AN EXPERIMENTAL STUDY OF CAPACITY EXPANSION AND SEQUENCING ALTERNATIVES FOR A FLAT ROLLED METAL PRODUCER

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

MEHMET MURAT ARER

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF
MASTER SCIENCE
IN
THE DEPARTMENT OF INDUSTRIAL ENGINEERING

SEPTEMBER 1997

Approval of the Graduate School of Natural and Applied Sciences.

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ABSTRACT

AN EXPERIMENTAL STUDY OF CAPACITY EXPANSION AND SEQUENCING ALTERNATIVES FOR A FLAT ROLLED METAL PRODUCER

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September 1997, 144 pages

In this thesis, a computer simulation study performed in a make-to-order producer of flat rolled aluminum foil and sheet/strip products is presented. A subsystem of the factory consisting of continuous casting, cold-rolling and annealing processes has been analyzed to investigate the effects of various capacity expansion alternatives and order sequencing rules on the selected performance measures of the production system.

The performance measures of concern are flow time, work-in-process levels, utilization of the processes, and tardiness related measures. Based on these performance criteria, the capacity expansion alternatives and sequencing rules have been evaluated with the objectives of satisfying the demand, balancing the process loads, and keeping the work-in-process inventory under control. In addition, various levels of increase in demand have been tried in a capacity expansion alternative that has excess production capacity under current demand.

Two simulation models have been developed, a combined continuous and discrete-event model for studying the continuous casting process only, and a pure discrete-event model for comparing various capacity expansion alternatives and sequencing rules in the subsystem of concern. Operational characteristics of the real system and past data have been analyzed extensively for modelling and validation purposes.

Analysis of variance (ANOVA) has been used for statistical analysis of the results. Within each capacity expansion alternative, observed values of performance measures have been tested to detect significant differences caused by the sequencing rules. Results of the experiment for each capacity expansion alternative are presented and discussed on the basis of objectives given above, and recommendations for the future work are made.

Keywords: Flat Rolled Metal Production, Combined Simulation, Capacity Planning, Sequencing Rules.

ÖZ

BİR HADDELENMİŞ YASSI METAL ÜRETİCİSİNDE KAPASİTE ARTIRIM VE SIRALAMA SEÇENEKLERİNİN DENEYSEL ÇALIŞMASI

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Eylül 1997, 144 sayfa

Bu tezde, sipariş üzerine üretim yapan bir haddelenmiş alüminyum folyo ve levha/şerit mamül üreticisinde yapılan bilgisayar benzetim çalışması sunulmuştur. Fabrikanın sürekli döküm, soğuk hadde ve tavlama proseslerini içeren alt sistemi, kapasite artırım seçenekleri ve sipariş sıralama kurallarının seçilen üretim sistemi performans ölçütleri üzerindeki etkilerini incelemek üzere analiz edilmiştir.

Üretim süresi, üretim içi stok seviyeleri, proses kullanım oranları ve sipariş gecikmesine ilişkin ölçütler, performans ölçütleri olarak seçilmiştir. Bu performans kriterlerine dayanarak, talepleri karşılamak, proses yüklerini dengelemek ve proses içi stok seviyelerini kontrol altında tutabilmek amacıyla kapasite artırım seçenekleri ve sıralama kuralları değerlendirilmiştir. Ek olarak, şu anki talep seviyesinde fazla üretim kapasitesine sahip kapasite artırım seçeneğinde değişik talep seviyeleri denenmiştir.

İki benzetim modeli kurulmuştur. Bir tanesi yalnızca sürekli döküm prosesini çalışabilmeği, diğer model seçilen alt sistemde kapasite artırım seçeneklerini ve sıralama kurallarının

karşılaştılmasını amaçlamaktadır. Gerçek sistemin işletim özellikleri ve geçmiş veriler model kurma ve doğrulama amacıyla analiz edilmiştir.

Sonuçların istatiksel analizinde varsayns analizi yöntemi kullanılmıştır. Herbir kapasite artırım seçeneğinde performans ölçütlerinin gözlenen değerleri, sıralama kurallarının sebep olabileceği önemli farklılaşmaları belirleyebilmek için test edilmiştir. Kapasite artırım seçeneklerinin deney sonuçları sunulup, yukarıda verilen amaçlar doğrultusunda tartışılmıştır. Son olarak, ileriki çalışmalar için öneriler yapılmıştır.

Anahtar Kelimeler: Haddelenmiş Yassı Metal Mamül, Benzetim, Kapasite Planlama, Sıralama Kuralları.

To My Mother, SUNA ARER

and

In Memory of My Father, RIDVAN ARER

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor, *Dr. Nur Evin Özdemirel*, for her supervision, guidance, and continual support throughout the course of this study. I also wish to express my appreciation to my co-supervisor, *Dr. M. Vedat Akdeniz*, for his co-supervision, valuable insights, comments, and constant encouragement.

I would like to state my sincere thanks to *Mr. Esat Nadir Eryılmaz* for his contributions at each stage of the study, close interest, never-ending support and encouragement, giving me vital strength through this study.

The support supplied by *ASSAN Alüminyum, Tuzla-İstanbul* (ASSAN Demir ve Sac Sanayii A.Ş.) is also gratefully acknowledged. Especially, I would like to express my appreciation to *Mr. Güngör Yıldızbayrak*, without whose expertise and support, this study could not have progressed successfully.

Finally, my greatest thanks are sent to *my parents* who shaped me with never-ending patience and love.

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CHAPTER 1

INTRODUCTION

Pressure of highly competitive market environments demanding flat rolled metal products in large amounts with desired mechanical properties have forced the metal industry to improve their manufacturing technologies with production processes offering both economical and metallurgical advantages. Consequently, technological innovations achieved especially in manufacturing of flat rolled aluminum products, not only introduce new technology that enhances the manufacturing functions and lowers the production costs, but also provide higher-quality products. Moreover, their flexibility allows the producer to meet current commitments and gives the opportunity to satisfy future production increases and customer requirements by implementing new casting techniques in the production environment.

Nevertheless, equal in importance to the choice of the suitable production technology is the determination of the required capacity levels of the production system components to keep the process loads balanced and satisfy the customer orders within their due dates. Likewise, production planning is another issue in the production system to get the benefit of selected production technology with appropriate capacity level. Sequencing the customer orders waiting to be processed in various steps of the production system is essential to increase the production, maintaining balanced processing loads on the components of the production system, high utilization of processes, and low work-in-process levels. Also, the flexibility of the production system, which allows to adapt to the variability in the product mix and possible increases in customer orders, is desirable in metal sector where competitiveness is influenced by operating costs and productivity.

The production system that we are concerned with throughout this study is a manufacturer of flat rolled aluminum products, namely aluminum sheet/strip and foil products. A subsystem of the factory consisting of continuous sheet casting, cold-rolling and annealing processes has been analyzed through computer simulation. This subsystem produces sheet coils of various aluminum alloys that are used in sheet/strip and foil production. However, continuous casting of sheet constitutes a bottleneck for the downstream production because of the capacity limitation of this process. Hence, the factory management has plans to expand the production capacity, not only in continuous sheet casting line but also in cold-rolling and annealing processes. In addition, it has been observed that there is no common practice in sequencing of the customer orders which have varying processing requirements and production routes in the system. Therefore, determination of the capacity of subsystem components and selection of the appropriate sequencing rule applicable in the system are two issues constituting the main focus of this research.

Simulation is a powerful analysis tool available for the design and operation of the complex processes and systems, as in our case. It can be defined as the process of developing a model of a real system and conducting experiments with this model for evaluating various strategies for the operation of the system. Simulation has become a widely used tool for studying the real world systems under various experimental conditions. Its application areas cover a wide range, particularly the cases where the system is too complex to be modelled and studied analytically. Consequently, organizations are turning increasingly to simulation as a vehicle for dynamic analysis prior to implementation.

As stated above, a computer simulation study has been carried out to investigate the effects of various capacity expansion alternatives and order sequencing rules on the selected performance measures of the production system. The performance measures of concern are flow time, work-in-process levels, utilization of the processes, and tardiness based measures. Based on these performance criteria, the best capacity expansion alternative and sequencing rule that will satisfy the demand in time, balance the process loads, and keep the work-in-process inventory under control have been tried to be identified. These also enable us to concern with eliminating the bottleneck and increasing the production to desired level. In addition, for the capacity expansion alternative that has excess production capacity with the current process load on the system, the demand rate has been increased in order to observe the behaviour of the system under various load levels.

The thesis is organized as follows:

In order to provide ease of presentation of the production system of concern, the manufacturing systems for flat rolled metal production are described briefly in Chapter 2, with references to the system of interest. Also, basic definitions and concepts in metalworking, main process components in continuous sheet/strip casting type production of flat rolled metal products, and designation and characteristics of aluminum alloys and products are given in Appendices A, B, and C, respectively, as references throughout the study.

In Chapter 3, the production system that we are concerned with is presented in detail, giving emphasis to the selected subsystem. Chapter 4 is dedicated to the description of the constructed simulation models. Assumptions, input and output parameters used during the execution of the model are explained. Design and analysis of the experiment are provided in Chapter 5. First, the selected factors and their levels are given. Then, the analysis of the experiment and discussion of the results are presented. For each capacity expansion alternative, the effects of the selected sequencing rules on the performance measures are tried to be investigated. Finally, Chapter 6 includes concluding remarks and some suggestions for future work.

CHAPTER 2

MANUFACTURING SYSTEMS FOR FLAT ROLLED METAL PRODUCTION

In this chapter, the manufacturing systems for the production of flat rolled metal products are presented, giving the emphasis to newly arising technological advances which have been accomplished in metal industry specific to manufacturing of sheet/strip and foil metal products and the production process components and equipment for flat rolled metal production.

Initially, the common approaches utilized in the present flat rolled metal production technology are briefly introduced to give the chance of comparing the production systems. Additionally, some basic concepts and definitions in metalworking literature are conferred in Appendix A, in order to achieve ease of the presentation of the study and discussion of the results.

2.1. Classification of Flat Rolled Metal Production Systems

There are basically three common approaches utilized in the present flat rolled metal production technology whose production steps are shown in Figure 2.1.

i) *Conventional Discontinuous Production:* After the melting operation is completed and the desired alloy composition is prepared, the production sequence typically starts by semi-continuous casting of direct chill (DC) ingots 50-75 cm thick. Heavy scale due to high temperature is removed initially by rolling the ingot. Then, the initial breakdowns of ingots into slabs is generally done by hot-rolling on the primary roughing mills. These mills are usually two-high reversing mills and these initial breakdown passes often involve only small reductions. The only purpose of this operation is the breakdown of the cast ingot into slabs for subsequent finishing into bars, plate or sheet. Since slabs are subsequently formed into other mill products, they are known as semi-finished products having 1-5 cm thickness. This is followed by further hot-rolling to obtain 0.25-0.60 cm thick coiled re-roll stock for flat rolled metal products manufacturing and other structural shapes. Therefore, such a "hot-line" production approach is not only appropriate for manufacturing of flat products but also other useful shapes such as tubes and rods. Further breakdowns are applied by cold-rolling, producing plate, sheet/strip and foil with good surface finish and increased mechanical strength, at the same time maintaining close control over the dimensions of the product. The difference between plate and sheet is determined by the thickness of the product. In general, plate has a thickness greater than 6 mm, although there are exceptions to this limit, depending on the width. Sheet and strip refer to rolled products which generally have a thickness less than 6 mm. In general, strip refers to rolled product with a width no greater than 600 mm, while sheet refers to the product of greater width.

ii) *Continuous Slab Casting:* In this production approach, continuous slab, typically 1-5 cm thick, is cast by introducing molten metal between parallel travelling mould surfaces. Then, in-line hot-mills reduce the hot slab to coils of re-roll stock. The continuous nature of this method allows the opportunity to eliminate several fabrication operations before hot-rolling operation involved in the traditional method. There are two approaches to slab casters. In Hazelett twin belt slab caster, water cooled steel belts are chosen to use belts for the moulds, whereas the Alusuisse Caster II employs massive metal chill blocks (Bachowski et al., 1988). In both cases, the slab exits the caster below recrystallization temperature, so that re-heating is generally required subsequent to hot-rolling. The combination of high casting rate and long mould length promotes significant solidification shrinkage, but this can easily be healed during the in-line hot-rolling step. Subsequent breakdowns for flat rolled metal products are applied by cold-rolling as in the case of conventional discontinuous production.

iii) *Continuous Sheet/Strip Casting:* The most common form of sheet/strip casting is the well-known roll casters, principally manufactured by Hunter Engineering, Lauener, Pechiney and Krupp (Bachowski et al., 1988). Twin roll casting has been accepted world-wide as a cost-effective method of producing a wide variety of flat rolled products. The twin roll casting process converts molten metal alloys directly into coiled sheet/strip suitable for cold-rolling by combining solidification and hot-rolling into a single operation; thus effectively eliminating the operations associated with traditional DC casting and hot-mill method of coil production. Nominal 6 mm thick coiled re-roll stock is produced by introducing molten metal between internally water cooled rolls. Significant hot deformation also takes place between the rolls, corresponding to the hot-rolling operation. On exiting the casting machine, the resultant solidified sheet/strip is wound into a coil suitable for cold-rolling, and further reductions in thickness are performed by cold-mills as in the previous cases, with interposing annealing operations to restore the ductility to the metal that has been severely strain-hardened.

Approaches in Flat Rolled Metal Production Systems

a) Conventional Discontinuous Production	*b) Continuous Slab Casting*	*c) Continuous Sheet/Strip Casting*
Melting and Alloy Preparation	Melting and Alloy Preparation	Melting and Alloy Preparation
↓	↓	↓
DC of Ingot *Product:* **Ingot**	Continuous Casting of Slab *Product:* **Slabs (Semi-finished products)**	Continuous Casting of Sheet/Strip *Product:* **Coilable Sheet/Strip**
↓	↓	↓
Sawing and Scalping	Re-heating	Cold-Rolling - Annealing Cycle *Product:* **Sheet/Strip or Foil Products in desired thickness**
↓	↓	
Homogenizing	Hot-Rolling and Edge Trim *Product:* **Coilable Sheet/Strip**	
↓	↓	
Re-heating	Cold-Rolling - Annealing Cycle *Product:* **Sheet/Strip or Foil Products in desired thickness**	
↓		
Hot-Rolling and Edge Trim *Product:* **Slabs (Semi-finished products)**		
↓		
Hot-Rolling *Product:* **Coilable Sheet/Strip**		
↓		
Cold-Rolling - Annealing Cycle *Product:* **Sheet/Strip or Foil Products in desired thickness**		

Figure 2.1. Comparison of the Three Most Common Methods for Manufacturing of Flat Rolled Metal Products

2.2. Production System Used in Flat Rolled Aluminum Products

In increasingly competitive world aluminum market, the direct production of coilable sheet/strips by the twin-roll casting process has become a standard practice in the aluminum industry due to both the financial and metallurgical advantages offered by the process.

Today, most of the commercial, non-heat treatable (strain-hardenable) aluminum alloys (see Appendix C) can be produced by the twin-roll casting process.

As indicated above, the enthusiasm about twin-roll casting derives from the potential benefits of the process that are both economic and metallurgical. First of all, the capital investment for a twin-roll caster is significantly lower than that of a conventional ingot-casting/hot-rolling process. Also, since the process combines solidification and hot-rolling into a single operation and produces sheet/strips that are readily coilable, the subsequent hot-rolling that is needed during a conventional strip production is spared, resulting in savings in energy. In addition, significant benefits accrue from the elimination of some cold-rolling passes. This lowers the processing cost of the sheet/strip and increases throughput tonnage in plants limited by the cold-mill capacity. Consequently, the lower capital investment and lower operational costs result in a significantly lower conversion cost for twin roll caster-based plants.

From a metallurgical perspective, the high solidification rate in the process enables the twin-rolled thin sheet/strip to have a refined metallurgical microstructure which is more appropriate to manufacture flat rolled aluminum products. Within this continuously cast structure, aluminum foil of 5.0 μm can be produced.

Tendency to cast thinner aluminum and recent advances in thin-gauge roll-casting have further improved the economic advantage of roll casters over the traditional hot-mill since further savings in energy, time, labour and capital investment are obtained by reduced number of passes in the cold-mill when the initial thickness is much lower than the conventional one (Beals et al., 1995 and Taraglio et al., 1995). These advances were the combined result of a better understanding of the fundamental solidification mechanisms, the evolution of the casting machinery, and associated automation to control the casting process.

Details of the processes and the associated machinery in continuous cast sheet/strip type production method of flat rolled metal products are described in Appendix B, to supply better understanding in presenting the system that the simulation study has been conducted. Moreover, designation and characteristics of aluminum alloys and products are given in Appendix C in order to provide ease of explanation of the product mix and production routes in the system.

CHAPTER 3

DESCRIPTION OF FLAT ROLLED METAL MANUFACTURING SYSTEM UNDER CONSIDERATION

As indicated in Chapter 1, in this thesis, a computer simulation study has been performed for a system manufacturing flat rolled metal products, more specifically aluminum sheet/strip and foil products. Essential characteristics of the system are presented in this chapter.

3.1. General Information About the Factory

The manufacturing system under consideration is one of the main producers of flat rolled aluminum products in metal industry in Türkiye. The factory located on a 250000 m^2 field in İstanbul-Türkiye was founded in 1987. It has increased its production capacity and improved its manufacturing technology continuously to increase its share in world aluminum market.

The product mix of the factory is composed of a variety of aluminum sheet/strip products that are used mainly in construction, and aluminum foil products with varying characteristics for use in isolation, packaging and household applications. Currently, the production capacity of the factory is approximately 20000 tons per year. However, this production capacity is not sufficient to meet all the demand. Therefore, the company has been searching for newly arising technologies, especially in continuous casting process, to expand its capacity. There have been huge investments some of which are in construction and some have already started trial production.

The production in the factory is mainly make-to-order. Customer orders are received with specific product characteristics and due dates, and then scheduled for production. The annual demand in 1995 was approximately 15200 tons for sheet/strip products and 2100 tons for foil products. The demand has been increasing since then. Furthermore, the expectation of increase in the share of foil products compared to sheet/strip products also forces the company to invest in foil production line in order to increase the capacity of foil production.

3.2. Product Mix

As stated, there are basically two flat rolled aluminum product types produced in the plant:

- foil products, (flat rolled metal having thickness less than 0.15 mm), and
- sheet/strip products, (flat rolled metal over 0.15 up to 6.0 mm in thickness).

They are processed into desired dimensions and forms in foil production and sheet/strip processing lines, respectively. The semi-finished products sent to these departments are the aluminum sheet coils that are

- continuously cast in-house with desired alloy composition and then processed to planned thickness, width and mechanical performance level (mechanical properties including hardness and strength of the material defined by the degree of strain hardening applied in cold-rolling operation) by subsequent cold-rolling and annealing operations in cold-mill and annealing stations.
- purchased from outside producers in various thickness, width and mechanical performance levels and then rolled and annealed in cold-mill and annealing stations.
- purchased from outside producers as foil stock having suitable thickness to be processed in foil production line. Those coils are routed to foil production line directly.

These sheet coils are regarded as semi-finished products since they are processed further to produce either sheet/strip or foil products. Therefore, as pointed out above, these sheet coils, after processed in cold-mill and annealing stations, are sent to either sheet/strip processing or foil production lines according to their processing routes. In sheet/strip processing line, sheet is formed into desired shape and dimensions and packaged for shipping to customer. In foil production line, the sheet that has been reduced to a certain thickness in cold-rolling operation are further rolled in intermediate and finishing foil mills and annealed to achieve final desired thickness and mechanical performance. Total order and production amounts of final products that were realized in 1995 are tabulated in Table 3.1. Also, Tables C.2 and C.3 in Appendix C summarize the most common uses of that the final products of the factory.

Table 3.1. Total Order and Production Amounts of Final Products in 1995

Form of the Final Product	Order Amount (kg)	% of Total	Production Amount (kg)	% of Total
Coiled Sheet/Strip	6,833,341	44.74	7,208,690	46.91
Cut to Length Plate Sheet	3,792,059	24.83	3,915,682	25.47
Corrugated Sheet/Strip (For roof and siding app.)	1,034,024	6.77	2,008,326	6.56
Pressed Plate	2,127	0.01	2,160	0.01
Accessory parts used in construction applications	191,394	1.25	127,889	0.83
Coiled Plate	382,316	2.5	393,715	2.56
Sandwich Panel	2,939,178	19.24	2,557,756	16.64
Other Sheet/Strip Products	98,078	0.64	154,037	1.00
TOTAL Amount of Sheet/Strip Products	15,272,521	**87.92**	15,368,255	**91.73**
TOTAL Amount of Foil Products	2,097,646	**12.08**	1,384,883	**8.27**
TOTAL	**17,370,163**	**100.0**	**16,753,138**	**100.0**

Final product properties that affect the production route and processing characteristics are:

1. Alloy composition: Chemical alloy composition gives the general mechanical and physical properties to the material. The reader may refer to Appendix C for related information about designation and characteristics of aluminum alloys.
2. Thickness: Determines the number of rolling operations required to obtain desired final thickness and mechanical performance for the final product.
3. Width.
4. Surface characteristics.
5. Mechanical properties (including hardness, strength, ductility and toughness): Mechanical properties of the final product depend on the alloy chemical composition and the degree of strain-hardening that is adjusted by cold-rolling and annealing operations. The temper (mechanical condition) designation of aluminum alloys determines the sequence of basic treatments to produce aluminum products in desired mechanical performance level. Appendix C provides more detailed information about temper designation of aluminum alloys.

As indicated above, the alloy composition is the most significant characteristic that determines the mechanical and physical behaviour of the materials. Therefore, alloy type with well defined composition specification is a commonly used criterion in selecting a material for a specific application. Generally, strain-hardenable aluminum alloys (see

Appendix C) are used to produce flat rolled sheet/strip and foil products. The strain-hardenable aluminum alloys that are cast or purchased in the manufacturing system under consideration can be listed as follows.

- 1000 series: ductile so has high formability; generally used in sheet/strip or foil form for packaging and isolation applications. Most common alloys used commercially in this group are: 1050, 1060, 1100, 1230, 1235.
- 3000 series: includes Mn; has high strength and elasticity; typically used as siding and roof material, or in kitchen utensils and pressure proof tube applications. Commercially used alloys in this group are: 3003, 3004, 3005, 3105.
- 8000 series: includes iron; typical applications are pilfer proof, cigarette foil and household foil. Commercially used alloys in this series are: 8011, 8050, 8079.
- AA90 alloy: it is the alloy specification having intermediate mechanical properties between 3000 and 8000 series; typically used in construction applications.

The amount of aluminum alloys used in 1995, in manufacturing of sheet/strip and foil products, are given in Table 3.2. These values show that there are a few popular strain-hardenable aluminum alloys in each group, demanded in various final thickness values and at different mechanical performance levels, and used commercially in various applications.

Table 3.2. The Amounts of Aluminum Alloys Used in Production in 1995

Alloy	Production Amount (Ton)	% of Total
1050	7,451	44.5
1100	574	3.4
3003	2,309	13.8
8011	816	4.9
Others (1230, 1235, AA90, 8079)	5,603	33.4
Total	**16,753**	**100.0**

3.3. Production Flow Characteristics

Production flow in the flat rolled aluminum products manufacturing system is illustrated in Figure 3.1. Production in the system starts with continuous casting of sheet having different chemical compositions in a particular order dictated by the process requirements. Basic factors that affect the order of alloys in casting sequence are:

- Amount of customer orders in a particular time interval for each alloy type.
- Some technical limitations in continuous casting line, including characteristics of aluminum alloys and casting rolls' surface conditions which will be discussed in detail in the following section.

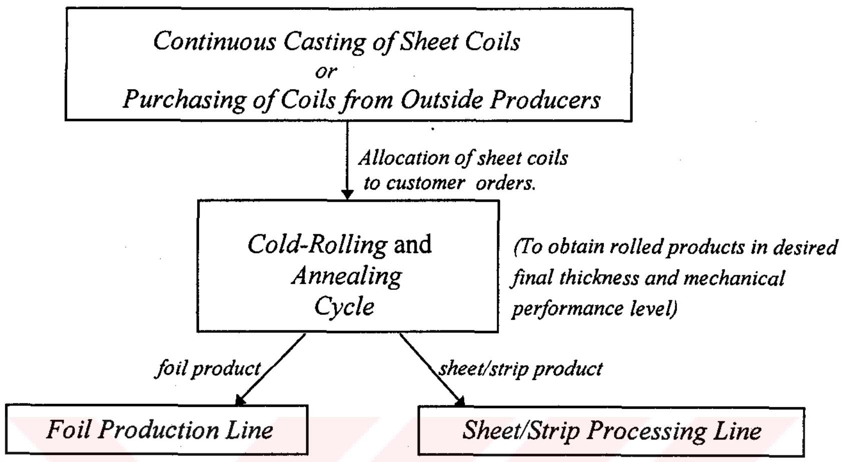

Figure 3.1. Flow of Production in the Manufacturing System

The output of casting, aluminum sheet having constant width and chemical composition (alloy type specified by the customer) is coiled around a reel to make it ready for further processing.

The annual capacity of the continuous caster is about 10000 tons whereas the annual total demand was approximately 17300 tons in 1995, as indicated in the previous section. Moreover, the demand has been increasing since then. Therefore, casting process in the factory constitutes the bottleneck for downstream production steps of sheet/strip and foil products. To overcome this capacity limitation, the factory management has been purchasing cast coils with varying chemical and mechanical properties from outside suppliers. Mainly, two forms of coils are purchased.

i. Sheet Coil Stock: Generally, they have thickness ranging in between 6-10 mm, and varying mechanical properties due to the variation in suppliers' production methods. Hence, these imported coils are often out of specifications and require different processing sequences.

ii. Foil Coil Stock: These are directly used for foil production since their thickness is suitable to be processed in the foil production line.

Although the factory management is forced to purchase coils from outside, it is unwilling to do so because of two reasons. These are:

1. Purchasing costs are higher than in-house casting, and
2. Purchased coils are often out of specifications creating quality problems and extra processing requirements.

As mentioned previously, the production is make-to-order. Customers specify requirements that they expect from the final product. Amount, dimensions (final thickness, width, and special product forms), alloy type (chemical composition), quality specifications, and mechanical properties (hardness, strength, toughness, ductility) are the basic product characteristics that are used to specify the final products.

The produced or purchased coils of cast sheet are allocated to customer orders. The common practice used in the factory in allocating coils to customer orders is as follows. For foil product orders, they try to use purchased foil stock in order to minimize the load on the cold-rolling process, and use in-house cast and purchased sheet coil stocks for the sheet/strip product orders. However, there are some cases in which this principle for foil production is not put into practice.

The coils are processed in a sequence of cold-rolling and annealing operations in order to obtain the desired final thickness and mechanical properties. The routing between these two processes is determined by the alloy type, desired final thickness and mechanical properties. Actually, except some common practices, there is no standard production sequence in cold-rolling and annealing cycle because of the following two reasons.

1. The incoming coils for the cold-rolling and annealing processes are not standard. They have varying initial thickness and mechanical properties.
2. There is a wide range of product mix demanded by the customers with various thickness, width, chemical composition, quality, and mechanical performance values. In particular, the desired mechanical performance levels cause changes in routing.

In general, coils that will be used for foil production go through the cold-rolling and annealing operations a number of times more than the ones allocated to sheet/strip products. Hence, they have larger number of operations and longer processing times.

After cold-rolling and annealing steps are finished in this sheet coil processing subsystem, coils are subsequently sent either to sheet/strip processing line or to foil production line where they are further processed to produce the finished products, as explained briefly in the previous section. The cold-rolling and annealing processes are described further in the following sections.

In sheet/strip processing line, after the sheet coils are stretched in tension-levelling line, they are processed into different forms in roll-forming and sandwich panel lines and reworked into desired dimensions in sheet/strip slitting and cut-to-length machines. In foil production line, on the other hand, further cold-rolling steps are performed on intermediate mill and on finishing foil mills. Finally, a full annealing operation is conducted in the foil annealing furnaces to obtain foil products in desired final thickness and mechanical properties. Then, these coils of foil are prepared in different dimensions by separation and slitting operations. The processes applied in sheet/strip processing and foil production lines, however, are beyond the scope of this study.

