.42	10.78	30998	30998	30998
2016935	910061	30/03/01	249	30/03/01	249	30/03/01	249	155.90	4.12	1490	1490	1490

2016950	901199	28/03/01	247	28/03/01	247	28/03/01	247	303.08	4.83	3200	3231	3200
2016951	910101	28/03/01	247	28/03/01	247	26/04/01	274	964.64	4.40	12000	12065	12000
2016955	910006	29/03/01	248	29/03/01	248	04/04/01	254	379.25	8.72	4500	4509	4500
2016977	901145	27/03/01	246	27/03/01	246	02/04/01	252	1012.59	16.76	12684	12684	12684
2016989	910101	29/03/01	248	29/03/01	248	29/03/01	248	40.39	0.08	135	135	135
2016990	910101	29/03/01	248	29/03/01	248	29/03/01	248	39.23	0.37	120	120	120
2017014	901142	30/03/01	249	30/03/01	249	25/04/01	273	1179.78	26.15	14842	14842	14842
2017017	910123	30/03/01	249	30/03/01	249	30/03/01	249	47.11	0.53	244	244	244
2017030	901038	29/03/01	248	29/03/01	248	29/03/01	248	48.60	0.33	241	241	241
2017031	901038	29/03/01	248	29/03/01	248	29/03/01	248	76.80	0.43	600	605	600