Material handling in such a complex manufacturing system is a major problem, hence effective storage and transportation systems are essential. In the factory, transportation of coils from one station to another is generally performed by forklifts. Within a station, however, carrying coils from one location to another is done by manually controlled cranes.

The coils are stored at particular stock areas at every step of the production. The stocks in the system are classified as follows.

- Coil Stock: Stock of aluminum sheet coils that are cast in-house or purchased from suppliers and ready to be processed. In some cases, coils of a specific alloy have to be cast in amounts more than the actual demand due to technical restrictions in the continuous casting line. These coils are stored in cast coil stock area. Similarly, coils purchased from other producers come to the system in batches and are stocked in purchased coil stock area.
- Foil Stock: Stock of coils that are purchased from suppliers to be used directly in foil production line.

- Work-In-Process Stock: Coils that are waiting to be processed in cold-rolling, annealing or further processes are kept in the work-in-process storage area.
- Semi-finished Product Stock: Coils of a specific alloy that are cast more than the actual demand are processed up to a certain planned thickness in cold-mill. These are then stored as semi-finished products to be allocated to the next customer order. However, the level of this stock is generally tried to be kept low in order to reduce the inventory costs.
- Finished Product Stock: These are sheet/strip and foil products waiting to be shipped to the customer.
- Raw Material Stock: Al-ingots purchased from the suppliers and alloying elements used in alloy preparation according to specified chemical composition.
- Scrap Stock: Work-in-produced scrap is recycled in melting operation to obtain molten metal in desired chemical composition. These are stocked according to their alloy type.

3.4. Definition of the Subsystem Under Consideration

We are concerned with the subsystem of the factory consisting of continuous casting, cold-rolling, and annealing processes. As described explicitly in the previous section, this subsystem produces aluminum sheet coils having various chemical compositions, thickness values, and mechanical performance levels. These coils are regarded as semi-finished products since they are used in sheet/strip and foil product manufacturing. The production flow in this subsystem is displayed in Figure 3.2 in which the flow of materials (coils in process) and information (cast order and search of coil stocks by incoming customer orders) are tried to be illustrated schematically.

Since the continuous casting process is a bottleneck for the downstream processes, and furthermore, there is a forecasted increase in demand especially for foil products, the management of the factory has been trying to expand the capacity by investing in recently arising technologies and installing new machinery.

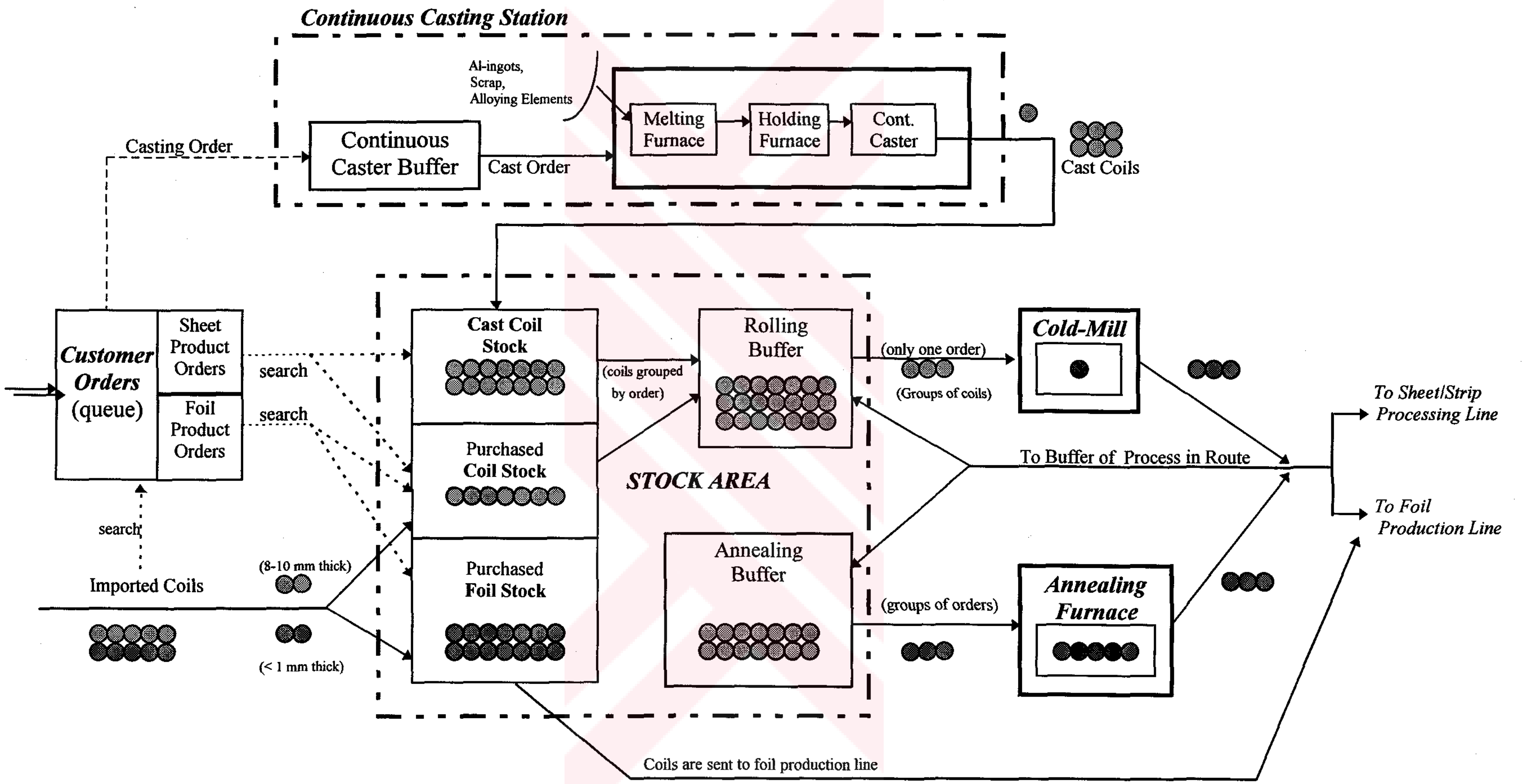

Figure 3.2. Production Flow in the Aluminum Sheet Coil Production Subsystem

Recently, trial production has been started with a 6.0 mm gauge in the newly installed continuous casting line which is capable of casting aluminum sheet in 1.0 mm thickness and 2000 mm width. This will bring economic advantages by saving energy, time, and labour as a result of reduced number of passes in the cold-mill. (This new casting line has been installed after the system analysis was completed. Therefore, it has been ignored in this study.) Moreover, construction of a new cold-mill with higher capacity than the current one is in progress. Factory management has further plans to invest in continuous casting, cold-rolling and annealing processes.

The purpose of this study is to investigate the effects of these capacity expansion alternatives on the sheet coil production and to come up with a capacity configuration that can balance the process loads. Additionally, the sequencing of customer orders waiting to be processed in cold-mill and annealing furnace is another important issue that will be considered to maintain a higher productivity and balanced production flow in the manufacturing system.

3.5. Coil Production System Components

In this section, the processes involved in the subsystem under consideration for the production of aluminum sheet coils and the system components in which these processes are performed are described.

Continuous Casting Line:

Components of Continuous Casting Line: The continuous casting line whose layout is illustrated in Figure 3.3 has three main components: a melting furnace, a holding furnace and a continuous sheet caster.

- Melting Furnace: A computer controlled melting furnace having 20 tons molten metal capacity, is used to melt all groups of aluminum alloys. The furnace is equipped with two regenerative burners and is capable of melting 3000 kg aluminum alloy per hour. Gas is used as the source of energy. Chemical analysis of the prepared alloys is carried out continuously with spectrometric methods.
- Holding Furnace: It has 10 tons molten metal holding capacity. It is equipped with one burner which regulates the temperature of the molten metal at desired and uniform level. Actually, holding furnace is the backup molten metal pool for the casting operation.

- Continuous sheet casting machine: It is an industrial Hunter twin roll, continuous sheet casting machine which is known as "SuperCaster". It is generally operated with casting gauges between 8 and 10.5 mm thickness and is capable of casting sheet products with 1700 mm width. Annual production capacity of this caster is approximately 10000 tons.

Process Description: The process starts with melting and preparing the desired aluminum alloy with chemical composition identified by customer specifications. Melting furnace is loaded by a charging machine that has approximately one ton loading capacity. The raw materials that are charged to the melting furnace are:

1. Al-ingots of approximately 600-1500 kg weight and with chemical composition consistent with alloy type that is being cast. These Al-ingots are purchased from suppliers.
2. Work-in produced scrap which is grouped by alloy type and placed in the stock area of continuous casting line.
3. Alloying elements (typically Mn, Fe, Si, Mg, etc.).

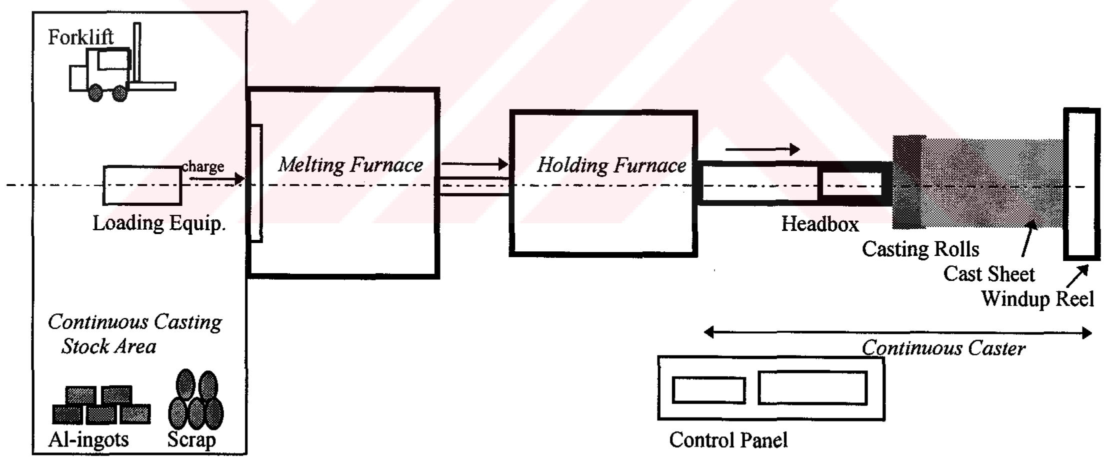

Figure 3.3. Layout of the Continuous Sheet Casting Line

When all the charged solid raw materials are melted, the desired alloy is prepared according to composition specifications by adding alloying elements in appropriate amounts. Molten alloy having a constant composition and temperature level is introduced to holding furnace after being degassed and filtered. The molten metal level in the headbox of the casting machine is adjusted by transferring a certain amount of molten metal from holding furnace to headbox through a ceramic runner whenever the level of molten metal in the headbox drops below a certain value. This operation is done automatically in a cyclic manner. Headbox controls the level of the molten metal that is sent to casting rolls, hence it regulates the pressure during casting. It is connected to a planar ceramic nozzle called "tip" which distributes the molten metal between the rolls of the machine. The width of the tip determines the width of the cast sheet. The molten metal enters the rolls bite and solidifies when contacts with the water-cooled rolls. On exiting the casting machine, the resultant solidified sheet is wound into a coil suitable for cold-rolling. (Interested reader may refer to Appendix B for more detailed information about the continuous casting process.)

Characteristics of Continuous Casting Process:

Casting proceeds in a cyclic manner where alloy types follow each other in the same order in every cycle. The duration of the cycle is approximately three to five weeks, depending on the casting rolls' surface condition and demand, because the amount of each alloy type cast in a cycle is roughly proportional to its demand during that period. Between cycles, both melting and holding furnaces are fully discharged and cleaned, the slag (oxide particles formed during melting) in the furnaces are removed. This cleaning operation lasts nearly five to six hours. At the same time, the casting rolls are changed and the used rolls are sent to grinding to prepare roll surfaces for further use. The reason for changing the casting rolls is the wear of the rolls because of high compression stresses and thermal shocks during casting. In each cycle, casting starts with the alloy type that has the lowest alloying element content among the ones that are planned to be cast in that period and proceeds with alloy types having higher alloying element contents. The reasons of this are:

1. The alloys having low alloying element content are softer compared to the alloy types having high alloying element content. Hence, such a practice decreases the rate of wear, extends the life, and increases the productivity of the casting rolls.
2. Shifting from an alloy type having low alloying element content to the one with high alloying element content in a casting cycle minimizes the time of alloy preparation in the furnace and prevents from casting of alloy which is out of specification.

The wear of the casting roll surface also affects the width of the cast sheet. As a result, there are three standardized casting widths used in the factory, namely 1320 mm, 1200 mm, and 1100 mm. For each width and alloy type, there is a specific tip (metal feeding system).

Hence, the tip must be changed whenever there is a change in the alloy or width within a casting cycle. The change of tip takes approximately two or three hours.

Consequently, the criteria used in planning the casting sequence of alloys are:

- Casting sequence starts with wide width tip and shifts to narrow width tip due to wear on the surface of casting rolls.
- Casting sequence starts with soft (ductile) alloy type and continues with harder alloy types, since the hard alloy types increase the rate of wear on the casting rolls.

However, there are some cases where the above criteria cannot be used. Any alloy type ordered in a huge amount or an order which has a close due date may have precedence in casting sequence. Moreover, in production planning of casting process, the amount of Al-ingots in stock, the accumulated scrap amount for a particular alloy type, and the desired final characteristics of the ordered product are also considered.

The final characteristics of the cast sheet that come out from the casting line are:

i. Alloy type.

ii. Thickness (alloy type dependent).

iii. Width (caster roll surface condition dependent).

There are many parameters that affect the quality of cast sheet, such as the casting thickness range and casting rate for each alloy type. The ranges of casting thickness and casting rate for each group of aluminum alloys have been specified and used to obtain a high quality structure. These ranges are tabulated in Table 3.3. There are also many specifications that must be met in sheet coil production. Parameters such as thickness, width, flatness, grain size, and chemical composition of the cast sheet must be within acceptable ranges and uniform. The inside and outside diameters of the coils must be above certain minimum levels. Otherwise, they are designated as casting scrap and sent back to melting operation.

Table 3.3. Casting Thickness and Casting Rate for Each Group of Aluminum Alloys

Alloys	Casting Thickness (mm)	Casting Rate (cm/min)
1000 series (1050, 1100, 1230, 1235)	9.8-10.2	75-80
8000 series (8011, 8079)	9.8-10.2	60-65
AA90	9.8-10.2	65-70
3000 series (3003)	8.0-8.5	65-75

Cast sheet coils satisfying the coil diameter standard weigh approximately five tons on the average. This property is consistent with the cyclic behaviour of the continuous casting process that is practised during regular casting. Casting of a standard size coil by the continuous caster and preparation of five tons molten alloy in the melting furnace both last roughly four hours. While casting proceeds in the caster, melting and preparation of newly charged five tons raw material is performed in the melting furnace for the subsequent casting operation. Hence, melting and casting are synchronized, and normally casting continues without interruption. However, during alloy type changeover or at the end of a casting cycle, the process is interrupted. The melting furnace is fully discharged for cleaning purposes at the end of each casting cycle. During alloy type changeover, on the other hand, molten metal in the melting furnace is reduced to approximately five tons to be able to prepare the chemical composition for the next alloy type. Also, the molten metal level in the holding furnace is reduced to a minimum level to minimize the spoiling of alloy composition due to mixing of two subsequently cast alloy types.

Operational Statistics for Continuous Casting Line: Annual production amounts of aluminum alloys in continuous casting line are given in Table 3.4 for 1995. The production amounts show that mainly six aluminum alloys were cast in 1995. These statistics are used to specify the alloy type of customer orders created in our simulation model. Some additional information about operation of the continuous caster in 1995 are tabulated in Table 3.5. These values are used in validation of the simulation models by comparing them with the results of simulation runs made with the current capacity.

Table 3.4. The Annual Production Amounts for Continuous Casting Line in 1995

	Cast Amount (kg)				
Alloy	**1100 mm width**	**1200 mm width**	**1320 mm width**	**TOTAL**	**%**
1050	772,380	236,320	1,014,250	2,022,950	20.57
1060	-	-	5,660	5,660	0.06
1100	68,890	-	368,990	437,880	4.45
1230	51,350	98,700	367,480	517,530	5.26
3003	-	269,810	2,440,010	2,709,820	27.56
3005	-	-	21,960	21,960	0.22
8011	270,550	-	917,130	1,187,680	12.08
8050	23,050	-	-	23,050	0.23
8079	26,310	-	-	26,310	0.27
AA90	180,570	1,315,060	1,385,160	2,880,790	29.30
TOTAL	1,393,100 (14.17%)	191,890 (19.52%)	6,520,640 (66.31%)	**9,833,630** (1901 coils)*	**100.0**

* Average Weight/Coil: 5172.8 kg

Table 3.5. Some Operational Statistics of Continuous Caster in 1995

Production Amount (kg)	9,833,630
Scrap Amount (kg)	123,160
Scrap Ratio (%)	1.25
Planned Production Time (hr)	8,310
Realized Production Time (hr)	7,911.1
Productivity (%)	95.2
Number of Tip Change (Annual)	114

Cold-Mill:

Characteristics of Cold-Mill: Cold-mill (see Figure 3.4 for the layout of the cold-mill station) was constructed by FATA Hunter in 1976 to roll specifically aluminum sheet/strip products. It has two speeds and edge trim capability. It is a two-high one-stand cold-mill with two rolls with equal dimensions, rotating in only one direction. It is capable of rolling down to 0.18 mm thickness with ± 0.015 mm thickness tolerance. The semi-finished products that are processed in the cold-mill are the coils cast in the continuous casting line of the factory and the purchased hot-rolled or cold-rolled coils which have various thickness, mechanical condition, and chemical composition values.

Process Description: The sheet/strip coil is rolled a number of times until the thickness demanded by the customer is achieved. After each pass of a coil, a 1.5-2 hour cooling period is required to avoid recrystallization which may occur because of subsequently applied cold-rolling operations. Similarly, the coils have to wait for a predetermined length of time (approximately 48 hours) to allow cooling after they come out of the casting line and in between the rolling and annealing processes to avoid recrystallization during rolling. In each pass, generally 30-50% reduction in thickness is attained. Meanwhile, the coils may be sent to the annealing operation to achieve the final desired strain-hardening level in the product. The main purpose of these cold-rolling-annealing cycles is to obtain a sheet/strip product with desired uniform thickness and flatness.

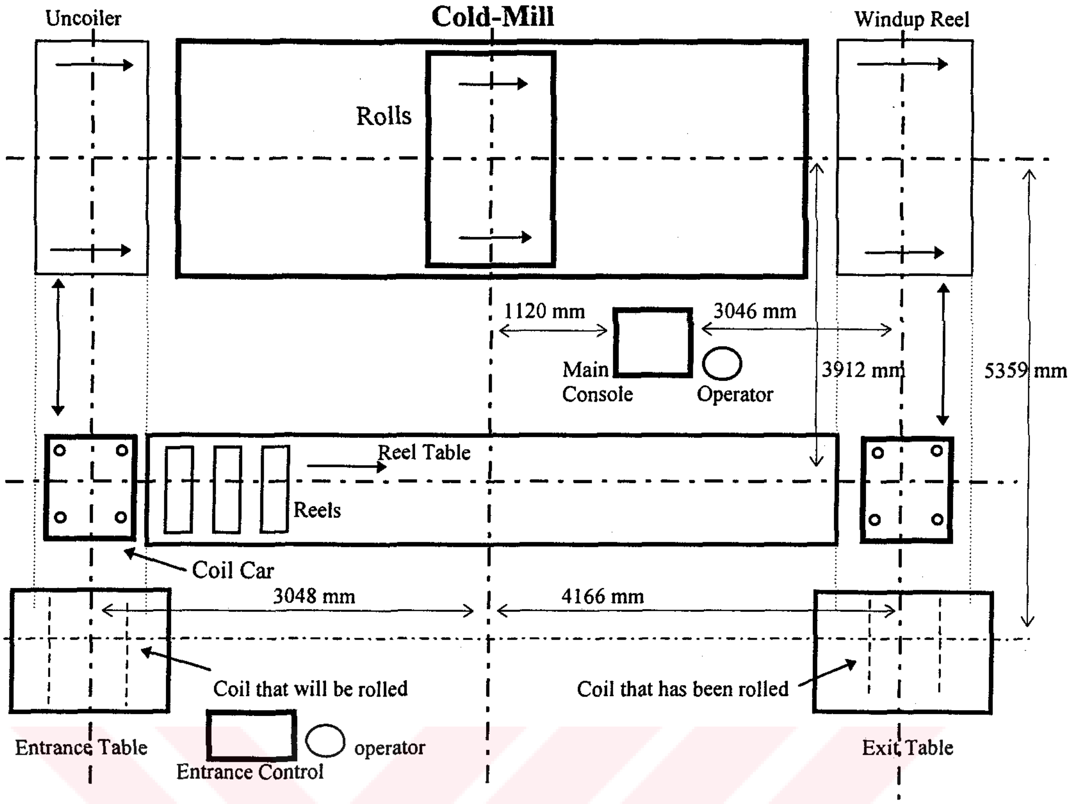

Figure 3.4. Layout of the Cold-Mill Station

Characteristics of Cold-Rolling Process:

In sequencing of jobs (coils allocated to customer orders) in cold-rolling process, the first criterion considered is the due date. The coils allocated to the customer order that has the earliest due date are scheduled and processed first. The coils of orders having the same due date are sequenced for cold-rolling operation according to the following criteria.

1. Width (from 1300 mm to 1000 mm): A coil having a narrow width may cause deterioration on the roll surfaces, and this affects the quality of the subsequently rolled coil which is wider. Therefore, in sequencing, the coils that are wider scheduled first, and the rolling operation proceeds with coils having narrower widths.
2. Thickness (from 0.18 mm to 5.0 mm): Since the sheet with thicker gauges require higher power and cause the rolls to wear off, the coils having thinner gauges, and requiring high quality surface finish and dimensional tolerances are rolled first.
3. Alloy type (1050 → 8011 → 3003): As in casting, sequencing coils in cold-rolling operation starts with the softest coils among the ones that are waiting in the buffer queue of the cold-mill. Then, the rolling process proceeds with harder alloy types. This practice decreases the rate of wear, extends the life, and increases the productivity of the rolls.

The operations in the cold-rolling process:

1. Attaching the coil to the uncoiler: Duration of this operation is not dependent on the product characteristics of the sheet that will be rolled.
2. Setups: Again, the duration of setups is independent of the product characteristics of the coil.
3. Pre-run: Before the rolling run is started, the sheet is gradually coiled around the windup reel for a small time period to provide the necessary rolling pressure. The time this operation takes depends on the entrance thickness of the sheet (but not on the other characteristics).
4. Run: This is the main rolling operation. The duration of this operation depends on the weight, entrance and exit width, entrance and exit thickness, alloy type, and rolling rate. The maximum rate that can be maintained in the rolling operation depends on the speed of the driving motor used for rolling. As mentioned before, the cold-mill has two speeds. While the maximum rate that can be achieved with the low speed is 120 m/min, this rate is 360 m/min with the high speed. Generally, the sheet having thickness higher than one mm is rolled by using the low speed since high power is required during rolling. Sheet with thickness less than one mm is rolled with the high speed. The rate of rolling, which depends on the speed used, is adjusted depending on the product characteristics of sheet, especially on the exit thickness. The rolling rates (at the windup reel) according to sheet characteristics are further discussed in Section 4.4.
5. Removal of the reel: After the rolling operation is completed, the uncoiled reel on the entrance side of the cold-mill is removed in order to proceed with the attachment of the next coil.

The standard times for the operations that are explained above were determined by a previously performed time study in the cold-mill station. The essentials of this time study and the standard times of operations will be discussed in the next chapter which is dedicated to description of the simulation models.

Operational Statistics for Cold-Rolling Process: Annual statistical information on the operation of cold-mill in 1995 are tabulated in Table 3.6. The figures given in the table are again used in validation of the simulation models by comparing them with the results of simulation runs made with the current capacity.

Table 3.6. Annual Cold-Mill Statistics Realized in 1995

Input Material Amount (kg)	103,573,658
Production Amount (kg)	102,876,271
Finished Product Amount (kg)	20,291,396
Scrap (kg)	697,387
Scrap (%)	0.67
Total Run (Number of Passes)	24,804
Weight/Coil (kg)	4,147.6
Planned Production Time (hr)	7,967.6
Realized Production Time (hr)	6,588.44
Productivity (%)	82.69

Annealing Furnace:

Characteristics of Annealing Furnace: A computer controlled, 40 ton capacity, horizontal batch-type annealing furnace is used for annealing operations. It is capable of annealing in atmospheric and inert atmosphere conditions. Eight coils each weighing approximately five tons can be processed simultaneously in the annealing furnace. By interposing annealing operations in between strain-hardening processes, the desired mechanical properties are attained in the material. Gas burners supply the source of heat. The furnace is also equipped with a charging car, nitrogen inert atmosphere capability, and coolers. The coils are loaded by the charging car which moves on rails in and out of the furnace. The layout of the annealing furnace station is given in Figure 3.5.

Process Description: In annealing operation, the coils are heated above a critical temperature level to convert the structure to uniform composition and strain-free condition. The coils are held at this temperature for a period of time. Then, they are slowly cooled at a controlled rate usually in furnace, followed by air cooling down to room temperature. The major purpose of the process is to restore the ductility in cold-rolled aluminum sheet coil that has been severely strain-hardened. Multiple aluminum sheet coils, even coils of multiple orders, can be processed simultaneously in the annealing furnace, provided that their processing requirements (temperature, annealing time, annealing atmosphere) are similar. The annealing operations applied to the different groups of aluminum alloys can be classified as follows.

- 1000, 8000 and AA90 series: At 350 ^{0}C for 12 hours; while 1000 series must be processed alone, the 8000 series and AA90 alloy can be grouped and processed together.
- 3000 series: At 450 ^{0}C for 14 hours.

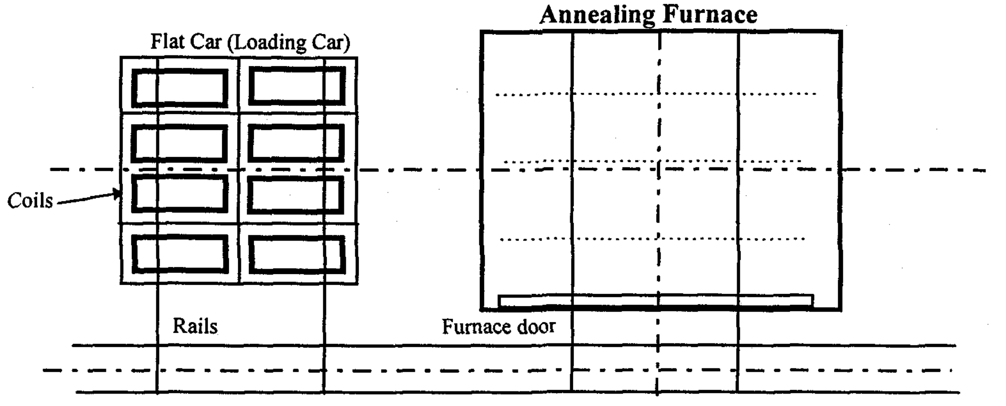

Figure 3.5. Layout of the Annealing Station

Operational Statistics for Annealing Process: Annual statistical information on the operations of annealing furnace in 1995 are tabulated in Table 3.7. These values are again compared with the results of the simulation runs for the validation purposes.

Table 3.7. Annual Annealing Furnace Statistics Realized in 1995

Production Amount (kg)	18,167,192
Number of Annealing Operations	590
Amount Processed/Annealing Operation (kg)	30,792
Planned Production Time (hr)	8,687
Realized Production Time (hr)	7,041.3
Productivity (%)	81.06

CHAPTER 4

SIMULATION MODELS

Many real systems are too complex to be studied analytically. These systems can be studied by means of simulation where the model is evaluated numerically and data are gathered in order to estimate the desired characteristics of the operating system. Consequently, regarding the complexity and stochasticity of the processes involved in the subsystem that we are concerned with, a computer simulation study have been performed. This chapter is allocated to the description of the simulation models constructed in this study.

According to Schriber (1987) "Simulation involves the modelling of a process or system in such a way that the model mimics the response of the actual system to events that take place over time." Hence, simulation in this study is considered as the process of designing a model of the real system, and conducting experiments with this model for the purpose of understanding the behaviour of the system. We also wish to evaluate various strategies and methods for the operation of the system, as suggested by Pegden et al. (1995).

The subsystem of concern is a mixture of process industry and discrete manufacturing. This leads to development of two simulation models. The first model, which is a combined continuous and discrete-event model where continuously changing state variables are dominant, is only for simulating the continuous casting process. The second model is a pure discrete-event model and includes all three processes, namely continuous casting, cold-rolling and annealing. The operational characteristics of the system, its boundary, descriptive variables and attributes used in the models, assumptions and definitions involved in modelling, and inputs and outputs of the models are presented in this chapter.

SIMAN (SIMulation ANalysis) (Pegden et al., 1995) is used as the simulation language for modelling the selected subsystem and the processes. A research package of Version V is used. According to Pegden et al. (1995), one of the most important advantages of SIMAN is the separation of the model frame and the experiment frame. The model frame is a functional description of the system's components and their interactions. In other words, the shop floor resources and their interactions with the incoming jobs are simulated by the model frame. On the other hand, the experimental frame specifies the experimental conditions under which the model is executed, including initial and boundary conditions, resource availability, type of statistics gathered, and length of run. Since experimental conditions are specified external to the model frame, they are easily changed without modifying the basic model definition. Additionally, Pegden et al. (1995) state that the primary reason for the popularity of SIMAN over the years is its modelling flexibility and its complementary structure, based on a powerful general-purpose simulation language having capabilities to model discrete, continuous, and combined systems. The source codes of the models developed in this study are given in Appendix D. The model and experiment frames of the models are briefly explained in the following sections. Verification and validation are performed to confirm that the models operate as intended and produce the outputs with an acceptable level of confidence so that the inferences drawn from the models are consistent with and applicable to the real system. These issues are also presented and discussed in this chapter.

4.1. Modelling Objectives

In the first of the two models, continuous casting process is analyzed and modelled separately from the rest of the system. The reason of this is partly the complexity and continuous nature of the casting process, which results in excessive execution times. Another reason is that the continuous caster operates in a cyclic and fairly independent manner from the other two processes in the system. This model is mainly used to estimate the setup times and casting times of aluminum sheet coils of specified weight for each of the alloy types that are commonly cast in the real system.

By using the parameters estimated from the first model, continuous casting is modelled at a higher level of abstraction in the second model. This allows us modelling of all three processes at similar level of detail and saves computation time. The purpose of modelling in this second case is twofold.

1) Analysis of the present capacity and comparison of the capacity expansion alternatives by investigating the effects of each alternative on coil production.

2) Analysis of the effects of various sequencing rules that can be used to dispatch the jobs waiting in the cold-mill and annealing furnace queues.

A number of performance measures, specifically flow time, work-in-process levels, utilization of the processes, and tardiness related measures are used as the criteria for selecting the best capacity expansion alternative(s) and sequencing rule(s) that will eliminate the bottleneck, increase the production, and balance the process loads.

4.2. Fitting Demand Related Input Distributions

A time consuming task has been encountered during development of these models which attempt to represent real world system, since modelling this coil production subsystem requires extensive data analysis to be able to set some of the simulation input parameters. Annual demand statistics of 1995 have been analyzed by using distribution fitting techniques to choose probability distributions that represent the demand pattern in both models. For this purpose, UNIFIT Version 2.15, which is an interactive computer package for fitting probability distributions to observed data, has been used.

There are basically two flat rolled aluminum product types produced in the factory: foil products, and sheet/strip products. Since the desired mechanical performance and final thickness levels of these products are reasonably distinct, the number and sequence of operations applied in the subsystem to these basic product types also differ. Moreover, although some of them overlap, generally different alloy types having various mechanical characteristics are used in the production of foil and sheet/strip products. Therefore, the arrivals of customer orders for the two basic types of products are modelled separately. Orders of these basic product types come to the system according to certain distributions that define the interarrival times, alloy types, quantities, thickness, and mechanical performance. Further description of these demand related distributions are given in this section.

First of all, from the overall demand data, empirical distributions have been fitted to represent the demand percentage (in weight) for each alloy type used for orders of sheet/strip and foil products. These values are shown in Table 4.1. As seen from the table, there are a few alloy types that are commonly demanded in manufacturing of both sheet/strip and foil products. The alloy types that are demanded in ignoble amounts are not considered in the models, therefore total ordered amounts in Tables 3.1 and 4.1 differ. The alloys are coded in the models according to their precedence in the casting process.

Table 4.1. Demand Distributions by Alloy Type for Sheet/Strip and Foil Products

Alloy Type	Amounts of Sheet/Strip Orders (kg)	%	Amounts of Foil Orders (kg)	%
1050 (1)*	8,143,476.4	54.38	96,208.0	4.01
1100 (2)	269,317.2	1.80	-	-
1230 (3)	-	-	1,432,379.0	59.7
1235 (4)	-	-	184,537.0	7.69
8011 (5)	493,316.0	3.29	274,403.1	11.44
8079 (6)	-	-	411,595.0	17.16
AA90 (7)	3,763,518.9	25.13	-	-
3003 (8)	2,305,164.3	15.39	-	-
Total	**14,974,792.8**	**100.0**	**2,399,122.1**	**100.0**

* Numbers in parentheses are used to code alloy types in the models.

The interarrival time of the customer orders, due dates, order quantities, desired final thickness, and mechanical performance level are also defined by fitted probability distributions. These distributions are given in Table 4.2. All the distributions, except the one for desired final thickness, are alloy independent since the available data are not adequate to permit a breakdown by alloys. Final thickness for coils of foil products is constant. However, the desired final thickness distributions for sheet/strip orders are generated separately for each alloy type to reflect the demand pattern. For this purpose, the final thickness values demanded during the year have been grouped into ranges, and a separate empirical distribution has been fitted for each alloy type. Grouping of final thickness values is guided by processing requirements. Desired final thickness, together with alloy type, defines the operation routings of coils in cold-rolling and annealing stations. Therefore, final thickness values that require similar routings are grouped together.

Several methods for specifying due date have been proposed in the literature (Eilon et al., 1976). A general procedure for determining the due date for a given order may incorporate the arrival time, the required number of operations and the expected total processing time. However, in our case, fitted distribution of true due dates that have been obtained from the real system is used assuming that due date assignment is random, i.e., it is not dependent on order size and process requirements since due date related data are not adequate to decompose by order size and process requirements.

Table 4.2. Demand Related Input Distributions

Demand Related Input Data		Probability Distribution
Interarrival time of customer orders	S*	Exponential (139.1 min)
	F	Exponential (562.1 min)
Due date for customer orders (added to order arrival time)	S	Triangular (4, 30, 197 days)
	F	Triangular (16, 31,170 days)
Order quantity	S	Exponential (3210.5 kg)
	F	Exponential (2974.3 kg)
Mechanical performance level	S	50% - H14, 50% - H18
	F	Constant (100% - H0)
Desired final thickness	S	Empirical for each alloy type
	F	Constant (100% 0.2 mm)

* S stands for sheet/strip orders, and F for foil orders.

It has been stated that the amounts of alloys that are cast in a casting cycle are decided by their quotas. These quotas are determined by the percentages (given in Table 4.1) of the nominal casting capacity in a cycle. There are two cases to be considered.

Case A: Continuous casting line satisfies only the sheet/strip demand.

Case B: Both sheet/strip and foil demand are satisfied by continuous casting line.

In either case, the shares of alloy types in the nominal casting capacity are identified as follows.

- *For foil demand*: $\text{DemandRate}_F = \dfrac{525600 \text{ min / year}}{562.1 \text{ min / order}} = 935.1 \text{ orders / year}$

$$\text{DemandRate}_F \cdot \text{AvgOrder}_F = 935.1 \text{ orders / year} \cdot 2974.3 \text{ kg / order} = 2{,}781{,}267.9 \text{ kg / year}$$

(This value is the annual expected demand for foil products.)

- *For sheet/strip demand:* $\text{DemandRate}_S = \dfrac{525600 \text{ min / year}}{139.1 \text{ min / order}} = 3778.6 \text{ orders / year}$

$$\text{DemandRate}_S \cdot \text{AvgOrder}_S = 3778.6 \text{ orders / year} \cdot 3210.5 \text{ kg / order} \doteq 12{,}131{,}195.3 \text{ kg / year}$$

(This value is the annual expected demand of sheet/strip products.)

It is seen from these values that, of the overall expected demand, 81.35% (in weight) is for sheet/strip products and 18.65% is for foil products. These percentages correspond approximately 521 tons quota for sheet/strip products and 119 tons quota for foil products of the 640 tons nominal casting capacity. In Table 4.3, the quotas for each alloy type are given for cases A and B.

Table 4.3. The Quotas of Aluminum Alloys in the Nominal Casting Capacity

Alloy Type	Case A: Only Sheet/Strip		Case B: Sheet/Strip + Foil				
			Sheet/Strip		*Foil*		Total
	Amount (kg)	%	Amount (kg)	%	Amount (kg)	%	
1050	348,000	54.38	283,000	54.38	5,000	4.01	288,000
1100	12,000	1.80	10,000	1.80	-	-	10,000
1230	-	-	-	-	71,000	59.7	71,000
1235	-	-	-	-	9,000	7.69	9,000
8011	21,000	3.29	17,000	3.29	14,000	11.44	31,000
8079	-	-	-	-	20,000	17.16	20,000
AA90	161,000	25.13	131,000	25.13	-	-	131,000
3003	98,000	15.39	80,000	15.39	-	-	80,000
Total	**640,000**		521,000		119,000		**640,000**

4.3. The First Model: Continuous Casting Process

The essential characteristics of the continuous casting process with its layout and technical properties of its components are discussed in Chapter 3. The SIMAN V codes of model and experiment frames of this model are given in Appendix D. As pointed out in the previous chapter, in this process, coils of aluminum sheet in various chemical compositions are produced by continuous casting of molten aluminum alloys. Analogous to these characteristics of the process, the amount of cast sheet and the levels of molten alloy in the melting furnace, holding furnace, and headbox of the caster change continuously. On the other hand, the coils that are obtained by winding the cast sheet around reels, come out of the casting line at discrete points of time as they satisfy the diameter standard. Likewise, customer orders arrive at the system at discrete time points.

Consequently, in this combined model, continuous-change state variables are used to reflect the continuous nature of the casting process whereas the exit of cast sheet coils to be processed in the cold-mill and annealing furnace stations, and the customer order arrivals are simulated by means of discrete events.

Finally, it must be noted that the cold-rolling and annealing processes that take place after casting are beyond the scope of this model. Therefore, the cast sheet coils that come out of the continuous caster are allocated to appropriate customer orders and then disposed off. At this point, they are assumed to be sent to cold-mill and annealing furnace stations to be processed into desired final thickness, form, and mechanical performance level.

4.3.1. Conceptual Formulation of the First Model

The modelling of the continuous casting process can be divided into three main stages. These stages and flow of entities in the model are illustrated schematically in Figure 4.1.

1) Customer order arrival:

When a customer order for a particular product type arrives, a demand entity is created. In the first model, since the processes after continuous casting are out of scope, the incoming customer order only specifies the desired alloy type and required amount. The amounts of orders that are generated in kg from the appropriate fitted distribution are rounded up to the nearest multiple of coil weight (1000 kg), so that an integer number of coils are allocated to each order. The demand entity checks if sufficient number of coils of desired alloy type are available in the stock area. The search orders of stocks by the demand entities of foil and sheet/strip products are shown in Figure 4.1. If required number of coils are found in those stocks, demand is satisfied. Otherwise, the customer order is placed in a queue where it waits until necessary number of coils of desired alloy are cast or purchased. Also, the requested amount of the particular alloy is recorded so that it can be cast in the subsequent casting cycle.

2) Determination of the amounts of alloys that will be cast in the subsequent casting cycle:

It has been noted that casting proceeds in a cyclic manner where alloys follow each other in the same order in each casting cycle. The amount of each alloy type that is cast in a cycle is roughly proportional to its expected demand during previous casting cycle. Therefore, in order to monitor the casting process, a module has been constructed in which the amount of each alloy that will be cast in the subsequent cycle is determined, and the amount of each alloy that will be cast in the current cycle is updated. At the beginning of each cycle, the alloys are re-sequenced in the buffer of casting line according to the criterion mentioned in the previous chapter.

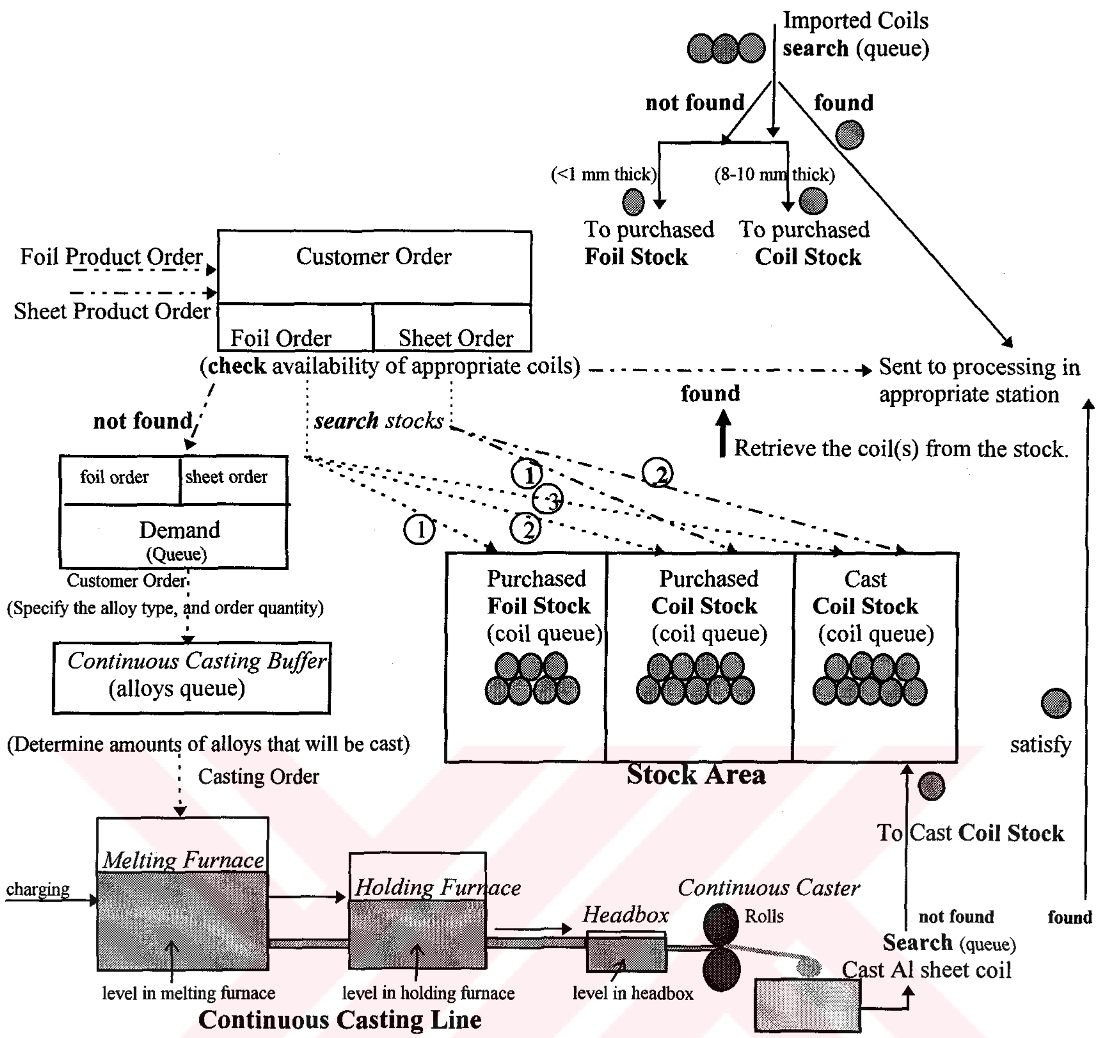

Figure 4.1. Flow of Entities Through the Continuous Casting Model

The nominal casting capacity per cycle is set as 640 tons, but it can be increased up to 800 tons. These approximate casting capacity values are consistent with those of the real system. In the model, each alloy that is commonly cast has a quota (expected demand for that alloy type in a cycle) which corresponds to a portion of the nominal casting capacity. At the beginning of a cycle, the casting line is scheduled to cast alloys in the amounts of their quotas. The excess capacity is used to increase the amount of alloys for which the demand in that cycle exceeds the expected amount, provided that casting of a particular alloy has not been finished at the time of demand arrival. In the real system, these amounts are determined depending on the availability of coils for purchasing, i.e., they generally purchase the alloys that are available from the suppliers and cast in-house those that are not available. However, this approach is not taken in the model because purchasing coils is not desirable. Therefore, the purchased foil and coil stocks are kept empty during the execution of the model.

3) Continuous casting:

In the casting process, the levels of molten alloy in the melting furnace, holding furnace, and headbox of the caster change continuously, as well as the amount of cast sheet. This requires the use of continuous-change state variables in the model. The values of these variables at any point in time are computed by numerical integration. The rates of change of these variables depend on the stages of continuous casting. Therefore, the stages of casting must be identified and separated by discrete events. At each of these discrete events, the rates of change of some continuous-change state variables are set to new values.

The stages of continuous casting process can be outlined by the following discrete events which signify the starting point of each stage.

Event 1: *Start of melting.* With the start of charging solid raw material including Al-ingots, in-house produced scrap, and alloying elements, melting of newly loaded material also starts. In order to determine the amount of raw material to be charged, the required amount of molten metal and the level of molten metal left in the melting furnace are considered. This also dictates the duration of melting operation. There are three cases to be considered.

- Case I: Starting to melt a new alloy at the beginning of a new casting cycle. At this point, the melting furnace is completely empty. Therefore, the amount of the solid material that has to be charged to melting furnace is higher compared to the cases where some molten metal is kept in the furnace. As a result, melting takes a longer time in this case.
- Case II: Starting to melt a new alloy in the current casting cycle. In this case, the molten metal level left from the previously cast alloy is at a minimum level.
- Case III: Regular loading and start of melting. As casting of a particular alloy goes on, there is a charging-melting-transferring cycle that is practised in the real system. The empty space formed in holding furnace by the casting of previous coil is filled by transferring molten alloy from melting furnace. After this transfer, the available space in melting furnace is as much as the weight of a single coil. Hence, only this amount of solid material is charged during regular loading, and melting restarts.

Event 2: *End of melting.* When all the charged solid material is melted, and the level of molten alloy reaches the predetermined value, alloy preparation is performed in accordance with the specifications.

Event 3: *Start of transfer molten alloy to holding furnace.* After composition control and alloying, transfer of prepared molten alloy to holding furnace is started. There are two additional conditions to be satisfied. These are:

1. The level of alloy in holding furnace must fall below a certain critical value. During regular casting, this critical value is approximately five tons. When, however, the alloy type will be changed, the level of molten metal is reduced to one ton to prevent different alloy types from mixing with each other. At the end of a casting cycle, holding furnace is completely discharged for cleaning purposes.
2. Alloys in holding and melting furnaces must be of the same type during regular casting.

Event 4: *End of transfer of molten alloy from melting furnace.* When molten alloy level in holding furnace reaches maximum capacity of the furnace, or when molten alloy level in melting furnace falls below the critical level, transfer from melting furnace is stopped. During regular casting, this critical level is 15 tons, but it is reduced to five tons when melting of a new alloy will be started. Melting furnace is completely discharged at the end of a casting cycle.

Event 5: *Start of casting.* When caster is ready to cast a new alloy (after casting tip is changed and rolls are prepared for the subsequent casting operation), and when sufficient amount of alloy is transferred to the holding furnace, casting operation is started.

Event 6: *End of casting.* During regular casting, when the coil diameter exceeds the predetermined level, the cast sheet is sheared and the casting operation continues without interruption. However, when the scheduled amount of a particular alloy has been cast, the casting operation is stopped, and preparation for a new alloy is started. In the real system, the casting operation is preempted due to breakdowns in the casting line, but those occasions are rare and ignored in the model.

4.3.2. Assumptions of the First Model

The major assumptions of the continuous casting model, some of which are discussed in the previous section, are summarized below.

- All demand related probability distributions have been fitted based on the analysis of one year's (1995) data as explained in Section 4.2. Therefore, the outputs of the model are valid only for the conditions realized in 1995.

- Customer order quantities generated from fitted distributions are rounded up to the nearest multiple of 1000 kg to be able to allocate an integer number of coils to each order.
- No shortage of raw material is assumed. Al-ingots, work-in process scrap, and alloying elements that are charged to melting furnace are assumed to be available on the stock area of melting furnace for all alloy types.
- Coil weight and width which are variable in the real system are taken as constant in the model. Coils of cast sheet are assumed to weigh one ton whereas this weight is approximately five tons in reality. The motivation behind this assumption is to reduce the rounding error in customer order quantities. This assumption can be justified because there is no interruption during regular casting of a particular alloy type. It means that during the time period in which one coil of five tons is produced in the real system, five coils of one ton are cast in the model. Likewise, the width of coils are assumed to be 1320 mm although there are three standardized casting widths used in practice, namely 1320 mm, 1200 mm, and 1100 mm. Narrower widths are mainly due to the wear of casting rolls. However, this is not desirable since casting with narrow widths reduces the production rate. Hence, in the real system, these worn rolls are tried to be changed immediately.
- No scrap or no low quality product is assumed in coil production. This is basically due to the lack of data to figure out the scrap rate in the system. However, the excess production amounts due to the rounding up of customer order quantities roughly correspond to the scrap percentage.
- No breakdowns are assumed in the casting process. This is again because of insufficient data to fit relevant probability distributions. However, breakdowns are known to occur rarely and do not have a significant effect on the production amounts.
- Coil purchasing from outside suppliers is ignored. Although the model has a module that allows arrival of purchased coils to meet excess demand for both sheet/strip and foil products, this module is not activated, and the corresponding stock areas are kept empty during the simulation runs.

4.3.3. Input of the First Model

The input parameters used in the simulation model of continuous casting process can be grouped as demand related and system related parameters.

Demand Related Input:

The interarrival time of customer orders, alloy type required, and order quantity are defined by using the fitted distributions given in Section 4.2.

System Related Input:

These input data designate the operational characteristics of the continuous casting line. (See "EXPRESSIONS" element of the experiment frame in Appendix D.1.2 for the values of input parameters.) They might be grouped as follows.

- Casting thickness and casting rate: The ranges of casting thickness and casting rate used for each aluminum alloy type are given as the input parameter, assuming that thickness and rate are uniformly distributed within respective ranges. These values are tabulated in Table 3.3.
- Duration of setup operations: The actual setup times for preparation of melting and holding furnaces for a new casting cycle, preparation of alloy composition, and duration of changing casting rolls and tip are given as input to the model.
- Other parameters whose values are obtained from the real system statistics include rate of charging raw material to melting furnace, rate of melting, and rate of transferring molten alloy from melting furnace to holding furnace and from holding furnace to the headbox of continuous caster.

4.3.4. Output of the First Model

This model is used for estimating three types of parameters required as input to the second model. It has been executed for the two cases explained in Section 4.2, and data obtained from the model have been analyzed to fit the following distributions. (See experiment frame of the second model in Appendix D.2.2 for these probability distributions.)

- Casting Cycle setup time:

  normal (330.1, 4.57 min) when the continuous casting line satisfies only sheet/strip demand.

  normal (330.0, 5.08 min) when both foil and sheet/strip demand are satisfied by continuous casting line.

- Alloy changeover setup time: normal for each alloy type of sheet/strip and foil products.
- Casting time per coil of sheet: normal for each alloy type of sheet/strip and foil products.

These above distributions are fitted by replicating the model 100 times which provides us a relative precision of 0.1 at most.

4.4. The Second Model: Coil Production Subsystem

The essential characteristics of the processes involved in the subsystem of concern are explained in Chapter 3. SIMAN V codes of model and experiment frames of the second model are given in Appendix D.2. This model, which is constructed to simulate continuous casting, cold-rolling, and annealing processes, is a pure discrete-event model. It has been executed with various capacity alternatives and sequencing rules to achieve the objectives stated in Section 4.1.

4.4.1 Conceptual Formulation of the Second Model

As in the first model, modelling has been performed by constructing modules of various stages in the aluminum sheet coil production subsystem. There are basically two types of entities flowing through this model: customer orders and cast sheet coils. Their flows through the model and interactions with the resources in the subsystem at different stages of processing are explained in the subsequent paragraphs. Figure 3.2 gives an overview of the model developed for the subsystem.

1) Customer order arrival:

The arrival of the customer orders for foil and sheet/strip products have been modelled separately, as in the first model. Creation of a demand entity for any product types is based on the demand related distributions discussed in Section 4.2. However, contrary to model 1, the arriving customer order specifies not only the alloy type and order quantity but also the desired thickness and mechanical performance level of the product. These specifications of the particular aluminum product are again generated according to probability distributions given in Tables 4.1 and 4.2, and are assigned to the “attributes” of the demand entity. Moreover, a due date is assigned for each customer order from the respective probability distribution. The due date generated is the true due date for the finished product. Hence, the time span between order arrival and due date includes not only coil production in our subsystem but also the downstream processes to obtain the final product. Accordingly, some slack time must be left for downstream processing after the coils come out of our model in order to satisfy the customer order due date.

The customer order quantity that is generated in kg from the fitted exponential distribution is rounded up to the nearest multiple of 1000 kg to determine the number of coils to be allocated to the corresponding customer order. Then, the appropriate stock areas (refer to Figure 4.1) are searched by the demand entity to see if sufficient number of coils of specified alloy type are available or not. If coils are available, they are allocated to the order. Otherwise, the order waits until the required number of coils are cast. Also, in the continuous casting line, that amount of specified alloy type is planned to be cast in the subsequent casting cycle.

2) Determination of the amounts of alloys that will be cast in the subsequent casting cycle:

The module that is used in model 1 for this purpose is also used in this model.

3) Continuous casting:

Contrary to model 1, continuous casting process in the second model has been modelled using the discrete-event approach. As mentioned before, the cycle and alloy changeover setup times and coil casting times are generated from distributions that have been fitted by running the first model.

Coil entities are created as the cast sheet coils having particular alloy type, weight, width and thickness come out of the continuous caster. The created coil entity searches the queue for demand entities waiting for coils of that particular alloy type. If no orders are waiting for that alloy type, or the coils accumulated in the cast coil stock are not sufficient to meet the order quantity, then the coil entity is placed in cast coil stock queue to be allocated later. On the other hand, if, with this new coil, the required number of coils are accumulated in the stock area, they are allocated to the waiting customer order. This means that coil entities and the demand entity are combined, and one representative group entity is created taking the attribute values of customer order. Then, this group entity is sent to cold-rolling and annealing stations to be processed into desired final product specifications.

4) Processing in cold-mill and annealing furnace:

Operation routings of the sheet coils between cold-rolling and annealing processes in the real system have been examined to determine processing sequences of coils allocated to customer orders. It has been found that the routings of coils depend on the final thickness and mechanical performance of the desired final product. While the final thickness determines the number of cold-rolling operations, the mechanical performance defines the sequence and number of annealing operations in a typical rolling-annealing cycle.

To be able to define the operation sequences properly, the product type in the model is defined by the alloy type, final thickness, and mechanical performance. This way, 90 different sheet/strip product types (5 alloy types × 9 final thickness values × 2 mechanical performance levels), and five different foil product types (5 alloy types having a standard thickness and mechanical performance level) have been identified as the semi-finished products of the subsystem. The operation sequences that are commonly applied to those product types in the real system are accordingly used in the model. Operation sequences as a function of final thickness and mechanical performance levels are given in Table 4.4.

The cold-mill is also modelled based on discrete events. As group entities, each of which represents a customer order and allocated coils, come to the cold-mill station, they are placed in the cold-rolling buffer and are sequenced according to their priorities. The priorities are decided depending on the sequencing rule used during the execution of the simulation model.

Table 4.4. Operation Sequences Depending on Final Thickness and Mechanical Performance

	Operation Sequences		
	for foil products	*for sheet/strip products*	
Final Thickness (mm)	H0 (mech. performance = 1)*	H14 (mech. performance = 2)	H18 (mech. performance = 3)
0.2	3R-A-4R-A-R-A**	3R-A-4R-A-R	5R-A-3R
0.3	-	6R-A-R	4R-A-3R
0.4	-	6R-A-R	5R-A-2R
0.5	-	5R-A-R	4R-A-2R
0.6	-	5R-A-R	4R-A-2R
0.7	-	4R-A-R	4R-A-2R
0.8	-	4R-A-R	3R-A-2R
1.0	-	4R-A-R	3R-A-2R
1.5	-	3R-A-R	2R-A-2R

* Codes used to denote the mechanical performance levels in the model. ** R: rolling, A: annealing.

The operations in the cold-rolling process are explained in Chapter 3. It has been noted that the duration of each operation, except actual rolling operation delay (run), can be based on a previously performed time study in the cold-mill station. The standard times for those operations are given in Table 4.5, and those figures have been used in the simulation model. On the other hand, the rolling operation delay in the model is computed by using the rolling rate (see Table 4.6) which is dependent on the characteristics of the coil, especially the exit thickness and alloy type. Thus, the duration of each rolling operation for one coil of a customer order is computed in the model as follows.

$$D_i = \frac{L_i}{R(t_i^{exit}, \text{AlloyType})} \qquad i = 1,\ldots\ldots,N \qquad (4.1)$$

where

N: Number of rolling operations to be applied to coils of a customer order.

D_i: Duration of the i^{th} rolling operation of a customer order in the operation sequence for one coil (min).

L_i: Length of the sheet for a coil at the end of the i^{th} rolling operation (m).

t_i^{Exit} : Exit thickness of the sheet at the end of the i^{th} rolling operation (mm).

$R(t_i^{Exit}, \text{AlloyType})$: Rolling rate defined as a function of exit thickness and alloy type (m/min). Ranges of this parameter are given in Table 4.6.

The above computation requires prior estimation of the exit thickness and length of sheet for a coil at the end of i^{th} rolling operation. However, those are functions of the number of rolling operations applied. Therefore, we need to find approximate exit thickness and coil length based on the number of rolling operations.

$$t_i^{Exit} = t^{Initial}(\text{AlloyType}) \cdot \prod_{j=1}^{i} PR(\text{AlloyType}, t_j^{Exit}) \qquad i = 1,\ldots,N \qquad (4.2)$$

$$L_i = \frac{m}{\rho \cdot w \cdot t_i^{Exit}} \cdot 10^{-3} \qquad i = 1,\ldots.,N \qquad (4.3)$$

where

$t^{Initial}(\text{AlloyType})$: Initial thickness of the sheet as cast condition (mm).

m : Weight of a coil (taken as 1000 kg).

ρ : Density of aluminum (2.71×10^{-6} kg/mm^3).

w : Width of the sheet (taken as 1320 mm).

$PR(AlloyType, t_n)$: Percent reduction applied in i^{th} rolling operation (dependent on alloy type). Ranges of percent reduction as a function of alloy type and exit thickness are given in Table 4.6.

The duration of a rolling operation for an entire customer order can be found by multiplying D_i with the number of coils allocated to the order.

As in the cold-rolling process, the group entities coming to the annealing furnace station are also placed in the annealing buffer and are dispatched to the annealing process according to the sequencing rule used in the simulation run. In annealing furnace, coils of multiple customer orders are batched according to their processing requirements. Various batching and lot sizing approaches are possible to increase the furnace efficiency (Lefrancois et al., 1991), but in this case, there is an additional constraint that only the alloys having similar processing requirements in terms of annealing time, temperature, and annealing atmosphere can be batched together.

Table 4.5. Standard Times of Operations in the Cold-Rolling Process

Operations in Cold-Rolling Process	*Standard Times (min.)*
Attachment of coil to the uncoiler	0.63
Setups	1.53
Pre-run	1.89
Run (rolling)	-
Removal of reel	0.85

Table 4.6. Rolling Rates as a Function of Aluminum Sheet Characteristics

Alloy Type	Speed	Exit Thickness (mm)	Reduction (%)	Rate (m/min)
3000	Low	10-5	30-40	10-40
	Low	5-1	30-40	80-100
	High	1-0.4	30-40	270-300
	High	0.4-0.18	20-40	240-270
1000	Low	10-5	40-50	40-80
	Low	5-1	40-50	80-120
	High	1-0.4	30-45	300-360
	High	0.4-0.18	20-35	300-340
8000	Low	10-5	40-45	40-80
	Low	5-1	40-45	80-110
	High	1-0.4	30-45	300-340
	High	0.4-0.18	20-35	270-320

Note: For AA90 alloy, the figures are same with 8000 series alloys.

4.4.2. Assumptions of the Second Model

The assumptions of the first model are also valid for the second model. The following additional assumptions are made for this model.

- In the model, the coils of a customer order are processed one after the other without preemption, leading to application of single setup and pre-run operations per order. This assumption provides consistency of the model with the real system conditions. It can be seen from Table 4.6 that the average weight of a coil that is processed in the cold-mill is approximately four tons in the real system whereas a coil weighs one ton in the model. The average order quantity is nearly 3.5 tons, resulting in the allocation of four coils of one ton (on the average) to each order in the model.
- The annealing furnace has a capacity of 40 tons and is capable of processing simultaneously eight coils each having an approximate weight of approximately five tons. In the model, it is assumed that the furnace can process up to 40 coils each weighing one ton, provided that processing requirements of those coils are the same.
- No transportation delays are assumed between the processes.

4.4.3. Input of the Second Model

The input parameters used in the simulation model of coil production subsystem can be grouped as demand related and system related parameters.

Demand Related Input:

As in the first model, the demand pattern in this model is also defined by the fitted distributions given in Section 4.2.

System Related Input:

- The operation sequences applied in the real system to achieve desired characteristics of the product are used as input to the model to determine the routings of coils between cold-rolling and annealing furnace. These operation sequences are tabulated in Table 4.4.
- The ranges of rolling rates and percent reductions depending on alloy type and exit thickness values of the aluminum sheet are given in Table 4.6. They are assumed to be

are uniformly distributed within respective ranges. Also, the standard times of the other operations in the cold-rolling process are set in the model as in Table 4.5. Finally, annealing process time for each aluminum alloy type are given in Section 3.5.

4.4.4. Output of the Second Model

The main output statistics that have been obtained from the execution of model 2 are used as performance measures. These statistics can be grouped under the four headings.

1. Flow time related statistics:
    - Waiting time of customer orders of both foil and sheet/strip products (until allocation of cast coils to orders).
    - Waiting time of cast coils in stock.
    - Rolling and annealing flow times per order.
    - Time in system for foil and sheet/strip orders.

2. Queue related statistics:
    - Length of foil and sheet/strip order queues.
    - Size of cast coil stock.
    - Length of rolling and annealing queues (in number of orders).

3. Utilization statistics:
    - Utilization of cold-mill(s).
    - Utilization of annealing furnace(s).
    - Average load of annealing furnace(s) (percentage of full coil spaces).

4. Tardiness related statistics:
    - Percentage of foil and sheet/strip orders satisfied.
    - Slack time remaining for downstream processing of foil and sheet/strip orders.
    - Number of tardy jobs and average tardiness for foil demand.
    - Number of tardy jobs and average tardiness for sheet/strip demand.

The detailed discussion of these performance measures are given in the following chapter which is dedicated to the design and analysis of the simulation experiment.

4.5. Verification and Validation of the Models

Throughout the verification process of the models, the unintentional errors in the modelling logic have been detected and removed by means of tracing extensively each step of the execution using SIMAN's interactive debugger. Also, output statistics have been examined closely to make sure that they are consistent with each other. For this purpose, equations similar to the following have been used.

- Order Waiting Time (till coil allocation) + Coil Cooling Time + Rolling Flow Time + Annealing Flow Time = Time in System for Order
- Amount of Customer Orders Satisfied + Amount of Customer Orders Waiting = Amount of Customer Orders Arrived

For validation, the output statistics of the simulation runs made at the current capacity and sequencing rule combination corresponding to the real system conditions have been compared with the actual figures obtained from the subsystem of concern. Amounts ordered, amounts processed, flow times of coils through the processes, and utilization of the processes have been used for this comparison. (The statistics of the real system realized in 1995 for the continuous casting, cold-rolling and annealing processes are given in Tables 3.5, 3.7 and 3.8, respectively.) The results of the model have been found to be consistent with the operational statistics of the real system. Some minor discrepancies can be attributed to the modelling assumptions.

4.6. Determination of Run Length and Number of Replications

In non-terminating systems such as ours, the steady-state behaviour of the system is of interest. The system is assumed to be in steady-state when the initial transient phase has diminished to the point where the impact of the initial conditions on the system's response is negligible.

Since model 1 is only used to determine some continuous casting process parameters that are needed as input to the second model, and since casting has a cyclic behaviour where the continuous-change parameters are initialized at the beginning of each casting cycle, it has been decided that no warm-up period is required, and a run length of one year (525600 min) is sufficient to simulate the casting process and to estimate desired parameters with an acceptable level of confidence.

The second model, however, has a significant initial bias. To decide on the warm up period in the second model, some initial runs have been made with the present capacity configuration, and system variables and statistics are monitored continuously throughout the runs. As a result of these runs, it has been concluded that a three month (131400 min) truncation period is sufficient for the system to reach the steady-state. Therefore, in each replication, the run length has been taken as one year (525600 min corresponding to 365 work days with three eight hour shifts per day) after truncation. This also provides the opportunity of comparing one year's data of the real system with those of the model.

Using variance estimators of various output statistics obtained by preliminary runs of the first model, it has been found that 100 replications are enough to estimate the continuous casting process parameters from the output data with a relative precision of 0.1. Similarly, after estimating the variance of various output statistics by preliminary runs of the second model, the required number of replications has been found to be 40 by using the operating characteristic curves (Montgomery, 1991). With this sample size, and significance level of $\alpha = 0.05$, differences between alternatives as large as one standard deviation can be detected with a maximum Type II error probability of $\beta = 0.08$. (See Table 4.7.) Moreover, the relative precision of individual confidence intervals of various output statistics is less than 0.15 (Law and Kelton, 1991). This assures us that the decided number of replications is adequate to analyze the subsystem of concern and to compare system alternatives.

Table 4.7. Sample Size Determination

n	ϕ	ϕ^2	a(n-1)	β
30	1.668	1.2915	261	0.30
40	2.224	1.4913	351	0.08

Note: $\alpha = 0.05$, $\phi^2 = \dfrac{nD^2}{2a\sigma^2}$

CHAPTER 5

DESIGN AND ANALYSIS OF THE EXPERIMENT

As stated by Montgomery (1991), "A designed experiment is a series of tests in which purposeful changes are made to input variables of a process or system so that the reasons of changes in the output response can be observed and identified." Hence, by statistical design of experiment, appropriate data that can be analyzed by statistical methods are collected, resulting in valid and objective conclusions.

In this thesis, experimental design approach (Montgomery, 1991) has been followed in designing and analyzing an experiment that will enable us to evaluate the performance of the aluminum sheet coil production subsystem under various capacity alternatives and order sequencing rules. Analysis of variance (ANOVA) is used for statistical analysis of the results.

5.1. Statement of the Problem

The essential characteristics of the subsystem of concern and the objectives of the study have been discussed in the previous chapters. For the sake of completeness, however, basic issues of this research are reviewed in the following paragraphs.

In the aluminum sheet coil production subsystem, continuous casting process is a bottleneck for the downstream processing due to its limited capacity. Therefore, investigation of various capacity alternatives in order to find the best capacity configuration is the first aim of this simulation study. Additionally, effects of various sequencing rules on the selected performance measures are to be determined within each capacity expansion alternative. Recommendations must be made regarding which rules improve selected performance measures.

In evaluating capacity and sequencing alternatives, our aim is to achieve the following objectives.

1. Satisfying the demand: The system must be able to produce sufficient coils to meet customer demand in time. To begin with, this must be achieved for the current demand level. Specific criteria for this objective would be minimizing tardiness related measures such as average tardiness and number of tardy jobs or maximizing mean slack time. In addition, the factory management wishes to be able to increase the production rate since the demand has been increasing. This, in turn, translates into increasing throughput and reducing flow time of coils through the system.
2. Balancing the process loads: The three major processes must have balanced loads so that none of them is a bottleneck in coil production or underutilized. This requires that the process utilization must be balanced and acceptably high. Also, the process queues must not contain excessive number of orders.
3. Keeping the work-in-process inventory under control: Although minimizing inventory levels is not the primary objective of this study, we cannot allow the inventories to build up as we try to satisfy the first objective above.

5.2. Choice of Factors and Factor Levels in the Experiment

In a designed experiment, the factors and their levels at which runs will be made must be identified. To decide on the factors and their levels, some preliminary runs have been made prior to the production runs. As a result of these runs, the sequencing technique that is used to dispatch orders waiting to be processed in the cold-mill and annealing furnace buffers has been designated as the only factor in ANOVA. Hence, within each capacity expansion alternative, observed values of performance measures are statistically analyzed to detect significant differences caused by the sequencing rules.

Capacity expansion, on the other hand, has not been considered as a factor in ANOVA, because it has been observed in the preliminary runs that the variations in the performance measures at different capacity alternatives are very large. In a system where there are only three major processes and two basic product types, doubling the capacity of one of these processes or introducing extra demand naturally bring drastic changes. Also, including capacity expansion as a factor in the analysis may easily result in violation of the constant variance assumption of ANOVA, because it is known from experience that the variance of the response often increases as its expected value increases. Nevertheless, in order to provide completeness of the discussion, the capacity expansion alternatives that have been analyzed through this simulation study are presented in this section.

The one-way analysis of variance is blocked by replications to be able to test potential effect of random number streams on the results.

Capacity Expansion Alternatives:

A capacity strategy must take into account a variety of factors, including the pattern of demand, and the cost of constructing and operating new facilities. As suggested by Nahmias (1993), "A firm that bases its strategy on maximization of capacity utilization runs the risk of incurring shortages in periods of higher than anticipated demand. An alternative strategy to increase productive capacity is to produce to inventory and let the inventory absorb demand fluctuations. However, this can be very risky. Inventories can become obsolete, and holding costs can become a financial burden."

In our simulation experiment, the demand pattern is fixed for basic product types by using interarrival time distributions. Therefore, satisfying the current demand level and balancing the process loads are the main issues in determining the capacity requirements of the system. However, achieving higher production levels is also kept in mind considering the expected increase in demand. The configurations given in Table 5.1 are tried in studying the capacity. These alternatives have been generated as we proceeded with the experimentation. Hence, choice of these alternatives are discussed in Section 5.6 along with the analysis of results.

Table 5.1. Capacity Expansion Alternatives

	Capacity Expansion Alternatives						
	S	***B***	***SC***	***BC***	***BCM***	***BCA***	***BCMA***
Sheet/Strip Demand	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Foil Demand	No	Yes	No	Yes	Yes	Yes	Yes
Number of Casting Lines	1	1	2	2	2	2	2
Number of Cold-Mills	1	1	1	1	2	1	2
Number of Annealing Furnaces	1	1	1	1	1	2	2

Sequencing Rules:

A sequencing rule is used to select the next job to be processed from a set of jobs awaiting service. To sequence a number of jobs, it is necessary to determine an order of precedence among the jobs. In other words, priorities must be assigned to the jobs according to a sequencing rule considered appropriate by the production management. Properly choosing the sequencing rule can provide dramatic improvements in the performance of the production systems.

In the sequencing/scheduling literature, terms such as scheduling rule, dispatching rule, priority rule, or heuristic are often used synonymously. Gere (1966) has made an attempt to distinguish between priority rules (sequencing rules), heuristics, and scheduling rules. He considers a sequencing rule as simply a technique which assigns to each waiting job a scalar value, the minimum of which, among jobs waiting at a machine, determines the job to be selected for processing over all others. On the other hand, he defines a heuristic to be simply some "rule of thumb," whereas a scheduling rule can consist of a combination of one or more priority rules and/or one or more heuristics.

Sequencing rules can be static, i.e., they can be applied at the beginning of the scheduling period and result in a fixed schedule for the period. In this case, job priorities do not change throughout the scheduling period. They can be very simple or extremely complex and may be classified in different ways according to their specific attributes, such as due date, total processing time, total number of operations, arrival time, slack time (based on total processing time and due date), and so on. Similar rules are available for the dynamic case, e.g., shortest imminent processing time, remaining processing time, and number of remaining operations.

Panwalkar and Iskander (1977) provide an extensive survey of sequencing rules and classify them according to their use. For each rule, all surveyed articles that use the rule are cited including the type of problem and measures of performance used. Most of these studies make use of simulation. They are stochastic in nature and provide a probabilistic viewpoint, treating job attributes as independent random variables with given distributions whose actual values are realized after a scheduling decision has been made. Therefore, the outcome of a scheduling decision depends on the realization of uncertain task parameters.

The performance of sequencing rules depends not only on the criterion chosen but also on the configuration of the production system under consideration. Therefore, results in literature often appear to be contradictory. In the review of sequencing rules by Montazeri and Van Wassenhove (1990), a list of sequencing rules is provided showing the performance of rules depending on the selected criteria and experimental conditions.

Nine sequencing rules are tried in our experiment for dispatching orders waiting in the queues of rolling and annealing processes. These rules are selected as the levels of factor after reviewing the literature on dispatching rules (see, for example, Abbott and Greene 1982; Panwalkar and Iskander, 1977) and choosing those that are applicable to the present system. In the model, the orders arriving at the buffer of either process are ranked such that any successor order with respect to a particular sequencing rule has lower priority than its predecessors.

The rules used in the experiment are classified into four groups according to their emphasis.

Arrival Time Dependent Rules: Rules that assign priority according to the sequence in which jobs arrive at the process.

- **FIFO:** Priority is given to the job that arrives at the queue first. In other words, the job to be processed is selected according to the first-in-first-out criterion. The FIFO rule is straight forward to implement and used as a standard in many comparisons.

Rules Dependent on Processing Requirements: Rules that assign priority depending on the processing times or number of operations of the jobs.

- **SPT:** The job having the shortest imminent processing time including the setup time is selected to be processed from a group of jobs waiting service. SPT is generally regarded as an efficient rule in that it tends to reduce average waiting time, and hence average flow time. This rule gains its power through the increased utilization achieved by moving jobs rapidly from full queues to empty ones. Therefore, it performs particularly well against the criterion of average work-in-process inventory since it arranges jobs waiting in the queue of a machine such that the job that can be completed most quickly on the machine is processed first. In the simulation model, the processing time of the orders in the cold-mill station are determined by Equation 4.1. In the annealing furnace, however, jobs are sequenced according to FIFO instead of SPT partly because there are strong batching restrictions, and partly because the processing times of many orders are the same anyway.

- **SRPT:** The job having the shortest remaining processing time is given the highest priority.

- **HYBRID:** This is a heuristic in which the jobs are sequenced in SPT order if they are likely to be early. Potentially tardy jobs, however, have precedence over all early jobs, and they are sequenced in FIFO order among themselves. This rule is implemented in the model as follows.

$$P_i = TP_{ij} \cdot \left[DD_i > (T_i + RP_{ij}) \right] \tag{5.1}$$

where

P_i: Priority of order i in the currently considered process queue.

TP_{ij}: Total processing time of order i (for all coils of the order, including the setup time) for operation j.

DD_i: Due date of order i.

T_i: Time at which order i joins the queue.

RP_{ij}: Remaining processing time of order i prior to operation j. Where n_i represents the total number of operations of order i, RP_{ij} is computed as:

$$RP_{ij} = \sum_{k=j}^{n_i} TP_{ik}$$

In Equation 5.1, the term in square brackets represents a condition that is evaluated as either true (1) or false (0). When the condition is true, i.e., the order still has a chance of being early at time T_i, then its priority is defined by its processing time. Otherwise, priority is evaluated as zero, and tardy orders are sequenced according to FIFO order.

- **SRNO:** This rule selects the job with the fewest number of remaining operations.

Due Date Dependent Rules: Rules that define the job priority as a function of the due date assigned to each job.

- **EDD:** This rule selects the job with the earliest due date. EDD is promising when the objective in the production system is to meet the customer due dates. EDD sequencing has in general been shown to minimize maximum tardiness, number of tardy jobs, and/or mean tardiness of all jobs. However, it does not guarantee the minimum number of tardy jobs or the minimum mean tardiness (Abbott et al., 1982).

- **USER:** The rule that is currently used in the production system is also tried in the experiment. In the real system, when sequencing the jobs, due date, number of completed operations and alloy type are considered, giving the emphasis to due date. Therefore, in the model, USER sequencing rule assigns a priority based on these factors. The order having the earliest due date has the highest priority. Between two orders having the same due date, the one that has the largest number of completed operations has higher priority. If these two attributes are the same for two orders, then alloy type defines the priority.

Slack Time Dependent Rules: Rules that assign priority depending on the slack time left to finish processing an order.

- **MST:** Minimum slack time rule ranks the jobs arriving at a process according to their respective slack times, and precedence is given to the job having the shortest slack time. Slack time for an order is computed as $DD_i - T_i - RP_{ij}$.

- **CR:** This rule ranks the jobs according to a critical ratio and priority is given to the job having the smallest ratio. This ratio can be defined as $(DD_i - T_i) / RP_{ij}$.

5.3. Response Variables Used in the Experiment

In selecting the response variables or measures of performance for an experiment, one must consider the objectives of the experiment and choose those variables that will serve the objectives. Statistical analysis of the selected performance measures typically aims at controlling the production system based on some objectives. Various output statistics generated by the second model are used as performance measures in accordance with the objectives discussed in Section 5.1. These statistics can be grouped under four main headings as follows.

Flow time related statistics:

- Waiting time of customer orders for foil and sheet/strip products (until allocation of cast coils to orders).
- Waiting time of cast coils in stock.
- Rolling and annealing flow times per order.
- Time in system (flow time) for foil and sheet/strip orders.

Queue related statistics:

- Length of foil and sheet/strip order queues.
- Size of cast coil stock.
- Length of rolling and annealing queues (in number of orders).

Utilization related statistics:

- Utilization of cold mill(s).
- Average load of annealing furnace(s) as percentage of furnace capacity.

Tardiness related statistics:

- Percentage of foil and sheet/strip orders satisfied.
- Slack time remaining for downstream processing for foil and sheet/strip orders.
- Number of tardy jobs and average tardiness for foil and sheet/strip orders.

A job (customer order) is defined as being tardy when it is completed after the intended due date. However, in our case, since the assigned due dates are true due dates for finished products, it is expected from the simulation runs that there will be no tardiness and orders will have slack times for downstream processing. Therefore, slack time is defined as the primary tardiness related measure. Because the downstream process times are unknown and expected to vary, it is assumed that maximizing average slack time will result in minimizing average tardiness in general.

5.4. Choice of the Experimental Design

Choice of the design involves the determination of the sample size (number of replications) and the statistical analysis method that enables us to detect the significant effects of experimental factors on the response variables.

The required number of replications that is adequate to analyze the subsystem of concern and to compare system alternatives has been determined as 40 by using the operating characteristic curves (Montgomery, 1991). The discussion of determination of sample size is given in Section 4.6.

It is necessary to design the experiment so that the variability arising not only from the factors but also from known sources of nuisance can be statistically controlled. Therefore, the *randomized complete block design* is chosen as the appropriate design. In this design, there is one factor (sequencing rule) and one nuisance variable (or blocking variable) which is the random number stream used for each replicate. Effectively, this design strategy improves the accuracy of the comparisons among the sequencing rules by eliminating the variability among the stream numbers.

The statistical model for the design is

$$y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \qquad i = 1,...,9; \;\; j = 1,.....,40 \qquad (5.2)$$

where μ is an overall mean, τ_i is the effect of the i^{th} treatment (sequencing rule), β_j is the effect of the j^{th} block (random number stream), and ε_{ij} is the usual random error term. The levels of our factor and blocking variable are taken as fixed. A detailed discussion of this design is provided by Montgomery (1991).

The experiment has been repeated for each capacity expansion alternative. The experimental settings and the values of input variables (parameters) are given in the previous chapter. The analysis of the experiment and discussion of the results are presented in Section 5.6. In the analysis, the block effects, β_j, are consistently found to be insignificant and eliminated from further considerations.

5.5. Performing the Experiment

The experiment has been performed by using a personal computer that has a Pentium-100 microprocessor with a 16-bit motherboard. One replication (simulation run) lasts approximately 7.5 minutes. The standard output report of SIMAN has been used to obtain the replication averages of performance measures, and EXCEL 5.0 has been used to compute averages of experimentation points and to perform ANOVA.

5.6. Analysis of the Experiment Results

Results of the experiment are summarized in Table 5.2 where average of all performance measures are given for each capacity expansion alternative. These averages are based on eight sequencing rules that are used in the experiment. SRPT rule is excluded in calculation of average values and ANOVA for reasons that will be discussed later in this section.

Predicted values of performance measures and corresponding Duncan's multiple range test (Montgomery, 1991) results are tabulated in Appendix F, Tables F.1 through F.14 for all sequencing rules within each capacity expansion alternative. These tables also include the significance levels of the ANOVA to identify whether or not there are significant differences between results of sequencing rules. Two example ANOVA tables are presented in Tables E.1 and E.2, Appendix E. Whenever the differences are significant, Duncan's multiple range test is performed to compare all pairs of sequencing rules, and the rules are ranked according to their performance to identify the best rule for each performance measure.

Before application of ANOVA, however, the adequacy of the ANOVA model given by Equation 5.2 should be checked for each case it is applied. The assumptions underlying the analysis of variance are that the data are adequately described by the model, and random errors are normally and independently distributed with mean zero and constant variance. The primary diagnostic tool is the residuals analysis (Montgomery, 1991). The residual can be defined as the difference between the actual and predicted values of an observation.

Model adequacy checking usually consists of constructing the normal probability plot of residuals and plotting residuals versus fitted values. The appearance of a moderate departure from normality does not necessarily imply a serious violation of the normality assumption.

Table 5.2. Summary Results of Capacity Expansion Alternatives

Performance Measures	***Capacity Expansion Alternatives***						
	S	B	SC	BC	BCM	BCA	BCMA
Foil Order Waiting Time (min/order)	-	130899 (90.9 days)	-	36.0	40.4	48.7	31.6
Sheet Order Waiting Time (min/order)	42530 (29.5 days)	82337 (52.7 days)	0.03	7.9	5.57	5.3	5.1
Cast Coil Waiting Time (min/order)	870.2	1120.4	157075 (109.1 days)	83447 (58.0 days)	82257 (57.1 days)	82268 (57.1 days)	82121 (57.0 days)
Cold-Rolling Flow Time (min/order)	41.9	97.6	49.5	570.3	40.32	804.1	35.7
Annealing Flow Time (min/order)	1272.8	1662.0	1768.0	5333.7	6063.1	1239.0	1248.4
Foil Order Flow Time (min/order)	-	139232 (96.7 days)	-	28178.0 (19.6 days)	27515.9 (19.1 days)	18402.7 (12.8 days)	13572.7 (9.4 days)
Sheet Order Flow Time (min/order)	47494.8 (33.0 days)	86928.7 (60.4 days)	5755.7 (4.0 days)	12966.4 (9.0 days)	10377.1 (7.2 days)	9995.1 (6.9 days)	5133.6 (3.6 days)
Foil Order Queue (time averaged #)	-	306.1	-	0.02	0.03	0.04	0.01
Sheet Order Queue (time averaged #)	412.9	888.9	0.0	0.03	0.02	0.01	0.02
Cast Coil Queue (time averaged #)	15.4	18.3	7121.7	3556.2	3511.1	3509.8	3507.2
Cold-Rolling Queue (time averaged #)	1.02	2.99	1.50	32.0	1.337	46.1	1.080
Annealing Queue (time averaged #)	3.34	7.39	7.54	68.4	86.77	6.24	6.357
Mill 1 Utilization (time averaged %)	50.87	60.91	59.28	96.23	46.60	97.09	47.00
Mill 2 Utilization (time averaged %)	-	-	-	-	46.58	-	46.98
Annealing Furnace 1 Load (time averaged %)	42.61	51.47	49.52	80.96	80.73	40.84	40.87
Annealing Furnace 2 Load (time averaged %)	-	-	-	-	-	40.88	40.85
% Foil Order Satisfied	-	54.06	-	91.52	91.64	94.41	95.84
% Sheet Order Satisfied	83.64	66.85	98.23	95.83	96.42	96.90	98.42
Slack Time of **Foil** Order (min/order)	-	-44405 (-30.8 days)	-	75583 (52.5 days)	76200 (53.0 days)	85811 (59.6 days)	90678 (63.0 days)
Slack Time of **Sheet** Order (min/order)	58464 (40.6 days)	15045 (10.4 days)	105154 (73.0 days)	97018 (67.4 days)	99357 (69.0 days)	100932 (70.1 days)	105634 (73.4 days)
Number of Tardy **Foil** Orders (#/year)	-	296.0	-	25.54	26.88	5.47	0.0
Average Tardiness of **Foil** Order (min/tardy order)	-	89874 (62.4 days)	-	17159 (11.9 days)	17599.2 (12.2 days)	4351.4 (3.0 days)	0.0
Number of Tardy **Sheet** Orders (#/year)	435.8	904.4	0.32	16.45	7.93	16.46	0.23
Average Tardiness of **Sheet** Order (min/tardy order)	44111 (30.6 days)	77151 (53.6 days)	451.7	20003 (13.9 days)	15452 (10.7 days)	12108 (8.4 days)	245.3

: Results obtained with SRPT Rule are excluded in calculation of average values.

Gross deviations from normality, however, are potentially serious and require further analysis. On the other hand, the usual approach to deal with non-constant variance is to apply a variance-stabilizing transformation and then to run ANOVA on the transformed data. In this study, the residual analysis is performed by using EXCEL 5.0 software. For the cases where the constant variance assumption is violated, the selected transformations that yield constant variance are also indicated in the tables of Appendix F. Sample normal probability and residual versus fitted value plots are given in Appendix E, Figures E.1 through E.6.

Before discussing the results of the experiment for each capacity expansion alternative, some general observations on which the discussion is based can be made as follows.

Observation 1: Main differences between cold-rolling and annealing processes from operational point of view are their unequal process times and average number of passes of coils through these processes. While the coils pass through cold-mill many times to achieve desired thickness, they are sent to the annealing furnace only once or twice (at most three times for foil products).

Observation 2: The two basic product types have some process and demand related distinctions. These may be listed as follows.

- Arrivals of sheet/strip orders are more frequent, increasing their share in the process load.
- Sheet/strip order quantities are larger compared to foil orders. This results in allocation of more coils to them. Therefore, sheet/strip orders have longer imminent and remaining processing times per order.
- Foil products have more operations than sheet/strip products. Hence, they have longer total process times, basically due to the large number of annealing operations they require. This results in longer remaining processing times per order in case of foil products.

Observation 3: Some problems are observed in the simulation runs of almost all capacity expansion alternatives when SRPT is used as the sequencing rule. Annealing flow time, annealing queue, time in system, number of tardy orders, and average tardiness for sheet/strip orders are very high with this rule. This may be attributed to difficulties in dispatching orders waiting for annealing in the SRPT case. Particular alloy types (3000 series) have significantly longer total processing times compared to other alloy types since generally thin and intermediate final thickness levels are desired in 3000 series alloys. Additionally, they can not be batched together with other alloys except AA90 due to process dissimilarity. As a result, alloys having shorter processing times always have precedence over 3000 series, and orders of 3000 series keep waiting in the annealing queue for an extremely long time, causing deterioration in related statistics. Consequently, in SRPT case, the annealing queue explodes with the accumulation of 3000 series orders. This also affects the rolling process and causes cold-mill to be underutilized, because many orders keep waiting for annealing furnace and can never get back to cold-mill. Therefore, the SRPT case is excluded in overall average and ANOVA computations.

Capacity Expansion Alternative S

As indicated in Table 5.1, in this capacity alternative, only the coil requirements of sheet/strip orders are assumed to be satisfied by the continuous casting line, and orders for foil products are not taken into consideration. This leads to a decline in the loads of the cold-rolling and annealing processes contrary to the conditions observed in the real system. However, with this characteristic of alternative S, the model better represents the circumstances in the casting line of the real system. As discussed in Chapter 3, the prescribed practice in the real system is allocation of in-house cast sheet coils to sheet/strip orders. The requirements of foil orders and the excess of sheet/strip orders that can not be met by the continuous casting line are generally satisfied by purchasing coils from the outside suppliers. Purchased coils increase the loads of cold-mill and annealing furnace in the real system.

This alternative is studied basically to determine the performance of the casting line and to analyze the system behaviour under this low demand condition. For this capacity alternative, the predicted values of performance measures for each sequencing rule and results of the corresponding Duncan's multiple range tests are presented in Tables F.1 and F.2, respectively.

As a general observation, the customer order waiting time, i.e., the time passed until allocation of required number of cast coils to the sheet/strip orders, and the length of the order queue are large (see Table 5.2), because the single casting line can not meet demand even when only sheet/strip demand is considered. Consequently, time in system for orders of sheet/strip products is also long and exceeds the acceptable levels for most of the sequencing rules. The time between arrival and completion of an order is roughly estimated as 30 days in the current system. The factory management thinks that reducing this figure down to 20 days would be a significant contribution, and further reduction is naturally desirable. Coil production in our system must take much shorter than 20 days so that the final product can be completed within this duration. In alternative S, however, completion of a sheet/strip order takes 18-40 days for various sequencing rules. As a result, the throughput is low. Roughly speaking, 84% of the arriving customer orders can be fully satisfied throughout the simulation run, while the remaining orders are probably waiting for cast coils. Extended duration of waiting time for the allocation of coils also influences the slack time left for the downstream processing. Reduction in the slack time may cause problems in meeting the order due dates. This is observed in the tardiness related measures as well. They are relatively high (compared to some other alternatives) as a result of long order waiting time for almost all sequencing rules. Contrary to these, cast coil waiting time and cast coil stock are low since there is a limited supply of cast coils, and these coils are immediately allocated to customer orders.

On the other hand, flow time of orders through cold-rolling and annealing, work-in-process (WIP) queues of these processes, and their utilization are low. This can be attributed to production of limited number of cast coils that will require processing in the cold-mill and annealing furnace stations. Regardless of the choice of dispatching rule, the two processes are underutilized and their WIP levels are low since there is too little work in the system. The observed values of flow times in the cold-rolling and annealing processes almost correspond to pure processing times (including setup) after casting. The time spent in rolling and annealing operations is only a small fraction of the order flow time, meaning that customer orders spend most of their times in the system by waiting for cast coils.

Compared to other sequencing rules, MST and CR (slack time related rules) seem to reduce order waiting time as seen also from Duncan's multiple range test results given in Table F.2. As a result of this, reduction in time in system for orders and number of tardy orders, and increase in slack time for downstream processing are observed. These significant improvements are due to the ability of these rules to select the critical orders that have shorter slack times. Average tardiness, however, is large mainly because, although there are fewer tardy orders, they end up waiting in queues for too long to make room for orders that are favoured by MST and CR. On the other hand, they do not provide any improvement in the length of customer order queue or percentage of orders satisfied during a year due to limited supply of cast coils. Some characteristics of MST and CR are also observed in SRPT case, but this rule results in an extremely large tardiness value due to the reasons given in Observation 3.

Similar characteristics are expected from the due date dependent rules (EDD and USER). However, they do not yield the same effect in sequencing the orders since certain job characteristics (processing times and number of operations) are not taken into consideration when assigning the priority. EDD and USER reduce number of tardy orders and minimize average tardiness since they select the orders having less time to their due dates. Such a behaviour is expected from EDD as reported in many researches (Abbott et al., 1982).

As expected, SPT minimizes the rolling WIP and flow time. However, it does not have an equally significant effect on annealing statistics due to batching restrictions. Because of the long waiting time in order queue, SPT rule does not perform well in minimizing order flow time when compared with the other rules. FIFO and HYBRID also behave similar to SPT in reducing the annealing flow time and WIP, but they can not reduce rolling flow time as much as SPT does.

In summary, this alternative suffers from the capacity limitation of casting. Among the sequencing rules, MST and CR seem to be the most promising rules.

Capacity Expansion Alternative B

When the foil demand is introduced in addition to the sheet/strip orders in the presence of a single casting line, the system simply explodes. The same observations made for alternative **S** are in general valid for this case, only the statistics take more extreme values. For alternative **B**, the predicted values of performance measures for each sequencing rule and Duncan's multiple range test results are tabulated in Tables F.3 and F.4.

In general, slack time remaining for downstream operations is very small for sheet and negative for foil, indicating that there is no time left for these operations. This is obviously due to excessive order waiting time until required number of coils can be allocated to an order.

As in the case of alternative **S**, MST and CR are the most promising rules that enable reduction in the order waiting time, leading to minimum time in system and maximum slack time for both foil and sheet/strip orders. Also, SRNO provides some improvements in the order waiting time of sheet/strip products, but this is due to differences in processing between foil and sheet/strip products that are discussed under Observation 2. Since foil products have larger number of operations, orders of sheet/strip products have precedence over foil orders when the sequencing rule is SRNO.

Increases in process utilizations compared to alternative **S** can also be attributed to higher number of operations that are applied to foil orders.

EDD and USER do not minimize average tardiness as they did in alternative **S**. In fact, these rules are dominated by MST and CR, as far as all tardiness related measures are considered.

As in alternative **S**, SPT rule dominates all other rules in terms of WIP statistics. FIFO and HYBRID also perform well in this respect, especially by reducing the flow time of annealing process. This may be ascribed to their similarity to SPT rule in sequencing the jobs.

Capacity Expansion Alternative SC

Addition of a second casting line serving only sheet demand has a drastic effect on some of the performance measures as expected. Order waiting time and order queue length are now virtually zero, and time in system for orders is approximately one tenth of what it is in alternative **S** due to increased coil supply. Cast coil stock, on the other hand, increases significantly for the same reason. Although there are some slight increases, flow times, queues, and utilizations of rolling and annealing processes are not affected as much as the above statistics. This means that adding a second casting line does not overload these processes or cause them to become bottleneck.

Tardiness related measures improve drastically, with tardy jobs almost vanishing. Percentage of orders satisfied increases for all sequencing rules from 84% observed in alternative **S** to 98%. Slack time also increases significantly, bringing flexibility to downstream processing.

The superiority of MST and CR over other sequencing rules is not true any longer. These two rules, together with SPT, result in only slightly better tardiness statistics. In general, the system seems to be well balanced in this case, and the sequencing rule used does not make a significant difference. For capacity alternative **SC**, the results of performance measures under each sequencing rule and respective Duncan's multiple range tests are given in Tables F.5 and F.6.

Capacity Expansion Alternative BC

The results of this alternative are provided in Tables F.7 and F.8. As in the previous cases, the tables include the predicted values of performance measures for each sequencing rule and results of Duncan's multiple range tests that are used to rank and group the sequencing rules. In this capacity alternative, since current sheet/strip and foil demand is satisfied immediately by increased cast coil supply, the loads of rolling and annealing processes increase and approach the conditions observed in the real system. Hence, in alternative **BC**, real system conditions in rolling and annealing processes are better represented.

When the foil orders are added in the presence of two casting lines, sheet/strip order statistics deteriorate in general. However, the most drastic changes compared to alternative **SC** are observed in the performance measures that are related with the rolling and annealing processes. Flow time and queue statistics of these processes increase significantly as overall demand increases, especially because foil products require longer processing times and larger number of operations compared to sheet/strip products. This behaviour suggests that addition of a new cold-mill and/or a new annealing furnace has the potential of improving the system performance.

Since the order waiting time and order queue statistics are virtually zero in this alternative, time in system for orders are dependent mainly on the processing times in cold-rolling and annealing stations. Any sequencing rule that provides better WIP and flow time statistics not only reduce the time in system but also performs well for tardiness related statistics. Contrary to other alternatives that are discussed up to now, the superiority of SPT rule in WIP related statistics is no longer valid. In alternative **BC**, FIFO and HYBRID appear to be the best rules in minimizing the rolling and annealing flow times, leading to minimum WIP levels in these processes. EDD, MST and USER perform as well as FIFO and HYBRID in minimizing the flow time and queue length of the rolling process. SPT has almost the same performance as FIFO and HYBRID only in minimizing the annealing flow time and queue length.

The differences between the time in system and slack time statistics for foil and sheet/strip products are obvious in this alternative. As expected, SRNO improves the time in system and slack time of the sheet/strip products since the foil products have more processing steps and precedence is given to sheet/strip orders. On the contrary, FIFO, MST, CR, and HYBRID improve the time in system and slack time of foil products. In this alternative, especially the conflicting results of SRNO and CR rules for foil and sheet/strip products are noteworthy.

EDD and USER are the best rules in tardiness related measures since they have certain advantages over other rules with their due date based structure. Their success in minimizing the tardiness related measures justifies the management in choosing USER as the sequencing rule since the main objective of the management is meeting the customer order due dates on time. However, neither of these rules performs well in terms of slack time left for downstream processing.

In summary, this alternative represents the minimal configuration where demand is satisfied within reasonable time, process loads are balanced, and number of tardy orders is small. Process utilizations are high at the expense of increased WIP levels. Hence, there is still room for further improvement. FIFO and HYBRID seem to be the best rules when all performance measures are considered.

Capacity Expansion Alternative BCM

As suggested in alternative **BC**, there are potential improvements in the performance measures that can be achieved by adding a new cold-mill or a new annealing furnace. In alternative **BC**, the cold-mill has an average utilization of 96% whereas this value is 81% for the furnace. Hence, in alternative **BCM**, the effects of adding a second cold-mill are explored. The results obtained in this capacity alternative are tabulated in Tables F.9 and F.10.

Order waiting time and order queue are not affected by addition of a new cold-mill since these statistics are dependent on cast coil availability. Contrary to the expectations, time in system for orders and tardiness related measures do not improve much. While reduction in time in system is insignificant for foil products, there is an approximately 20% reduction for sheet/strip products compared to alternative **BC**. As expected, rolling flow time and rolling queue decrease significantly compared to alternative **BC**, and utilization of each cold-mill is almost half of what it is for a single mill. Slight improvement in time in system for the sheet/strip products can be attributed to the reduction in rolling flow time.

Annealing time and annealing queue increase slightly, because orders can now be processed in cold-mills and are sent to the annealing furnace more frequently. This causes an increase in the process load of the annealing furnace, and orders wait longer in the annealing queue in this case. Although overall average load of the annealing furnace is only 81% as it can be seen from Tables 5.2 and F.9, it cannot be increased further because orders with dissimilar processing requirements cannot be batched together in the furnace. Hence, the annealing process becomes a bottleneck in alternative **BMC** with the queue length of 87. Therefore, adding a new mill to the system does not by itself provide much improvement in the overall system performance.

Among the sequencing rules, SPT stands out as the rule that provides the best system performance in general, followed by FIFO and HYBRID. SPT improves not only the flow time, queue, and utilization statistics but also the tardiness related measures, with the exception of sheet/strip tardiness measures for which EDD and USER are the best. EDD and USER yield virtually zero number of tardy orders and minimum average tardiness for both foil and sheet/strip products.

Capacity Expansion Alternative BCA

This alternative is the symmetrical case of alternative **BCM**; this time a second annealing furnace is added to the system considering the queue size of annealing furnace in alternative **BC** (68 on the average) compared to that of cold-mill (32 on the average). In this case, annealing time and length of annealing queue decrease significantly compared to alternative **BC** whereas rolling time and rolling queue increase slightly as a result of the shift in the load balance. Also, it should be noted that average load of each annealing furnace is halved. The results obtained in alternative **BCA** are tabulated in Tables F.11 and F.12.

Time in system for orders and tardiness related measures improve significantly in this alternative. Reduction in time in system is 35% for foil orders and 20% for sheet/strip orders compared to alternative **BC**. Therefore, any improvement in the annealing flow time affects the system performance significantly. Hence, it may be concluded that the marginal utility of an additional annealing furnace is higher than that of an additional cold mill. However, when a second furnace is added, the single cold-mill becomes a bottleneck with an average utilization of 97% and queue length of 46.

There is not a single sequencing rule that improves all performance measures. SPT, FIFO, SRNO and HYBRID are the rules giving the most promising results in WIP related statistics. It can be seen from Tables F.11 and F.12 that queues and utilizations are best improved with SPT. SRNO performs well in minimizing the flow time of sheet/strip products, but results in long time in system for foil orders since foil products have relatively larger number of operations as explained in Observation 1. Contrary to SRNO rule, CR favours foil orders in terms of time in system. As the foil orders, in general, have longer remaining processing time, they are given higher priority when CR is used. On the other hand, EDD seems to improve flow time related statistics for both foil and sheet/strip orders and represents an acceptable compromise.

Finally, it is apparent that the best rules for tardiness related measures are EDD, USER, FIFO, and HYBRID, noting that HYBRID behaves like FIFO as far as tardy jobs are concerned.

Capacity Expansion Alternative BCMA

The results of alternative **BCMA** are given in Tables F.13 and F.14. In general, for this alternative, it can be stated that when the resource availability is doubled for each of the three processes, flow time and queue statistics for rolling and annealing reach their lowest values, and their utilizations are halved.

As seen in Table 5.2, time in system for orders is reduced by 50% for foil products and 60 % for sheet/strip products compared to alternative **BC**. Slack time and tardiness measures also improve drastically. Consequently, it can be concluded that doubling the resource capacities of rolling and annealing processes simultaneously has a more significant effect on the system than adding only one cold mill or one annealing furnace at a time.

In this alternative, one may expect that casting, with two casting lines, becomes the determining factor again when the capacity of rolling and annealing processes are doubled. However, waiting time of orders for cast coils is very low and cast coil stock is high, meaning that there is a sufficient supply of coils.

The differences between sequencing rules are insignificant for most of the cases in this alternative compared to the other capacity expansion alternatives, mainly because the system is underutilized. (Process utilizations are below 50%, and queues are empty.) Consequently, if there is too little work, processes are idle regardless of the dispatching rules whereas too much work permits any rule to fully utilize the shop. According to Tables F.13 and F.14, SPT performs slightly better in terms of queue and utilization statistics. It also improves the time in system for sheet orders. Time in system for foil orders, however, is best improved with USER and EDD. SRNO, HYBRID and FIFO improve the annealing furnace statistics.

While the differences in foil tardiness measures are insignificant, sheet tardiness measures are lower when CR and MST are used. Although these differences are statistically significant, their practical significance is questionable for alternative **BCMA** under current demand.

5.7. Results of Experiment at Various Demand Levels

Based on the results of the experiment in which the performance of the system is analyzed under various capacity expansion alternatives, we have decided to perform additional simulation runs to investigate the behaviour of the system under increased demand. The basic motivation behind this is that the demand has steadily been increasing since 1995 and is expected to increase in the future. Also, in alternative **BCMA**, the system is underutilized, and it seems possible to increase the production. Therefore, in alternative **BCMA**, various demand levels are experimented with to determine the level at which the system becomes fully utilized or saturated. Obvious performance measures of interest in this case are shop utilization, WIP levels, and balance of the process loads. For this purpose, among the more promising sequencing rules in alternative **BCMA**, three of them are selected: EDD, SPT and SRNO.

The demand levels selected for the experimentation are

- current demand,

- 1.25 times the current demand,
- 1.5 times the current demand, and
- 2.0 times the current demand.

Experimental conditions are similar to the previous case. The expected values for each performance measure are estimated to determine the effects of various demand levels on the system performance. As in the previous case, ANOVA is used for comparison of sequencing rules within each demand level, followed by Duncan's multiple range test to rank the sequencing rules. Likewise, residuals are analyzed to test the validity of the ANOVA model, and variance stabilizing transformations are applied to data when necessary. Overall average values of performance measures obtained at each demand level are tabulated in Table 5.3. The expected values of performance measures for each sequencing rule and Duncan's multiple range test results are presented in Tables F.15 through F.20.

It can be easily seen from Table 5.3 that, with increasing demand, the time in system measures for both foil and sheet/strip products increase as a result of the drastic increases in waiting time of orders for cast coils. Order queues, particularly that of sheet/strip orders, become longer, and tardiness related measures deteriorate. However, the WIP levels and utilizations of rolling and annealing processes are not affected significantly, mainly because the casting process again becomes a bottleneck for the system with increasing demand. Increase in time in system statistics also affects the slack time; it decreases with increasing demand and becomes negative for foil orders when the demand is doubled. Looking at the flow time and slack of foil and sheet/strip orders, we can conclude that alternative **BCMA** can meet 1.25 times the current demand, but further increase in production may not be possible.

Choice among the sequencing rules is not clear, because each rule improves certain performance measures but causes deterioration of others. SPT seems to be the best rule in minimizing the WIP related measures at all demand levels, and this may be attributed to low process flow times achieved with SPT. Tardiness related measures, however, are minimized by EDD as expected. With increasing load on the system, the tradeoff caused by SRNO and EDD between foil and sheet/strip orders becomes obvious. In a fully utilized system, SRNO gives precedence to the orders having minimum number of operations. Therefore, especially the time in system and slack time of sheet/strip orders are reduced with SRNO. EDD, on the other hand, favours the foil orders in terms of the same performance measures.

Table 5.3. Summary of Results for Alternative **BCMA** at Various Demand Levels

Capacity Alternative	BCMA (2 casters, 2 cold-mills, 2 annealing furnaces)			
Performance Measures	*Demand Levels*			
	Current demand	Demand * 1.25	Demand * 1.5	Demand * 2.0
Foil Order Waiting Time (min/order)	31.6	2793.7 (1.9 days)	55785.1 (38.7 days)	170426 (118.4 days)
Sheet Order Waiting Time (min/order)	5.1	4498.4 (3.1 days)	37195.8 (25.8 days)	86754.6 (60.2 days)
Cast Coil Waiting Time (min/order)	82121.0 (57.0 days)	10631.4 (7.4 days)	2449.6 (1.7 days)	619.3
Cold-Rolling Flow Time (min/order)	35.7	49.1	66.7	55.6
Annealing Flow Time (min/order)	1248.4	1314.4	1472.9	1467.2
Foil Order Flow Time (min/order)	13572.7 (9.4 days)	16705.0 (11.6 days)	67726.2 (47.0 days)	178968 (124.3 days)
Sheet Order Flow Time (min/order)	5133.6 (3.6 days)	9751.9 (6.8 days)	42418.4 (29.5 days)	91145.0 (63.3 days)
Foil Order Queue (time averaged #)	0.01	8.1	170.4	675.1
Sheet Order Queue (time averaged #)	0.02	42.5	517.9	1728.1
Cast Coil Queue (time averaged #)	3507.2	428.8	72.9	20.4
Cold-Rolling Queue (time averaged #)	1.08	2.28	3.72	2.89
Annealing Queue (time averaged #)	6.36	9.01	12.14	11.50
Mill 1 Utilization (time averaged %)	47.00	60.01	62.62	58.36
Mill 2 Utilization (time averaged %)	46.98	59.97	62.60	58.36
Annealing Furnace 1 Load (time averaged %)	40.87	51.29	53.06	50.44
Annealing Furnace 2 Load (time averaged %)	40.85	51.22	52.66	50.45
% Foil Order Satisfied	95.84	94.58	80.68	50.51
% Sheet Order Satisfied	98.42	96.90	85.69	67.85
Slack Time of Foil Order (min/order)	90678.0 (63.0 days)	87435.4 (60.7 days)	34934.8 (24.3 days)	-75791.0 (-52.6 days)
Slack Time of Sheet Order (min/order)	105634 (73.4 days)	101132 (70.2 days)	68142.7 (47.3 days)	18729.4 (13.0 days)
Number of Tardy Foil Orders (#/year)	0.0	4.83	288.8	729.4
Average Tardiness of Foil Order (min/tardy order)	0.0	30525.0 (21.2 days)	42421.5 (29.5 days)	105019 (72.9 days)
Number of Tardy Sheet Orders (#/year)	0.23	33.0	664.1	1834.5
Average Tardiness of Sheet Order (min/tardy order)	245.3	12986.0 (9.0 days)	50025.4 (34.7 days)	110700 (76.9 days)

CHAPTER 6

CONCLUSION

In this thesis, a production system of flat rolled aluminum foil and sheet/strip products is studied. A subsystem of the plant consisting of continuous casting, cold-rolling and annealing processes has been analyzed by means of computer simulation to investigate the effects of various capacity expansion alternatives and order sequencing rules on the selected performance measures of the production system.

The performance measures are flow time, work-in-process levels, utilization of the processes, and tardiness related measures. The statistical analysis of these selected performance measures aims at identification of the best capacity expansion alternative and the sequencing rule based on the objectives of (1) satisfying the demand, (2) balancing the process loads, and (3) keeping work-in-process inventory under control. We are also concerned with increasing production in the subsystem. Additionally, for the capacity expansion alternative that has excess production capacity with the current demand level, the demand rate has been increased in order to observe the behaviour of the system under various load levels.

Based on the results of the simulation study and discussions given in Chapter 5, we can draw the following conclusions.

1. The output statistics of the simulation runs made at the present capacity and sequencing rule combination and the actual figures obtained from the subsystem of concern are consistent with each other. Therefore, it can be stated that the developed models are credible for studying and analyzing the subsystem of concern.

2. The continuous casting process is the major bottleneck in aluminum sheet coil production system. Hence, adding a second casting line to the system has the most drastic effect on the system performance.

3. Alternative **SC** is the smallest system configuration that maintains balanced process loads when only sheet/strip orders are under consideration. It also requires the lowest investment, construction of a second casting line. When foil demand is also included (alternative **BC**), the system is still capable of meeting sheet/strip orders within reasonable time (nine days on the average, with 67 days of slack left for downstream processing). Foil orders, however, take longer time to finish (19 days on the average with 53 days of slack).

4. System performance can not be improved unless first the capacity of the casting line is increased to a level that will satisfy the demand. Since, cast coil supply with current casting capacity can never fully utilize the two downstream processes, a capacity increase in these processes is meaningless. (We have confirmed this in an alternative where we have a second annealing furnace but no additional casting line.)

5. Once the casting capacity is doubled, the annealing furnace becomes the bottleneck. Therefore, an additional furnace has a higher marginal utility than an additional cold mill. Hence, alternative **BCM** is not very effective in improving the system performance when compared with the alternative **BC**. Alternative **BCA**, on the other hand, yields fairly close results to **BCMA** and requires lower investment.

6. Among the capacity expansion alternatives investigated, alternative **BCMA** results in the best overall system performance in terms of flow time of orders, queue statistics and tardiness related measures, but process utilizations are relatively low. However, it will be possible to utilize the processes better in the near future as the demand is predicted to increase.

7. Alternative **BCMA** can handle up to 25% increase in demand. When the demand level is further increased, continuous casting process again becomes a bottleneck in the production system.

8. Conflicting results are obtained in analyzing the performance of sequencing rules under different capacity configurations because each rule improves certain performance measures but cause deterioration of others. The suitable sequencing rule must be selected after a capacity expansion configuration is decided, and by considering the overall objective of the system and the tradeoffs between various performance measures. In our case, in general, if the work-in-process inventory is very small, there are a few choices to be made and it does not make much difference what rule is used. If the work-in-process inventory is large, on the other hand, almost any rule will provide close to 100% utilization. Nevertheless, it can be concluded that for alternatives in which the casting line is a bottleneck (alternatives **S** and **B**), MST and CR provide the best performance in reducing time in system and tardiness related measures by minimizing the waiting time of orders for allocation of cast coils. For alternative **BC**, which is the minimal configuration to meet both sheet/strip and foil demand, FIFO and HYBRID are the most promising rules. They improve most of the performance measures. The next alternative worth consideration is **BCA** which requires more investment but provides considerable improvements over alternative **BC**. EDD seems to be the best sequencing rule for this alternative. Finally, **BCMA** in general performs best when SPT is used. **BCMA** should be considered if the demand indeed increases because otherwise the system is underutilized with current demand. With these suggestions, the ultimate choice of capacity expansion alternative must be made by the factory management, considering the investment requirements of each alternative.

9. SPT stands out as the rule that yields the best system performance in WIP and utilization related measures, followed by FIFO and HYBRID. Finally, tardiness related measures are best minimized with EDD and USER.

As seen from the last conclusion, the task is quite formidable because of conflicting results and tradeoffs involved in many cases. For specific performance criteria, different rules perform better under different capacity configurations. Main reason for this is the change of performance of sequencing rules with changing operating conditions. Therefore, there is a need to perform studies involving the application of other sequencing rules or heuristics under a wide range of operating conditions to arrive at general conclusions. As extension of this is sequencing of orders for the annealing process where batching restrictions may require development of process specific sequencing heuristics.

In this study, the capacity of one or more processes is doubled, assuming that identical resources are used. This is mainly to simplify modelling and input data analysis. In reality, different technologies and commercial products are available for all three processes involved. In a further study, these technologies and products may be surveyed and capacity increase at other discrete levels can be considered. In doing this, an extensive demand forecast also needs to be done.

As explained in the previous chapters, foil and sheet/strip orders have certain shares under current demand level. Predictions show an increase in the share of foil orders in the overall demand. Hence, the percentages of sheet/strip and foil orders may be varied, keeping the demand level constant to see the performance of system under various product mix conditions.

It has been stated that due date assignment in the model is random. Process requirements and order size of customer orders are not considered during assigning due dates. In a further study, different due date assignment strategies and techniques can be experimented with to determine the required capacity under various due date assignment policies and to develop a due date assignment system that is applicable in the real system.

Finally, as various demand levels have been tried in alternative **BCMA** to identify the demand level at which the system is fully utilized, it is seen that this alternative can handle 25% increase in demand but not 50% increase. In a further study, the demand can be increased at various levels within the range 25%-50% to be able to estimate more precisely how far the production can be increased. This would also help the factory management in capacity planning.

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APPENDIX A

BASIC DEFINITIONS AND CONCEPTS IN METALWORKING

The ultimate goal of a manufacturing process is to produce components of a selected material with a required geometrical shape and a structure optimized for a proposed service environment. At this point, the importance of metals in modern technology should be indicated with their ease of forming into useful shapes such as tubes, rods, and sheets. There are two basic ways to generate useful shapes.

1. By plastic deformation processes in which the volume and mass of the metal are conserved and the metal is displaced from one location to another.
2. By metal removal or machining processes in which material is removed in order to give it required shape.

Equal in importance to the creation of useful shapes by plastic forming processes is the control of mechanical properties of the workpiece by metalworking processes. For example, blowholes and porosity in a cast-ingot may be eliminated by metalworking processes, to the improvement of ductility and fracture toughness. In many products, the precise control of deformation (strain hardening), temperature, and strain rate during processing is required to develop the optimum structure and mechanical properties.

A.1. Classification of Metalworking Processes

Processes developed for specific metalworking applications may be classified into only a few categories on the basis of the type of forces applied to the workpiece as it is formed into shape (Dieter, 1988). These categories are:

1. Direct-compression type processes,
2. Indirect-compression type processes,

3. Tension type processes,
4. Bending processes, and
5. Shearing processes.

As seen, the stresses producing the deformations can be tension, compression, shear, or various combinations of these. In case of direct-compression processes, the force is applied to the surface of the workpiece, and the metal flows at right angles to the direction of the compression. The chief examples of this type of process are forging and rolling. However, in indirect-compression processes case, including wire-drawing, tube-drawing, extrusion, and deep-drawing, the primary applied forces are frequently tensile, but the indirect compressive forces developed by the reaction of the workpiece with the die reach high values and cause deformation of the workpiece into desired shape. (Figure A.1 illustrates the typical forming operations with acting stresses on the workpiece.)

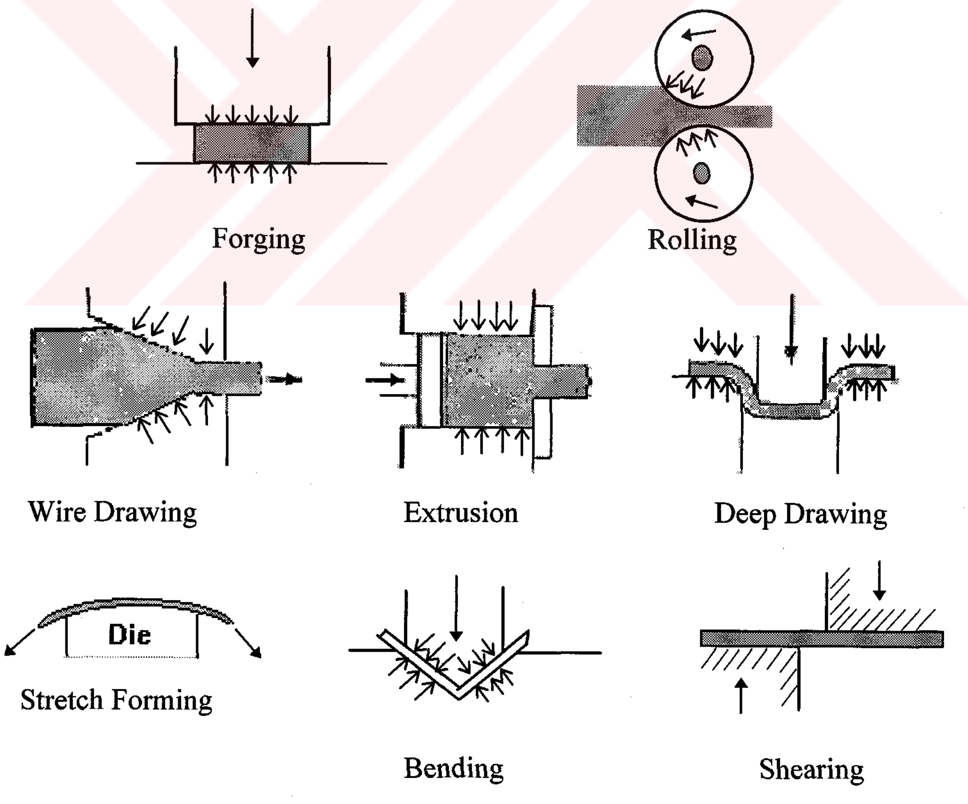

Figure A.1. Typical Forming Operations

A.2. Effects of Temperature in Metalworking

Metalworking processes are commonly classified into *hot-working* and *cold-working* operations.

Cold-working: Plastically deforming of a metal at low temperatures results in an increase in strength and hardness and decrease in ductility. This strain-hardening is attributed to increase in the density of defects in the lattice structure (Dieter, 1988; Verhoeven, 1975). Consequently, plastic deformation which is carried out in a temperature region and over a time interval such that the effects of strain hardening in the structure is not relieved is called cold-work. Strain hardening or cold-working is an important industrial process that is used to harden metals or alloys. Nevertheless, when cold-working is excessive, the metal will fracture before reaching the desired size and shape. Also, since strain hardening is not relieved in cold-working, the required flow stress increases with deformation. Therefore, in order to avoid such difficulties, annealing operations introduced to soften the cold-worked metal and restore the ductility. This sequence of repeated cold-working and annealing is frequently called the cold-work anneal cycle. (Figure A.2 illustrates the changes in mechanical properties involved in this cycle.) Although the need for annealing operations increases the cost of forming by cold-working, particularly for reactive metals which must be annealed in vacuum or inert atmosphere, it provides a degree of versatility in controlling the mechanical properties of the workpiece. By suitably adjusting the cold-work anneal cycle, the part can be produced with any desired degree of strain hardening. If the finished product must be stronger than the fully annealed material, then the final operation must be a cold-working step with the proper degree of deformation to produce the desired strength. If it is desired to have the final part in the fully softened condition, then an anneal follows the last cold-working step.

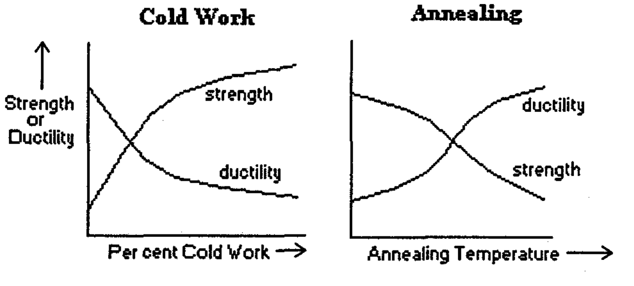

Figure A.2. Typical Variation of Strength and Ductility in Cold-Work-Anneal Cycle

Hot-working: Hot-working is defined as deformation under conditions of temperature and strain rate such that recovery processes take place simultaneously with the deformation; that is to say, in hot-working, the strain hardening and distorted grain structure produced by deformation are very rapidly eliminated by the formation of the new strain-free grains as the result of recrystallization (Verhoeven, 1975). Therefore, very large deformations are possible in hot-working with essentially no strain hardening because the recovery processes keep pace with the deformation. Hot-working not only results in a decrease in the energy required to deform the metal and an increase ability to flow without cracking, but also the rapid diffusion at hot-working temperatures aids in decreasing the chemical inhomogeneities of the cast-ingot structure. Blowholes and porosity are eliminated by the welding together of these cavities, and the coarse columnar grains of the casting are broken down and refined into smaller equiaxed re-crystallized grains. These changes in structure from hot-working result in an increase in ductility and toughness over the cast state. However, there are certain disadvantages of hot-working. Because high temperature are usually involved, surface reactions between the metal and the furnace atmosphere become a problem. Ordinarily, hot-working is done in air, so that oxidation results, and a considerable amount of metal may be lost. Moreover, rolled-in oxide makes it difficult to produce good surface finishes on hot-rolled products. Furthermore, the structure and the properties of hot-worked metals are generally not so uniform over the cross section as in metals which have been cold-worked and annealed. Since the deformation is always greater in the surface layers, the metal will have a finer re-crystallized grain size in this region. Because the interior will be at higher temperatures for longer times during cooling than will be external surfaces, grain growth can occur in the interior of large pieces, which cool slowly from the working temperature.

Hot-working occurs at an essentially constant flow stress, and because the flow stress decreases with increasing temperature, the energy required for the deformation is generally much less for hot-working than for cold-working. Most hot-working operations are carried out in a number of multiple passes, or steps. Generally the working temperature for the intermediate passes is kept well above the minimum working temperature in order to take advantage of the economies offered by the lower flow stress. It is likely that some grain growth will occur subsequent to the recrystallization at these temperatures. Since a fine-grain-sized product is usually desired to achieve high toughness and strength simultaneously, common practice is to lower the working temperature for the last pass to the point where grain growth during cooling from the working temperature will be negligible. This finishing temperature is usually just above the minimum recrystallization temperature.

In order to ensure a fine re-crystallized grain size, the amount of deformation in the last pass should be relatively large.

A.3. Annealing of Cold-Worked Workpiece

The cold-worked state is a condition of higher internal energy than the undeformed metal. With increasing temperature the cold-worked state becomes more and more unstable. Eventually the metal softens and reverts to a strain-free condition. The overall process is known as annealing. Annealing is very important commercially because it restores the ductility to a metal that has been severely strain-hardened. Therefore, by interposing annealing operations after severe deformation it is possible to deform most metals to a very great extent.

The process of annealing can be divided into three fairly distinct processes: recovery, recrystallization, and grain growth. Recovery is usually defined as the restoration of the physical properties of the cold-worked metal without any observable change in microstructure. Recrystallization is the replacement of the cold-worked structure by a new set of strain-free grains. It is evidenced by a decrease in hardness or strength and an increase in ductility. Consequently, all effects of strain hardening are eliminated. The stored energy of cold-work, in other words, amount of deformation is the driving force for both recovery and recrystallization, so that the temperature at which recrystallization occurs is not a fixed temperature in the sense of a melting temperature. If the new strain-free grains are heated at a temperature greater than that required to cause recrystallization, there will be a progressive increase in grain size. The driving force for grain growth is the decrease in free energy resulting from a decreased grain-boundary area due to an increase in grain size (Verhoeven, 1975).

APPENDIX B

MAIN PROCESS COMPONENTS IN CONTINUOUS SHEET/STRIP CASTING TYPE PRODUCTION OF FLAT ROLLED METAL PRODUCTS

Continuous Casting of Sheet/Strip:

The twin roll continuous casting of metal alloys was developed into a commercial process by American Hunter Engineering and French Pechiney in the early 1950's (Li, 1995; Vangala et al., 1992; Beals et al., 1995 and Taraglio et al., 1995). Since then, the process has gained world-wide acceptance, in especially aluminum industry, as an economical method for producing a wide variety of flat rolled products. The early machines (known as "standard" casters) were limited in casting width and alloy composition. In the late 1970's Hunter introduced a much more robust machine (known as the SuperCaster) which offered an increase in productivity and was capable of casting a wider range of alloy at sheet widths up to 2.0 m, and significantly improving the quality (Vangala et al., 1992).

The twin roll casting process converts molten metal alloy directly into thin cast sheet/strip suitable for cold-rolling; thus, effectively eliminate the ingot casting, sawing, scalping, re-heating and hot-rolling associated with the traditional DC ingot and hot-mill method of production. Therefore, twin roll casting not only significantly reduces the capital investment required, it also produces considerable savings in energy through a reduction of processes and manpower, thus reducing the producer's conversion cost. These economic benefits give roll caster based plants a pricing advantage in the increasingly competitive world flat metal product market. Moreover, the simultaneous solidification and hot-rolling in the twin roll casting process produces a characteristic refined microstructure with a fine cell size and intermetallic particle distribution with some residual worked structure, requiring different downstream rolling and annealing practices to those applied for conventional DC ingot and hot-milled material. In many commercial products the inherently fine microstructure of the roll cast sheet/strip is advantageous producing products including fin, foil and building applications, with superior formability and good corrosion properties.

Traditionally, industrial twin roll casters have been operated at casting gauges between 6 and 10 mm, the selection of the exact casting gauge depending on the type, separating force and torque capabilities of the casting machine, the final product requirements, and casting rolling costs. For most final products, the cast gauge is between 6-7 mm to minimize the cold-rolling costs. The heavier casting gauges are normally employed when a heavy gauge, fine grained, minimum earring final product is required. These higher casting gauges also have the advantages of reducing the loading on the casting machine and extending caster roll shell life.

In a typical continuous roll casting line, molten metal of a constant composition and temperature level is degassed and filtered before being introduced into the "headbox" of the casting machine. The headbox is connected to a planar ceramic pouring nozzle commonly known as the "tip" which distributes the metal between the rolls of the machine. The width of the nozzle determines the width of the cast sheet/strip. The 15^0 tilt of the caster allows regulation of the nozzle exit pressure by control of the headbox level. This feature permits smooth flow of the metal from the nozzle to the internally water-cooled rolls. The roll spacing is held constant by a hydraulic system. The exit of the nozzle is slightly ahead of the centerline of the rolls. The distance from the exit of the nozzle to the centerline of the rolls is referred to as the "setback". Molten metal enters the roll bite and is instantly chilled (sudden solidification) on contact with the water-cooled rolls. As the alloy flows towards the exit point of the rolls, a solidification front is developed. The position of the solidification front is controllable and depends on the various process parameters like the line speed, sheet/strip thickness, setback, etc. After complete solidification, the metal exits the roll nip, undergoing a certain hot reduction. The integral rolling process allows precise control of the cast sheet/strip dimensions, producing a sheet/strip of exact thickness. The caster rolls are independently driven by separate DC motors, synchronized by a sophisticated digital control system which monitors and regulates many of the critical parameters in the casting process. The surfaces of the caster rolls are continuously sprayed with a water-based suspension of graphite or boron nitride to act as a lubricant and parting agent. On exiting the casting machine the strip passes through a set of pinch rolls and a traveling shear before being wound into a coil. In normal operation the pinch rolls are not engaged, winder tension being applied directly to the nip of the casting machine. When the desired coil size is reached, the pinch rolls are engaged to maintain tension at the nip of the machine, the strip is cut using the traveling shear and the coil removed without interrupting the casting process. Once the cut end of the strip reaches the winder, normal winder tension can be re-established and the pinch rolls are disengaged until the next coil change operation (Li, 1995 and Vangala et al., 1992). The most common defects in twin-roll cast sheets are mainly heat line/void formation, centerline segregation, sticking, surface streaking, rolled-in nozzle particles, edge cracking, and tearing (Li, 1995).

In the recent years, there have been reports in the literature of mathematical models, which indicate that reducing the casting gauge below traditional operating range should significantly increase roll caster productivity (Saitoh et al., 1989). These results agreed with some initial trials on production Hunter casters (Beals et al., 1995 and Taraglio et al., 1995). Consequently, during the early 1990's FATA Hunter and Norandal USA started an extensive joint research and development project into "Thin-Gauge/High-Speed Casting" technology to meet the new demand for lighter gauges and increased productivity (Beal et al., 1995). It has been shown that by reducing the casting gauge to approximately 5 mm, there is a small increase in the caster productivity. But when the cast thickness is reduced below 3 mm there is an even greater increase. In addition, the reduction in the casting gauge may also reduce the loading on the cold-mill by eliminating rolling mill passes. The first of a new generation of thin-gauge/high-speed twin roll casting machines (FATA Hunter SpeedCaster) is now in operation at the Norandal USA, Huntingdon (Tennessee) facility. At February 1996 start-up of the machine, a down-gauging program has commenced which combined normal 5.6 mm gauge production with a series of casting trials at progressively lighter gauges (Beals et al., 1995). To differentiate this new generation of caster from Hunter's conventional SuperCaster, this new machine has been denoted as the Hunter "SpeedCaster".

Cold-Rolling Process:

The process of plastically deforming metal by passing it between rolls is known as rolling. This is the most widely used metalworking process in industry because it leads itself to high production and close control of the final product. It is used to produce sheet and strip superior surface finish and dimensional tolerances compared with hot-rolled sheet/strip. In addition, the strain hardening resulting from the cold reduction may be used to give increased strength. In deforming metal between the rolls, the work is subjected to high compressive stresses from the squeezing action of the rolls and to surface shear stresses as a result of the friction between the rolls and the metal. The frictional forces are also responsible for drawing the metal into the rolls. A rolling mill consists basically of rolls, bearings, a housing for containing these parts, and a drive for applying power to the rolls and controlling their speed. The forces involved in rolling can easily reach many MN. Therefore, very rigid construction is needed, and very large motors are required to provide the necessary power.

Rolling mills can be conveniently classified with respect to the number and arrangement of the rolls (Figure B.1). The simplest and most common type of rolling mill is the two-high mill. Rolls of equal size are rotated only in one direction. An obvious improvement in productivity results from the use of a two-high reversing mill, in which the work can be passed back and forth through the rolls by reversing their direction of rotation. Another solution is the three-high mill, consisting of an upper and lower driven roll and a middle roll which rotates by friction.

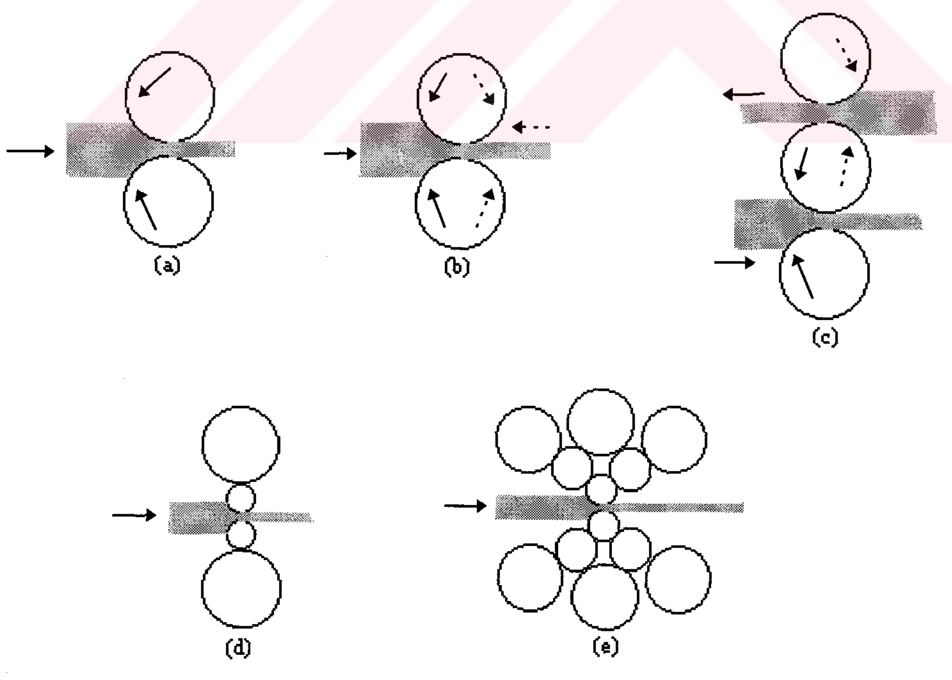

Figure B.1. Typical Arrangements of Rolls for Rolling Mills (a) Two-High; (b) Two-High Reversing; (c) Three-High; (d) Four-High; (e) Cluster

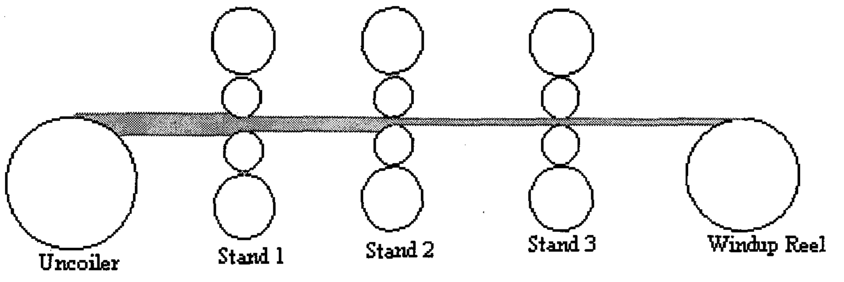

Figure B.2. Schematic Representation of Sheet/Strip Rolling in a Three-Stand Mill

A large decrease in the power required for rolling can be achieved by the use of small-diameter rolls. However, because small-diameter rolls have less strength and rigidity than large rolls, they must be supported by larger-diameter backup rolls. The simplest mill of this type is the four-high mill. Very thin sheet can be rolled to very close tolerances on a mill with small-diameter work rolls. The cluster mill, in which each of the work rolls is supported by two backing rolls, is a typical mill of this kind. For high production it is common to install a series of rolling mills one after another in tandem (Figure B.2). Each set of rolls is called a stand. Since a different reduction is taken at each stand, the sheet/strip will be moving at different velocities at each stage in the mill. The speed of each set of rolls is synchronized so that each successive stand takes the sheet/strip at a speed to the delivery speed of the preceding stand. The uncoiler and windup reel not only accomplish the functions of feeding the stock to the rolls and coiling up the final product but also can be used to supply a back tension and a front tension to the sheet/strip.

In establishing the reduction in each pass or in each stand, it is desirable to distribute the work as uniformly as possible over the various passes without falling very much below the maximum reduction for each pass. Generally the lowest percentage reduction is taken in the last pass to permit better control of flatness, gage, and surface finish.

A variety of problems in rolling, leading to specific defects, can arise depending on the interaction of the plastically deformed workpiece with the elastically deforming rolls and rolling mill. Under the influence of the high rolling forces, the rolls flatten and bend, and the entire mill is elastically distorted. In order to roll to precise thickness, it is necessary to know the elastic constant of the mill. The roll gap must be perfectly parallel, otherwise one edge of the sheet will be decreased more in thickness than the other, and since volume and width remain constant, this edge of the sheet elongates more than the other, and the sheet bows. There are two aspects to the problem of the shape of a sheet. The first is the uniform thickness over the width and along the length and the second is the flatness of sheet. Other forms of inhomogenous deformation can lead to problems with cracking, especially edge cracking (Dieter, 1988).

Annealing Process:

Annealing is a heat treatment under controlled heating and cooling condition for the purpose of reducing hardness, removing residual stresses, improving toughness, refining grain size and restoring the ductility to a metal that has been severely strain-hardened. Eventually the metal softens and reverts to a strain-free condition. Therefore, by interposing annealing operations after severe deformation it is possible to deform most metals to a very great extent. In process annealing, the workpiece is heated to above recrystallization temperature to convert the structure homogeneous uniform composition and temperature condition, and is held at this temperature for a period of time, then slowly cooled at controlled rate below the recrystallization temperature usually in furnace, followed by air cooling to room temperature.

To facilitate heat treatment, many types of heating equipment have been developed in a wide range of sizes. Furnaces can be either batch-type or continuous-type. Batch furnaces are those in which the workpiece remains stationary throughput its time in the furnace and may be either of horizontal or vertical (DeGarmo et al., 1988).

Horizontal batch-type furnaces are often called box furnaces. A door is provided on one end to permit work to be inserted and removed. Gas or electricity provides the source of heat. For large or long workpieces, car-bottom are used. The work is loaded by a flatcar, which is moved on rails into the furnace. Horizontal furnaces are relatively easy to construct in any size, are easily insulated, and are thermally efficient.

In continuous furnaces, the workpieces are moved through the furnace during the heat treatment operation by some type of conveyor or push mechanism. These furnaces are generally used for large production runs of the same or similar parts.

APPENDIX C

DESIGNATION AND CHARACTERISTICS OF ALUMINUM ALLOYS AND PRODUCTS

The properties provided by aluminum an its alloys make aluminum one of the most versatile, economical and attractive metallic materials for a broad range of uses from soft, highly ductile wrapping foil to the most strength demanding engineering applications. A number of unique and attractive properties account for the engineering significance of aluminum: its workability (formability), its light weight, its high corrosion resistance, and its good electrical and thermal conductivity (Avner, 1974).

Most aluminum is used in the form of alloys. These have much greater strength than pure aluminum yet retain the advantages of light weight, good conductivity, and corrosion resistance. Some alloy are now available that have tensile properties that are superior to those of low-alloy-high-yield-strength structural steel. On a strength-to-weight basis, most of the aluminum alloys are superior to steel, but wear, creep and fatigue properties are generally rather poor.

Its high workability enables to be rolled to any desired thickness, drawn, forged, and extruded to almost any shape. Its low density and high specific strength (strength-to-weight ratio) coupled with the high strength of some aluminum alloys, permits design and construction of strong, lightweight structures which are advantageous for anything that moves The high corrosion resistance of aluminum is due to the self-protecting, thin, invisible oxide film that forms immediately on exposing surface to the atmosphere. This oxide is resistant to many corrosive media and serves as a corrosion-resistant barrier to protect the underlying metal (Avner, 1974). It has no toxic reactions, and thus is highly suitable for processing, handling, storing, and packaging of foods and beverages.

C.1. Designation of Aluminum Alloys

Alloy Designation System for aluminum and aluminum alloys was standardized by "The Aluminum Association" in 1954 and given in Table C.1. Aluminum alloys designed for fabrication can be divided into two basic types: those that achieve strength by solid-solution strengthening and cold-working and those that are strengthened by heat treatment (age hardening). The standard four-digit designation system for aluminum is used. The first digit indicates the major alloy grouping. The second digit generally indicates a modification of the original alloy, and the last two digits indicate the particular alloy within the family. In the 1xxx series, however, the last three digits denote the purity of the aluminum.

Commercially pure aluminum, 1xxx alloys (99.0 + percent Al) are suitable for applications where good formability or very good resistance to corrosion are required and where high strength is not necessary. It has been used extensively for cooking utensils, various architectural components, food and chemical handling and storage equipment, and welded assemblies. Aluminum-Manganese alloys (3xxx series) are very popular strain hardenable group. One of the alloys in this group is the popular 3003 alloy, which has good formability, very good resistance to corrosion, and good weldability. Typical applications are utensils, food and chemical handling and storage equipment, gasoline and oil tanks, pressure vessels, and piping.

Table C.1. Designation for Aluminum Alloy Groups by Aluminum Association

Major Alloying Element	Aluminum Association No.
A) Work-hardenable alloys, not heat treatable	
Aluminum, 99.00 % and greater	1xxx
Manganese	3xxx
Magnesium	5xxx
B) Precipitation-hardened alloys, heat-treatable	
Copper	2xxx
Silicon	4xxx
Magnesium and Silicon	6xxx
Zinc	7xxx
C) Groups having intermediate properties	
Other elements	8xxx
Unused series	9xxx

The temper designation follows the alloy designation and is separated from it by a dash. The Aluminum Association Temper Designation System is based on the sequences of basic treatments used to produce the various tempers (mechanical property).

- F: as fabricated. Applies to products shaped by cold-working, hot-working or casting processes in which no special control over thermal conditions or strain hardening is employed. There is no guarantee of mechanical properties.
- O: Annealed, Re-crystallized. Applies to products that are annealed to obtain lowest strength temper, and to improve ductility and dimensional stability.
- H: Strained-hardened. This applies to products which have their mechanical properties increased by cold-working (strain-hardening) only, with or without supplementary heat treatment to produce some reduction in strength. The H is always followed by two or more digits. The first digit indicates the specific combination of basic operations as follows.
    - H1: Strain-hardened only. Applies to products that are strain hardened to obtain the desired strength without supplementary thermal treatment. The second digit designates the amount of cold-work (degree of hardness) performed, with the numeral “8” representing the full-hard condition. Therefore, half hard is H14, quarter hard is H12.
    - H2: Strain-hardened then partially annealed. Applied to products that are cold-worked to a harder temper and then have their strength reduced to desired level by partial annealing. The digit following the H2 indicates the degree of strain hardening remaining after the product has been partially annealed.
    - H3: Strain hardened and stabilized. Applies to products that are strain hardened and whose mechanical properties are stabilized by a low-temperature thermal treatment that slightly decreases tensile strength and improves ductility. The digit following the H3 indicates the degree of strain hardening after stabilization.
- W: Solution heat-treated only.
- T: Thermally treated (heat treated). Applies to products that are thermally treated, with or without supplementary strain hardening, to produce stable tempers.

C.2. Aluminum Flat Rolled Products

Commercial aluminum products are divided into five major categories based on production method as well as geometric configuration. These categories are: a) flat rolled products (sheet, plate and foil); b) rod, bar, and wire; c) tubular products; d) shapes; e) forgings.

Flat rolled products include plate, sheet/strip, and foil. They are manufactured either by hot-rolling, or by hot and cold-rolling, or by continuous sheet/strip casting and cold-rolling. They are rectangular in cross section and have uniform thickness. "Plate" refers to a product having a thickness greater than 6 mm. The most common uses are aircraft structures, marine, cryogenic and pressure-vessel applications.

When a flat product is over 0.15 through 6 mm in thickness, it is classified as "sheet". Sheet is supplied in flat form, in coils, or in pieces cut to length from coils. Foil is a product up through 0.15 mm thick. Most foil is supplied in coils, although it is also available in rectangular form. Most common applications that aluminum foil and sheet/strip products are used are given in Tables C.2 and C.3, respectively, with appropriate strain-hardenable aluminum alloy selections.

Table C.2. Most Common Applications of Aluminum Foil Products

Foil Products	Alloys
Can, Cartons, and Package Labels, Canister and Package Liners, Medical Supply Wraps, Food Wraps, Soap and Toiletry Wraps, Cigarette Foil, Food and Tobacco Pouches, Electrical and Mechanical Parts Wraps, Freezer and Baking Foil, Novelty and Florist Foil	1230, 1145
Rigid Foil Containers	1230, 1145, 3003, 8011
Bottle and Container Caps	1230, 1145, 3003
Gift and Christmas Wrap	1230, 1145, 8079
Condenser Foil	1190, 1199
Cable Wraps and Shielding	1230, 1100
Reflective Insulation, Moisture Barriers, Wall Paper Foil	1230

Table C.3. Most Common Uses of Aluminum Sheet/Strip Products

Sheet/Strip Products	Alloys
Siding and Roofing Industry, Resident, Windows and Door Frames, Grills, Heat and Conditioning Ducts, Fan Blades, Refrigerators Liners and Evaporators, Furniture and Irrigation Tubing (Welded), Insulating Jacketing, Shower Enclosures, Cabinets	3105, 3003, 5005, 5010, 5050
Fume Exhaust Ducts	1100, 3003, 3105
Truck Trailer Panels, Fences, Parasols	3004, 3006, 5050, 5052, 5051
Radio and TV Chassis	3003, 5005
Electrical Cable Sheathing	1145
Shielding Cans, Oil and Fruit Juice Cans, Kitchen Utensils, Kitchen Pots and Pans	1100, 3003
Wash Basins	1100, 3003, 5005
Road Signs	3003, 5052
Can Body Stock	3004
Can Lid Stock	5086, 5182
Can Tab Stock	5042
Impact Extrusion Slugs	1100, 1060, 1070, 1080
Moisture Barriers	1100

APPENDIX D

SIMAN SOURCE CODE OF THE SIMULATION MODELS

D.1. SIMAN Source Code of the First Model: Continuous Casting Process

D.1.1. Model Frame (Model 1)

```
BEGIN,Yes;

;Initialization.
          CREATE:1;
          DELAY:TFIN;
                    WRITE,file1:NREP,TAVG(CCSetTime),TMIN(CCSetTime),TMAX(CCSetTime),TNUM(CCSetTime);
                    WRITE,file2:NREP,TAVG(CastTim1),TMIN(CastTim1),TMAX(CastTim1),TNUM(CastTim1);
                    WRITE,file3:NREP,TAVG(CastTim2),TMIN(CastTim2),TMAX(CastTim2),TNUM(CastTim2);
                    WRITE,file4:NREP,TAVG(CastTim3),TMIN(CastTim3),TMAX(CastTim3),TNUM(CastTim3);
                    WRITE,file5:NREP,TAVG(CastTim4),TMIN(CastTim4),TMAX(CastTim4),TNUM(CastTim4);
                    WRITE,file6:NREP,TAVG(CastTim5),TMIN(CastTim5),TMAX(CastTim5),TNUM(CastTim5);
                    WRITE,file7:NREP,TAVG(CastTim6),TMIN(CastTim6),TMAX(CastTim6),TNUM(CastTim6);
                    WRITE,file8:NREP,TAVG(CastTim7),TMIN(CastTim7),TMAX(CastTim7),TNUM(CastTim7);
                    WRITE,file9:NREP,TAVG(CastTim8),TMIN(CastTim8),TMAX(CastTim8),TNUM(CastTim8);
          WRITE,file10:NREP,TAVG(SetTime1),TMIN(SetTime1),TMAX(SetTime1),TNUM(SetTime1);
          WRITE,file11:NREP,TAVG(SetTime2),TMIN(SetTime2),TMAX(SetTime2),TNUM(SetTime2);
          WRITE,file12:NREP,TAVG(SetTime3),TMIN(SetTime3),TMAX(SetTime3),TNUM(SetTime3);
          WRITE,file13:NREP,TAVG(SetTime4),TMIN(SetTime4),TMAX(SetTime4),TNUM(SetTime4);
          WRITE,file14:NREP,TAVG(SetTime5),TMIN(SetTime5),TMAX(SetTime5),TNUM(SetTime5);
          WRITE,file15:NREP,TAVG(SetTime6),TMIN(SetTime6),TMAX(SetTime6),TNUM(SetTime6);
          WRITE,file16:NREP,TAVG(SetTime7),TMIN(SetTime7),TMAX(SetTime7),TNUM(SetTime7);
          WRITE,file17:NREP,TAVG(SetTime8),TMIN(SetTime8),TMAX(SetTime8),TNUM(SetTime8):DISPOSE;

;Casting Cycle initialization.
          CREATE:,1;
          ASSIGN:SetupTime=TNOW:NEXT(RenewCast);
          CREATE:,1:NEXT(Casting);

;Imported Stocks.
          CREATE,BatchCoil:ImpPeriodCoil;
          ASSIGN:NS=SheetImp;
          BRANCH,1:
                    IF,NumStock.GT.1,ImpCoil:
                    ELSE,Dis;

          CREATE,BatchFoil:ImpPeriodFoil;
          ASSIGN:NS=FoilImp;
          BRANCH,1:
                    IF,NumStock.GT.2,ImpFoil:
                    ELSE,Dis;
ImpCoil   ASSIGN:CoilStock=CoilStock+1;
          QUEUE,NS+NumAlloy:DETACH;
```

```
ImpFoil   ASSIGN:FoilStock=FoilStock+1;
          QUEUE,NS+(NumAlloy*2):DETACH;
Dis       DISPOSE;
```

*;Arrival of **Foil** Order.*
(Search the Aluminum Sheet Coil and Foil Stocks to allocate appropriate coils to this order OR command to continuous casting station to cast required amont the coil of Al sheet with appropriate alloy.)

```
          CREATE:FoilIntArr;
          ASSIGN:NS=AlloyFoil:
                 Amount=FoilAmount:
                 Alloy=NS:
                 AmountTotal=0:
                 NCoilFoil=AINT(Amount/CoilWeight)+1;
ConSearch        WHILE:AmountTotal.LT.NCoilFoil*CoilWeight;
                 IF:NQ(NS+(NumAlloy*2)).NE.0;
                      ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                          FoilStock=FoilStock-1;
                      REMOVE:1,NS+(NumAlloy*2),FoilFin:NEXT(ConSearch);
                 ELSE;
                      IF:NQ(NS+NumAlloy).NE.0;
                           ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                               CoilStock=CoilStock-1;
                           REMOVE:1,NS+NumAlloy,FF1:NEXT(ConSearch);
                      ELSE;
                           IF:FC.EQ.2;
                           IF:NQ(NS).NE.0;
                                ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                                    CastStock=CastStock-1;
                                REMOVE:1,NS,FF2:NEXT(ConSearch);
                           ELSE;
                                ASSIGN:Weight=NCoilFoil*CoilWeight-AmountTotal;
                                BRANCH,2:
                                     ALWAYS,Demand1:
                                     ALWAYS,Cast;
                           ENDIF;
                           ENDIF:NEXT(Demand1);
                      ENDIF;
                 ENDIF;
                 ENDWHILE:NEXT(Demand1);

Demand1          TALLY:NS,Amount;
                 TALLY:NS+NumAlloy,NCoilFoil*CoilWeight;
                 TALLY:NS+(NumAlloy*2),AmountTotal:DISPOSE;
FoilFin          TALLY:NS+(NumAlloy*7),CoilWeight:DISPOSE;
FF1              TALLY:NS+(NumAlloy*8),CoilWeight:DISPOSE;
FF2              TALLY:NS+(NumAlloy*9),CoilWeight:DISPOSE;
```

*;Arrival of **Sheet** Order.*
(Search the Aluminum Sheet Coil Stocks to allocate appropriate coils to this order OR command to continuous casting station to cast required amont the coil of Al sheet with appropriate alloy.)

```
          CREATE:SheetIntArr;
          ASSIGN:NS=AlloySheet:
                 Amount=SheetAmount:
                 Alloy=NS:
                 AmountTotal=0:
                 NCoilSheet=AINT(Amount/CoilWeight)+1;
          WHILE:AmountTotal.LT.NCoilSheet*CoilWeight;
          IF:NQ(NS).NE.0;
                 ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                     CastStock=CastStock-1;
                 REMOVE:1,NS,SS1;
          ELSE;
                 IF:NQ(NS+NumAlloy).NE.0;
                      ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                          CoilStock=CoilStock-1;
                      REMOVE:1,NS+NumAlloy,SS2;
                 ELSE;
                      ASSIGN:Weight=NCoilSheet*CoilWeight-AmountTotal;
                      BRANCH,2:
```

```
                                        ALWAYS,Demand2:
                                        ALWAYS,Cast;
                          ENDIF;
          ENDIF;
          ENDWHILE:NEXT(Demand2);
Demand2                   TALLY:NS+(NumAlloy*3),Amount;
                          TALLY:NS+(NumAlloy*4),NCoilSheet*CoilWeight;
                          TALLY:NS+(NumAlloy*5),AmountTotal:DISPOSE;

SS1                       TALLY:NS+(NumAlloy*9),CoilWeight:DISPOSE;
SS2                       TALLY:NS+(NumAlloy*8),CoilWeight:DISPOSE;
```

;The amount of each Al alloy that will be cast in the subsequent cast cycle is determined and the amount of each Al alloy that will be cast in the current cast cycle is updated.

```
Cast      COUNT:NS,Weight;
          TALLY:NS+(NumAlloy*6),Weight;
          ASSIGN:CastDemand(NS)=CastDemand(NS)+Weight:
                  CastDemandT=CastDemandT+Weight:
                  Alloy=NS;
          IF:CastDemand(NS).GT.AveCast(NS,FC);
                  IF:CastTotal+Weight.LE.MaxCast*CL;
                          SEARCH,CastBuffer:NS.EQ.Alloy;
                          IF:J.NE.0.OR.(MeltType.EQ.NS.AND.UpdateCap.NE.1);
                                  ASSIGN:Cast(NS)=Cast(NS)+Weight:
                                          CastTotal=CastTotal+Weight:DISPOSE;
                          ENDIF;
                  ENDIF;
          ASSIGN:WaitOrder(NS)=WaitOrder(NS)+Weight:
                  WaitOrderT=WaitOrderT+Weight:DISPOSE;
          ENDIF:DISPOSE;
```

;Cast cycle is renewed. (The amount of each Al alloy that will be cast in subsequent cast cycle is set.)

```
RenewCast       ASSIGN:Num=0:
                        CastTotal=0:
                        CastCycle=0:
                        CastDemandT=0:
                        WaitOrderT=0:
                        STATE(MeltFurnace)=ReadyMelt;
                WHILE:Num.LT.NumAlloy;
                ASSIGN:Num=Num+1:
                        CastDemand(Num)=WaitOrder(Num)*(WaitOrder(Num).LE.AveCast(Num,FC))+
                                        AveCast(Num,FC)*(WaitOrder(Num).GT.AveCast(Num,FC)):
                        CastDemandT=CastDemandT+CastDemand(Num):
                        WaitOrder(Num)=MX(0,WaitOrder(Num)-CastDemand(Num)):
                        Cast(Num)=AveCast(Num,FC):
                        CastTotal=CastTotal+Cast(Num);
                ENDWHILE;
                ASSIGN:Num=0;
Con1            WHILE:Num.LT.NumAlloy;
                ASSIGN:Num=Num+1;
                IF:WaitOrder(Num).LE.MaxCast*CL-CastTotal;
                        ASSIGN:CastDemand(Num)=CastDemand(Num)+WaitOrder(Num):
                                CastDemandT=CastDemandT+WaitOrder(Num):
                                Cast(Num)=Cast(Num)+WaitOrder(Num):
                                CastTotal=CastTotal+WaitOrder(Num):
                                WaitOrder(Num)=0;
                ELSEIF:WaitOrder(Num).GT.MaxCast*CL-CastTotal;
                        ASSIGN:CastDemand(Num)=CastDemand(Num)+(MaxCast*CL-CastTotal):
                                CastDemandT=CastDemandT+(MaxCast*CL-CastTotal):
                                Cast(Num)=Cast(Num)+(MaxCast*CL-CastTotal):
                                CastTotal=MaxCast*CL:
                                WaitOrder(Num)=WaitOrder(Num)-(MaxCast*CL-CastTotal):
                                WaitOrderT=WaitOrderT+WaitOrder(Num);
                ENDIF;
                IF:Cast(Num).NE.0;
                        ASSIGN:NS=Num;
                        DUPLICATE:1,Con1:NEXT(Schedule);
                ENDIF;
                ENDWHILE;
                SIGNAL:S1:DISPOSE;
```

;The sequence of Al alloys that is determined in the "RenewCast" module is retained.

```
Schedule        QUEUE,CastBuffer;
                WAIT:S1,1;
                ASSIGN:CastCycle=1*(NQ(CastBuffer).EQ.0):
                        MeltType=NS:
                        NewComp(MeltType)=1:
                        MFMin=MFCri(1):
                        DecInCap=0:
                        UpdateCap=0;
```

;Check the level of molten metal in the melting furnace and determine the amount of Al alloy that will be prepared.

```
Check1   IF:UpdateCap.EQ.0;
         IF:Cast(MeltType)-CastAmount(MeltType)-LevelHF*(MeltType.EQ.HoldType)
            -HFMin*(MeltType.NE.HoldType)+(HFCri(2)+MFCri(2))*(CastCycle.EQ.0)
            +(HFCri(3)+MFCri(3))*(CastCycle.EQ.1).LT.ActMFCap;
         ASSIGN:RequiredAmount=Cast(MeltType)-CastAmount(MeltType)-LevelMF
                        -LevelHF*(MeltType.EQ.HoldType)-HFMin*(MeltType.NE.HoldType)
                        +(HFCri(2)+MFCri(2))*(CastCycle.EQ.0)+(HFCri(3)+MFCri(3))*(CastCycle.EQ.1):
               DecInCap=ActMFCap-LevelMF-RequiredAmount:
               MFMin=MFCri(2)*(CastCycle.EQ.0)+MFCri(3)*(CastCycle.EQ.1):
               UpdateCap=1;
         ENDIF:NEXT(Load);
         ENDIF:NEXT(Check2);
```

;Renew the cast cycle OR Shift to new Al alloy in the scheduled sequence OR Wait until the level in the melting furnace reaches to specified level.

```
Check2   IF:(CastAmount(CastType)+LevelHF-HFMin).GE.Cast(CastType);
         IF:CastCycle.NE.1;
                SIGNAL:S1:DISPOSE;
         ENDIF:NEXT(RenewCast);
         ENDIF:NEXT(Con);
```

;Charging the melting furnace and start of ***Event 1*** *(start of melting).*

```
Load     ASSIGN:STATE(MeltFurnace)=Loading:
               EmptySpace=(ActMFCap-DecInCap)-LevelMF;
         DELAY:MFLoadingTime;
         ASSIGN:EmptySpace=MX(0,EmptySpace-MFLoad):
               MFCap=(ActMFCap-DecInCap)-MX(0,EmptySpace):
               RateMF=MeltRate:
               STATE(MeltFurnace)=Melting:
               MeltTime=TNOW;
         QUEUE,MFForkQue;
         SEIZE:ForkMF;
         WHILE:EmptySpace.GT.0.0;
                DELAY:LoadEquipTime;
                DELAY:MFLoadingTime;
                ASSIGN:EmptySpace=MX(0,EmptySpace-MFLoad):
                MFCap=(ActMFCap-DecInCap)-MX(0,EmptySpace);
                SIGNAL:S2;
         ENDWHILE;
         ASSIGN:MFCap=(ActMFCap-DecInCap)-MX(0,EmptySpace);
         SIGNAL:S2;
         DELAY:LoadEquipTime;
         RELEASE:ForkMF:DISPOSE;
```

;Start of ***Event 2*** *(end of melting).*

```
         DETECT:LevelMF,P,MFCap,100.0;
         ASSIGN:RateMF=0:
               STATE(MeltFurnace)=Waiting;
         IF:MFCap.GE.(ActMFCap-DecInCap);
                TALLY:MeltType+(NumAlloy*13),TNOW-MeltTime;
                ASSIGN:STATE(MeltFurnace)=MeltPre;
                DELAY:HotCleaning;
Alloy           DELAY:AlloyPre;
                BRANCH,2:
                        WITH,PAccept,Con:
                        WITH,PReject,Alloy;
```

```
Con                 ASSIGN:STATE(MeltFurnace)=Waiting;
                    QUEUE,Ready1;
                    SCAN:STATE(HoldFurnace).EQ.ReadyTrans;
                    ASSIGN:STATE(MeltFurnace)=Transfering:
                            STATE(HoldFurnace)=Holding:
                            HoldType=MeltType:
                            RateMF=-TransRate1:
                            RateHF=RateHF+TransRate1:DISPOSE;
          ELSE;
                    QUEUE,MeltCon;
                    WAIT:S2,1;
                    ASSIGN:RateMF=MeltRate:
                    STATE(MeltFurnace)=Melting:DISPOSE;
          ENDIF:DISPOSE;
```

;Start of ***Event 3*** *(start of transferring liquid metal to holding furnace).*

```
          DETECT:LevelHF,N,HFMin,100.0;
          IF:HFMin.EQ.HFCri(3);
                    ASSIGN:RateHF=0:
                            STATE(HoldFurnace)=HFPre;
                    DELAY:HoldFurPre;
          ELSEIF:HFMin.EQ.HFCri(2);
                    QUEUE,CastCon;
                    SCAN:STATE(ConCaster).NE.Casting;
                    ASSIGN:RateHF=0;
          ENDIF;
          ASSIGN:STATE(HoldFurnace)=ReadyTrans:DISPOSE;
```

;Start of ***Event 4*** *(end of transferring liquid metal from melting furnace).*
(When liquid metal in the melting funace falls below the predefined critical level.)

```
          DETECT:LevelMF,N,MFMin,100.0;
          IF:LevelMF.LE.MFCri(3);
                    ASSIGN:HFMin=HFCri(3):
                            RateMF=0.0:
                            RateHF=RateHF-TransRate1*(RateHF.GT.0):
                            STATE(MeltFurnace)=MFPre:
                            CCSetupTime=TNOW;
                    IF:LevelHF.LT.HFCap.AND.NewComp(HoldType).EQ.1;
                              DUPLICATE:1,Con2;
                    ENDIF;
                    DELAY:MeltFurPre;
                    TALLY:CCSetTime,TNOW-CCSetupTime;
                    ASSIGN:SetupTime=TNOW:
                            STATE(MeltFurnace)=ReadyMelt:NEXT(RenewCast);
          ELSEIF:LevelMF.LE.MFCri(2);
                    ASSIGN:HFMin=HFCri(2):
                            RateMF=0.0:
                            RateHF=RateHF-TransRate1*(RateHF.GT.0):
                            STATE(MeltFurnace)=ReadyMelt:
                            SetupTime=TNOW;
                    IF:LevelHF.LT.HFCap.AND.NewComp(HoldType).EQ.1;
                              DUPLICATE:1,Con2;
                    ENDIF;
                    SIGNAL:S1:DISPOSE;
          ENDIF:DISPOSE;
```

;Start of ***Event 4*** *(end of transferring liquid metal from melting furnace).*
(When the liquid metal level in holding furnace exceeds maximum capacityof holding furnace.)

```
          DETECT:LevelHF,P,HFCap,100.0;
          ASSIGN:RateMF=0.0:
                  RateHF=RateHF-TransRate1*(RateHF.GT.0);
          IF:LevelMF.GT.MFMin.OR.MFMin.EQ.MFCri(1);
                    DUPLICATE:1,Check1;
          ENDIF;
          IF:NewComp(HoldType).EQ.1;
                    ASSIGN:HFMin=HFCri(1)*((MFMin.EQ.MFCri(1)).OR.
                                (LevelMF.GT.MFCri(2).AND.MFMin.EQ.MFCri(2)).OR.
                                (LevelMF.GT.MFCri(3).AND.MFMin.EQ.MFCri(3)))+
                                HFCri(2)*(LevelMF.LE.MFCri(2).AND.MFMin.EQ.MFCri(2))+
                                HFCri(3)*(LevelMF.LE.MFCri(3).AND.MFMin.EQ.MFCri(3));
```

```
                DELAY:CompCheck;
Con2            ASSIGN:NewComp(HoldType)=0:
                      NewCast=1;
                QUEUE,Ready2;
                SCAN:NQ(CastQue).NE.0;
                SIGNAL:S3:DISPOSE;
        ENDIF:DISPOSE;
```

;Start of ***Event 5*** *(start of casting).*

```
Casting ASSIGN:STATE(ConCaster)=Ready;
        QUEUE,CastQue;
        WAIT:S3,1;
        ASSIGN:CastType=HoldType:
              CastTime=TNOW:
              RateHB=RateHB+TransRate2:
              RateHF=RateHF-TransRate2;
        TALLY:CastType+(NumAlloy*16),TNOW-SetupTime:DISPOSE;

        DETECT:LevelHB,P,HeadboxCap,100.0;
        IF:NewCast.EQ.1;
                ASSIGN:LevelCC=CastMin:
                      CastThick=Thick(CastType):
                      CastWidth=RollWidth(1):
                      STATE(ConCaster)=Casting:
                      NewCast=0:
                      CycleEnd=1:
                      CastAmount(CastType)=0:
                      RateCC=CastRate(CastType)*CastThick*CastWidth*density:
                      RateHB=RateHB-(CastRate(CastType)*CastThick*CastWidth*density)-TransRate2:
                      RateHF=RateHF+TransRate2:DISPOSE;
        ENDIF;
        ASSIGN:RateHB=RateHB-TransRate2:
              RateHF=RateHF+TransRate2:DISPOSE;

        DETECT:LevelHB,N,HeadboxCri,50.0;
        IF:(LevelHF+LevelCC).GE.CastCri.AND.STATE(ConCaster).EQ.Casting;
                ASSIGN:RateHB=RateHB+TransRate2:
                      RateHF=RateHF-TransRate2:DISPOSE;
        ELSEIF:(LevelHF+LevelCC).LT.CastCri.AND.STATE(ConCaster).EQ.Casting;
                BRANCH,2:
                       IF,LevelCC.LT.CastCri,Scrap:
                       ALWAYS,EndCast;
        ENDIF:DISPOSE;

        DETECT:LevelHB,N,HeadboxMin,100.0;
        ASSIGN:RateHB=0:DISPOSE;
```

;End of casting of a coil.
(When coil diameter exceeds the predefined critical value.)

```
        DETECT:LevelCC,P,CastMax,100.0;
        IF:LevelCC.LT.CastCri;
Scrap           TALLY:CastType+(NumAlloy*10),LevelCC;
                ASSIGN:LevelCC=CastMin;
                DELAY:CoilUnload;
                QUEUE,ForkMFQue;
                SEIZE,1:ForkMF;
                DELAY:CoilLoad;
                DELAY:TransScrap;
                DELAY:CoilUnload;
                RELEASE:ForkMF:DISPOSE;
        ELSE;
                TALLY:CastType+(NumAlloy*11),LeveLCC;
                ASSIGN:NS=CastType:
                      CastAmount(NS)=CastAmount(NS)+LevelCC:
                      LevelCC=CastMin;
                BRANCH,2:
                       ALWAYS,Con3:
                       IF,CastAmount(NS).GE.Cast(NS),EndCast;
Con3            DELAY:CoilUnload;
                QUEUE,CraneMFQue;
                SEIZE,1:CraneMF;
```

```
                DELAY:CoilLoad;
                DELAY:TransCoil;
                DELAY:CoilUnload;
                RELEASE:CraneMF;
                IF:CastAmount(NS).GT.CastDemand(NS);
                        TALLY:NS+(NumAlloy*17),CoilWeight;
                        ASSIGN:CastStock=CastStock+1;
                        QUEUE,NS:DETACH;
                ENDIF;
                TALLY:NS+(NumAlloy*18),CoilWeight:DISPOSE;
        ENDIF;
```

;Start of ***Event 6*** *(end of casting).*
(Shift to casting of subsequently sequenced Al alloy).

```
EndCast ASSIGN:RateCC=0:
                LevelCC=CastMin:
                STATE(ConCaster)=CasterPre:
                RateHB=-Scrap(3)*(LevelHB.GT.HeadboxMin)+0:
                RateHF=-Scrap(2)*(LevelHF.GT.HFMin);
        IF:CastAmount(CastType).LT.Cast(CastType);
                TALLY:CastType+(NumAlloy*12),Cast(CastType)-CastAmount(CastType);
        ENDIF;
        TALLY:CastType+(NumAlloy*14),TNOW-CastTime;
        TALLY:CastType+(NumAlloy*15),((TNOW-CastTime)/AINT(CastAmount(CastType)/CoilWeight));
        ASSIGN:CastAmount(CastType)=0;
        DELAY:ChangeRoll*(CycleEnd.EQ.1)+ChangeDie*(CycleEnd.EQ.0);
        ASSIGN:CycleEnd=0*(CycleEnd.EQ.1):NEXT(Casting);

END;
```

D.1.2. Experiment Frame (Model 1)

```
BEGIN,Yes,No;

PROJECT,        Tez,ARER;

CONTINUOUS,     4,,.1,.1,1;

ATTRIBUTES:     Amount;

VARIABLES:      F1,0.14585:F2,0.44714:F3,0.60215:F4,1.0:
                L1,0.77495:L2,0.81174:L3,0.83023:L4,1.0:
                ImpPeriodCoil,12819.51:ImpPeriodFoil,30917.65:BatchCoil,280:BatchFoil,127:
                NumStock,1:FoilStock:CoilStock:
                PF1,0.0401:PF2,0.63714:PF3,0.71406:PF4,0.82844:PF5,1.0:
                PL1,0.54381:PL2,0.5618:PL3,0.59474:PL4,0.84606:PL5,1.0:
                M1,562.08:M2,139.13:W1,2974.315:W2,3210.518:
                Alloy:AmountTotal:NCoilFoil:NCoilSheet:CoilWeight,1000.0:
                Num:NumAlloy,8:Weight:CastDemand(8):WaitOrder(8):
                CastDemandT:WaitOrderT:CastTotal,640000.0:Cast(8):MaxCast,800000.0:CL,1.0:S1,1:
                AveCast(8,2),348000,12000,0,0,21000,0,161000,98000,
                        288000,10000,71000,9000,31000,20000,131000,80000:
                CastCycle:MeltType:HoldType:CastType:NewComp(8):
                RequiredAmount:UpdateCap:DecInCap:EmptySpace:
                MFCap,20000.0:ActMFCap,20000.0:MFMin:MFCri(3),15000.0,5000.0,0.0:
                HFMin:HFCri(3),5000.0,1000.0,0.0:HFCap,10000.0:
                S2,2:PAccept,1.0:PReject,0.0:NewCast:CycleEnd:S3,3:
                HeadboxCri,100.0:HeadboxCap,400.0:HeadboxMin,0.0:
                CastMin,0.0:CastCri,1000.0:CastMax,1000.0:CastAmount(8):CastThick:CastWidth:CastStock:
                RollWidth(3),132.0,120.0,110.0:density,0.00271:Scrap(3),20.0,60.0,20.0:
                MeltTime:CastTime:SetupTime:CCSetupTime:FC,2;

EXPRESSIONS:    FoilImp,DISCRETE(F1,3,F2,4,F3,5,F4,6):
                SheetImp,DISCRETE(L1,1,L2,2,L3,5,L4,8):
                FoilIntArr,EXPO(M1):
                SheetIntArr,EXPO(M2):
                FoilAmount,EXPO(W1):
                SheetAmount,EXPO(W2):
                AlloyFoil,DISCRETE(PF1,1,PF2,3,PF3,4,PF4,5,PF5,6):
```

```
                AlloySheet,DISCRETE(PL1,1,PL2,2,PL3,5,PL4,7,PL5,8):
                MFLoad,UNIF(1000.0,1500.0):
                MFLoadingTime,UNIF(1.0,3.0):
                LoadEquipTime,UNIF(2.0,4.0):
                HotCleaning,UNIF(15.0,20.0):
                AlloyPre,UNIF(25.0,30.0):
                HoldFurPre,UNIF(60.0,90.0):
                MeltFurPre,UNIF(300.0,360.0):
                CompCheck,UNIF(5.0,10.0):
                ChangeRoll,UNIF(300.0,360.0):
                ChangeDie,UNIF(90.0,120.0):
                CoilLoad,UNIF(0.5,1.0):
                CoilUnload,UNIF(0.5,1.0):
                TransScrap,UNIF(2.0,4.0):
                TransCoil,UNIF(2.0,4.0):
                MeltRate,UNIF(41.667,55.556):
                TransRate1,140.0:TransRate2,50.0:
                CastRate(8),UNIF(75.0,80.0),UNIF(70.0,75.0),UNIF(70.0,75.0),UNIF(70.0,75.0),
                        UNIF(60.0,65.0),UNIF(60.0,65.0),UNIF(65.0,70.0),UNIF(65.0,75.0):
                Thick(8),UNIF(0.98,1.02),UNIF(0.98,1.02),UNIF(0.98,1.02),UNIF(0.98,1.02),
                        UNIF(0.98,1.02),UNIF(0.98,1.02),UNIF(0.98,1.02),UNIF(0.8,0.85);

QUEUES:         CastStock1:CastStock2:CastStock3:CastStock4:CastStock5:CastStock6:CastStock7:CastStock8:
                CoilStock1:CoilStock2:CoilStock3:CoilStock4:CoilStock5:CoilStock6:CoilStock7:CoilStock8:
                FoilStock1:FoilStock2:FoilStock3:FoilStock4:FoilStock5:FoilStock6:FoilStock7:FoilStock8:
                CastBuffer:MFForkQue:MeltQue:Ready1:MeltCon:TransCon:CastCon:
                Ready2:CastQue:EndCast:ForkMFQue:CraneMFQue;

LEVELS:         LevelMF:
                LevelHF:
                LevelHB:
                LevelCC;

RATES:          RateMF:
                RateHF:
                RateHB:
                RateCC;

STATESETS:      MeltStates,Loading,Melting,ReadyMelt,MeltPre,Waiting,Transfering,MFPre:
                HoldStates,ReadyTrans(IDLE),Holding(BUSY),HFPre(INACTIVE):
                CasterStates,Ready(IDLE),Casting(BUSY),CasterPre(INACTIVE);

RESOURCES:      MeltFurnace,CAPACITY(1),MeltStates:
                HoldFurnace,CAPACITY(1),HoldStates:
                ConCaster,CAPACITY(1),CasterStates:
                ForkMF,CAPACITY(1):
                CraneMF,CAPACITY(1);

FREQUENCIES:    STATE(MeltFurnace):
                STATE(HoldFurnace):
                STATE(ConCaster);

COUNTERS:       CDemand1:CDemand2:CDemand3:CDemand4:CDemand5:CDemand6:CDemand7:CDemand8;

TALLIES:        FoilDemand1:FoilDemand2:FoilDemand3:FoilDemand4:
                FoilDemand5:FoilDemand6:FoilDemand7:FoilDemand8:
                FoilAmount1:FoilAmount2:FoilAmount3:FoilAmount4:
                FoilAmount5:FoilAmount6:FoilAmount7:FoilAmount8:
                FoilSat1:FoilSat2:FoilSat3:FoilSat4:FoilSat5:FoilSat6:FoilSat7:FoilSat8:
                SheetDemand1:SheetDemand2:SheetDemand3:SheetDemand4:
                SheetDemand5:SheetDemand6:SheetDemand7:SheetDemand8:
                SDemand1:SDemand2:SDemand3:SDemand4:SDemand5:SDemand6:SDemand7:SDemand8:
                SheetSat1:SheetSat2:SheetSat3:SheetSat4:SheetSat5:SheetSat6:SheetSat7:SheetSat8:
                Cast1:Cast2:Cast3:Cast4:Cast5:Cast6:Cast7:Cast8:
                FromFoilSto1:FromFoilSto2:FromFoilSto3:FromFoilSto4:
                FromFoilSto5:FromFoilSto6:FromFoilSto7:FromFoilSto8:
                FromCoilSto1:FromCoilSto2:FromCoilSto3:FromCoilSto4:
                FromCoilSto5:FromCoilSto6:FromCoilSto7:FromCoilSto8:
                FromCastSto1:FromCastSto2:FromCastSto3:FromCastSto4:
                FromCastSto5:FromCastSto6:FromCastSto7:FromCastSto8:
                Scraped1:Scraped2:Scraped3:Scraped4:Scraped5:Scraped6:Scraped7:Scraped8:
                Cast1:Cast2:Cast3:Cast4:Cast5:Cast6:Cast7:Cast8:
                UnCast1:UnCast2:UnCast3:UnCast4:UnCast5:UnCast6:UnCast7:UnCast8:
                MeltTime1:MeltTime2:MeltTime3:MeltTime4:MeltTime5:MeltTime6:MeltTime7:MeltTime8:
```

```
                CastTime1:CastTime2:CastTime3:CastTime4:CastTime5:CastTime6:CastTime7:CastTime8:
                CastTim1:CastTim2:CastTim3:CastTim4:CastTim5:CastTim6:CastTim7:CastTim8:
                SetTime1:SetTime2:SetTime3:SetTime4:SetTime5:SetTime6:SetTime7:SetTime8:
                ToCastSto1:ToCastSto2:ToCastSto3:ToCastSto4:ToCastSto5:ToCastSto6:ToCastSto7:ToCastSto8:
                ToDemand1:ToDemand2:ToDemand3:ToDemand4:ToDemand5:ToDemand6:ToDemand7:ToDemand8:
                CCSetTime;

CSTATS:         LevelMF:
                LevelHF:
                LevelHB:
                LevelCC;

DSTATS:         NQ(CastStock1):NQ(CastStock2):NQ(CastStock3):NQ(CastStock4):
                NQ(CastStock5):NQ(CastStock6):NQ(CastStock7):NQ(CastStock8):CastStock:
                NQ(CoilStock1):NQ(CoilStock2):NQ(CoilStock3):NQ(CoilStock4):
                NQ(CoilStock5):NQ(CoilStock6):NQ(CoilStock7):NQ(CoilStock8):CoilStock:
                NQ(FoilStock1):NQ(FoilStock2):NQ(FoilStock3):NQ(FoilStock4):
                NQ(FoilStock5):NQ(FoilStock6):NQ(FoilStock7):NQ(FoilStock8):FoilStock:
                NQ(CastBuffer):Cast(1):Cast(2):Cast(3):Cast(4):Cast(5):Cast(6):Cast(7):Cast(8):
                CastDemand(1):CastDemand(2):CastDemand(3):CastDemand(4):
                CastDemand(5):CastDemand(6):CastDemand(7):CastDemand(8):CastDemandT:
                WaitOrder(1):WaitOrder(2):WaitOrder(3):WaitOrder(4):
                WaitOrder(5):WaitOrder(6):WaitOrder(7):WaitOrder(8):WaitOrderT;

OUTPUTS:        TAVG(CCSetTime):TMIN(CCSetTime):TMAX(CCSetTime):
                TAVG(CastTim1):TAVG(CastTim2):TAVG(CastTim3):TAVG(CastTim4):
                TAVG(CastTim5):TAVG(CastTim6):TAVG(CastTim7):TAVG(CastTim8):
                TAVG(SetTime1):TAVG(SetTime2):TAVG(SetTime3):TAVG(SetTime4):
                TAVG(SetTime5):TAVG(SetTime6):TAVG(SetTime7):TAVG(SetTime8):
                TMIN(CastTim1):TMIN(CastTim2):TMIN(CastTim3):TMIN(CastTim4):
                TMIN(CastTim5):TMIN(CastTim6):TMIN(CastTim7):TMIN(CastTim8):
                TMIN(SetTime1):TMIN(SetTime2):TMIN(SetTime3):TMIN(SetTime4):
                TMIN(SetTime5):TMIN(SetTime6):TMIN(SetTime7):TMIN(SetTime8):
                TMAX(CastTim1):TMAX(CastTim2):TMAX(CastTim3): TMAX(CastTim4):
                TMAX(CastTim5):TMAX(CastTim6):TMAX(CastTim7):TMAX(CastTim8):
                TMAX(SetTime1):TMAX(SetTime2):TMAX(SetTime3):TMAX(SetTime4):
                TMAX(SetTime5):TMAX(SetTime6):TMAX(SetTime7):TMAX(SetTime8);

FILES:  1,file1,"ccb1.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        2,file2,"ccb2.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        3,file3,"ccb3.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        4,file4,"ccb4.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        5,file5,"ccb5.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        6,file6,"ccb6.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        7,file7,"ccb7.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        8,file8,"ccb8.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        9,file9,"ccb9.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        10,file10,"ccb10.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        11,file11,"ccb11.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        12,file12,"ccb12.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        13,file13,"ccb13.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        14,file14,"ccb14.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        15,file15,"ccb15.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        16,file16,"ccb16.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD:
        17,file17,"ccb17.dat",SEQ,"(i3,3x,f15.5,3x,f15.5,3x,f15.5,3x,i6)",ERR,No,HOLD;

REPLICATE,      100,0,525600;
END;
```

D.2. SIMAN Source Code of the Second Model: Coil Production Subsystem

D.2.1. Model Frame (Model 2)

```
BEGIN,Yes;

;Initialization.
          CREATE:,1;
          DELAY:TFIN;
          WRITE,file1:NREP,TAVG(FoilAmountDem),TNUM(FoilAmountDem),
                    TAVG(FoilAmountDem)*TNUM(FoilAmountDem),TAVG(FoilDemWait),TNUM(FoilDemWait);
          WRITE,file2:NREP,TAVG(SheetAmountDem),TNUM(SheetAmountDem),
                    TAVG(SheetAmountDem)*TNUM(SheetAmountDem),
                    TAVG(SheetDemWait),TNUM(SheetDemWait);
          WRITE,file3:NREP,TAVG(CastStWait),TNUM(CastStWait);
          WRITE,file4:NREP,TAVG(RollTimeCoil),TNUM(RollTimeCoil),TAVG(RollTime),TNUM(RollTime),
                    TAVG(RollAmount),TNUM(RollAmount),TAVG(RollAmount)*TNUM(RollAmount)*1000,
                    TAVG(RollEndAmount),TNUM(RollEndAmount),
                    TAVG(RollEndAmount)*TNUM(RollEndAmount)*1000;
          WRITE,file5:NREP,TAVG(AnnTime),TNUM(AnnTime),TAVG(AnnAmount),TNUM(AnnAmount),
                    TAVG(AnnAmount)*TNUM(AnnAmount)*1000,TAVG(AnnCount),TNUM(AnnCount);
          WRITE,file6:NREP,TAVG(FoilDemFin),TNUM(FoilDemFin),TAVG(FoilDemFin)*TNUM(FoilDemFin),
                    TAVG(FoilFinRatio),TNUM(FoilFinRatio),TAVG(FoilTimeInPro),TNUM(FoilTimeInPro),
                    TAVG(FoilSlack),TNUM(FoilSlack),TAVG(FoilTardyAmount),TNUM(FoilTardyAmount),
                    TAVG(FoilTardyTime),TNUM(FoilTardyTime);
          WRITE,file7:NREP,TAVG(SheetDemFin),TNUM(SheetDemFin),TAVG(SheetDemFin)*TNUM(SheetDemFin),
                    TAVG(SheetFinRatio),TNUM(SheetFinRatio),TAVG(SheetTimeInPro),TNUM(SheetTimeInPro),
                    TAVG(SheetSlack),TNUM(SheetSlack),TAVG(SheetTardyAmount),TNUM(SheetTardyAmount),
                    TAVG(SheetTardyTime),TNUM(SheetTardyTime);
          WRITE,file8:NREP,DAVG(FoilDemandQue),DAVG(SheetDemandQue),
                    DAVG(CastStockQue),DAVG(CoilStockQue),DAVG(FoilStockQue);
          WRITE,file9:NREP,DAVG(CastT),DAVG(CastDemandTotal),DAVG(WaitOrderTotal);
          WRITE,file10:NREP,DAVG(RollBufferQue),DAVG(NumMillQue),
                    DAVG(AnnealBufferQue),DAVG(NumAnnealQue);
          WRITE,file11:NREP,DAVG(Mill1Uti),DAVG(Mill2Uti),DAVG(Furnace1Uti),DAVG(Furnace2Uti),
                    DAVG(Furnace1AvgLoad),DAVG(Furnace2AvgLoad);
          WRITE,file12:NREP,FC,SeqRuleDem,SeqRuleMill,SeqRuleAnn:DISPOSE;


;Casting Cycle initialization.
          CREATE:,1:NEXT(RenewCast);


;Imported Stocks.
          CREATE,BatchCoil:ImpPeriodCoil:Mark(WaitTime);
          ASSIGN:NS=SheetImp;
          BRANCH,1:
                    IF,NumStock.GT.1,ImpCoil:
                    ELSE,Dis;

          CREATE,BatchFoil:ImpPeriodFoil:MARK(WaitTime);
          ASSIGN:NS=FoilImp;
          BRANCH,1:
                    IF,NumStock.GT.2,ImpFoil:
                    ELSE,Dis;

ImpCoil   ASSIGN:CoilStock=CoilStock+1;
          QUEUE,NS+(NumAlloy*3):DETACH;

ImpFoil   ASSIGN:FoilStock=FoilStock+1;
          QUEUE,NS+(NumAlloy*4):DETACH;

Dis       DISPOSE;
```

*;Arrival of **Foil** Order.*
(Search the stocks to allocate the required amount of coils to this order OR the requested amount of the particular alloy is recorded so that it can be cast in the subsequent casting cycle.)

```
        CREATE:FoilIntArr:MARK(TimeIn);
        ASSIGN:Alloy=AlloyFoil:
                FinalThick=FoilThick:
                MecPerform=FoilMecPerform:
                Amount=FoilAmount:
                DueDate=TNOW+FoilDueDate:
                NS=Alloy*100+FinalThick*10+MecPerform;

        IF:SeqRuleDem.LT.5;
                ASSIGN:Length=CoilWeight/(density*Width(1)*ExpThickness(1,AINT(NS/100))):
                        ProcessTime=ExpLoadingMill+ExpCoilSetting+ExpPreRun(1)+
                                Length/ExpMillRate(AINT(NS/100),1):
                        Priority=TimeIn*(SeqRuleDem.EQ.1)+DueDate*(SeqRuleDem.EQ.2)+
                                ProcessTime*(SeqRuleDem.EQ.3)+NumOprSeq((NS-AINT(NS/10)*10),
                                (AINT(NS/10)-(AINT(NS/100)*10)))*(SeqRuleDem.EQ.4);
        ELSEIF:SeqRuleDem.GE.5.AND.SeqRuleDem.LE.8;
                ASSIGN:NPro=IS:
                        NumMillOpr=0:
                        RemProTime=0;
                WHILE:NPro.LT.NumOprSeq((NS-AINT(NS/10)*10),(AINT(NS/10)-(AINT(NS/100)*10)));
                ASSIGN:NPro=NPro+1:
                        NumMillOpr=NumMillOpr+1*(MSQ(NS,NPro).EQ.ColdMill):
                        ThickRange=1*(ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.5)+
                                2*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.5
                                .AND.ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.1)+
                                3*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.1

        .AND.ExpThickness(NumMillOpr,AINT(NS/100)).GE.ThickCri(AINT(NS/100)))+
                                4*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.ThickCri(AINT(NS/100))):
                        RemProTime=(RemProTime+ExpLoadingMill+ExpCoilSetting+
                                ExpPreRun(1)*(ThickRange.LE.2)+ExpPreRun(2)*(ThickRange.GT.2)+
                                ExpSampleTaking*(MSQ(NS,NPro+1).EQ.(FinishFoil.OR.FinishSheet).OR.
                                (MSQ(NS,NPro+1).EQ.AnnealFur.AND.MSQ(NS,NPro+2).EQ.
                                (FinishFoil.OR.FinishSheet)))+ ExpCoilRemoving*(NPro.NE.1)+
                                (CoilWeight/(density*Width(1)*ExpThickness(NumMillOpr,AINT(NS/100))))
                                /ExpMillRate(AINT(NS/100),ThickRange))*(MSQ(NS,NPro).EQ.ColdMill)+
                                (ExpSetupFurnace+ExpAnnCoilRemove+Anneal)
                                *(MSQ(NS,NPro).EQ.AnnealFur);
                ENDWHILE;
                ASSIGN:Priority=RemProTime*(SeqRuleDem.EQ.5)+
                        (DueDate-TNOW-RemProTime)*(SeqRuleDem.EQ.6)+
                        ((DueDate-TNOW)/RemProTime)*(SeqRuleDem.EQ.7)+
                        ProcessTime*(DueDate.GT.(TNOW+RemProTime)) *(SeqRuleDem.EQ.8);
        ELSEIF:SeqRuleDem.EQ.9;
                ASSIGN:Priority=(AINT(DueDate/1440.0)*1000 +AINT(NS/100));
        ENDIF;

        ASSIGN:AmountTotal=0:
                AmountFin=0:
                NCoilFoil=AINT(Amount/CoilWeight)+1;
        IF:NQ(AINT(NS/100)).NE.0;
                BRANCH,1:
                        IF,Priority.LT.AQUE((AINT(NS/100)),1,5),RemF:
                        ELSE,QueF;
        ENDIF;
RemF    IF:NQ(AINT(NS/100)+(NumAlloy*2))*(FC.EQ.2)+NQ(AINT(NS/100)+(NumAlloy*3))+
            NQ(AINT(NS/100)+(NumAlloy*4)).GE.NCoilFoil;
                WHILE:AmountTotal.LT.NCoilFoil*CoilWeight;
                IF:NQ(AINT(NS/100)+(NumAlloy*4)).NE.0;
                ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                        AmountFin=AmountFin+CoilWeight:
                        FoilStock=FoilStock-1;
                REMOVE:1,AINT(NS/100)+(NumAlloy*4),FoilFin;
                ELSEIF:NQ(AINT(NS/100)+(NumAlloy*3)).NE.0;
                        ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                                CoilStock=CoilStock-1;
                        REMOVE:1,AINT(NS/100)+(NumAlloy*3),FF1;
                ELSEIF:NQ(AINT(NS/100)+(NumAlloy*2)).NE.0.AND.FC.EQ.2;
                        ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                                CastStock=CastStock-1;
```

```
                    REMOVE:1,AINT(NS/100)+(NumAlloy*2),FF2;
               ENDIF;
               ENDWHILE:NEXT(Demand1);
QueF     ELSEIF:FC.EQ.2;
               ASSIGN:Weight=NCoilFoil*CoilWeight-AmountTotal;
         TALLY:AINT(NS/100)+(NumAlloy*3),NCoilFoil*CoilWeight-AmountTotal;
         BRANCH,2:
               ALWAYS,Demand1:
               ALWAYS,Cast;
         ENDIF;

Demand1  ASSIGN:Amount=Amount-AmountFin:
              NCoilFoil=AINT(Amount/CoilWeight)+1:
              FoilDemQue=FoilDemQue+1:
              FoilDemAmount=FoilDemAmount+(NCoilFoil*CoilWeight);
         TALLY:AINT(NS/100),Amount;
         TALLY:AINT(NS/100)+NumAlloy,NCoilFoil*CoilWeight;
         TALLY:FoilAmountDem,NCoilFoil*CoilWeight;
         TALLY:AINT(NS/100)+(NumAlloy*2),AmountTotal-AmountFin;
         QUEUE,AINT(NS/100):DETACH;

FoilFin  TALLY:NS+(NumAlloy*12),INT(WaitTime);
         TALLY:NS+(NumAlloy*13),CoilWeight:DISPOSE;

FF1      TALLY:NS+(NumAlloy*14),INT(WaitTime);
         TALLY:NS+(NumAlloy*15),CoilWeight:NEXT(IntFoil);
FF2      TALLY:NS+(NumAlloy*16),INT(WaitTime);
         TALLY:CastStWait,INT(WaitTime);
         TALLY:NS+(NumAlloy*17),CoilWeight:NEXT(IntFoil);

Sta1     ASSIGN:FoilDemQue=FoilDemQue-1;
         TALLY:AINT(NS/100)+(NumAlloy*4),INT(TimeIn);
         TALLY:FoilDemWait,INT(TimeIn);
         TALLY:AINT(NS/100)+(NumAlloy*5),(AINT(Amount/CoilWeight)+1)*1000:DISPOSE;
```

*;Arrival of **Sheet** Order.*
(Search the stocks to allocate the required amount of coils to this order OR the requested amount of the particular alloy is recorded so that it can be cast in the subsequent casting cycle.)

```
         CREATE:SheetIntArr:MARK(TimeIn);
         ASSIGN:Alloy=AlloySheet:
              FinalThick=SheetThick:
              MecPerform=SheetMecPerform:
              Amount=SheetAmount:
              DueDate=TNOW+SheetDueDate:
              NS=Alloy*100+FinalThick*10+MecPerform:
              NPro=IS:
              RemProTime=0;
         IF:SeqRuleDem.LT.5;
              ASSIGN:Length=CoilWeight/(density*Width(1)*ExpThickness(1,AINT(NS/100))):
                     ProcessTime=ExpLoadingMill+ExpCoilSetting+ExpPreRun(1)+
                           Length/ExpMillRate(AINT(NS/100),1):
                     Priority=TimeIn*(SeqRuleDem.EQ.1)+DueDate*(SeqRuleDem.EQ.2)+
                         ProcessTime*(SeqRuleDem.EQ.3)+NumOprSeq((NS-AINT(NS/10)*10),
                         (AINT(NS/10)-(AINT(NS/100)*10)))*(SeqRuleDem.EQ.4);
         ELSEIF:SeqRuleDem.GE.5.AND.SeqRuleDem.LE.8;
              ASSIGN:NPro=IS:
                     NumMillOpr=0:
                     RemProTime=0;
              WHILE:NPro.LT.NumOprSeq((NS-AINT(NS/10)*10),(AINT(NS/10)-(AINT(NS/100)*10)));
              ASSIGN:NPro=NPro+1:
                     NumMillOpr=NumMillOpr+1*(MSQ(NS,NPro).EQ.ColdMill):
                     ThickRange=1*(ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.5)+
                           2*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.5
                           .AND.ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.1)+
                           3*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.1
                           .AND.ExpThickness(NumMillOpr,AINT(NS/100))
                           .GE.ThickCri(AINT(NS/100)))+4*(ExpThickness(NumMillOpr,AINT(NS/100))
                           .LT.ThickCri(AINT(NS/100))):
                     RemProTime=(RemProTime+ExpLoadingMill+ExpCoilSetting+
                           ExpPreRun(1)*(ThickRange.LE.2)+ExpPreRun(2)*(ThickRange.GT.2)+
                           ExpSampleTaking*(MSQ(NS,NPro+1).EQ.(FinishFoil.OR.FinishSheet).OR.
                           (MSQ(NS,NPro+1).EQ.AnnealFur.AND.MSQ(NS,NPro+2).EQ.
```

```
                              (FinishFoil.OR.FinishSheet)))+ ExpCoilRemoving*(NPro.NE.1)+
                              (CoilWeight/(density*Width(1)*ExpThickness(NumMillOpr,AINT(NS/100))))
                              /ExpMillRate(AINT(NS/100),ThickRange))*(MSQ(NS,NPro).EQ.ColdMill)+
                              (ExpSetupFurnace+ExpAnnCoilRemove+Anneal)
                              *(MSQ(NS,NPro).EQ.AnnealFur);
            ENDWHILE;
            ASSIGN:Priority=RemProTime*(SeqRuleDem.EQ.5)+
                        (DueDate-TNOW-RemProTime)*(SeqRuleDem.EQ.6)+
                        ((DueDate-TNOW)/RemProTime)*(SeqRuleDem.EQ.7)+
                        ProcessTime*(DueDate.GT.(TNOW+RemProTime)) *(SeqRuleDem.EQ.8);
        ELSEIF:SeqRuleDem.EQ.9;
            ASSIGN:Priority=(AINT(DueDate/1440.0)*1000+AINT(NS/100));
        ENDIF;

        ASSIGN:AmountTotal=0:
            NCoilSheet=AINT(Amount/CoilWeight)+1;
        IF:NQ(AINT(NS/100)+NumAlloy).NE.0;
            BRANCH,1:
                IF,Priority.LT.AQUE((AINT(NS/100)+NumAlloy),1,5),RemS:
                ELSE,QueS;
        ENDIF;
RemS    IF:NQ(AINT(NS/100)+(NumAlloy*2))+NQ(AINT(NS/100)+(NumAlloy*3)).GE.NCoilSheet;
            WHILE:AmountTotal.LT.NCoilSheet*CoilWeight;
            IF:NQ(AINT(NS/100)+(NumAlloy*2)).NE.0;
                ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                    CastStock=CastStock-1;
                REMOVE:1,AINT(NS/100)+(NumAlloy*2),SS1;
            ELSEIF:NQ(AINT(NS/100)+(NumAlloy*3)).NE.0;
                ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                    CoilStock=CoilStock-1;
                REMOVE:1,AINT(NS/100)+(NumAlloy*3),SS2;
            ENDIF;
            ENDWHILE:NEXT(Demand2);
QueS    ELSE;
            ASSIGN:Weight=NCoilSheet*CoilWeight-AmountTotal;
            TALLY:AINT(NS/100)+(NumAlloy*9),NCoilSheet*CoilWeight-AmountTotal;
            BRANCH,2:
                ALWAYS,Demand2:
                ALWAYS,Cast;
        ENDIF;

Demand2 ASSIGN:SheetDemQue=SheetDemQue+1:
            SheetDemAmount=SheetDemAmount+(NCoilSheet*CoilWeight);
        TALLY:AINT(NS/100)+(NumAlloy*6),Amount;
        TALLY:AINT(NS/100)+(NumAlloy*7),NCoilSheet*CoilWeight;
        TALLY:SheetAmountDem,NCoilSheet*CoilWeight;
        TALLY:AINT(NS/100)+(NumAlloy*8),AmountTotal;
        QUEUE,AINT(NS/100)+NumAlloy:DETACH;

SS1     TALLY:NS+(NumAlloy*16),INT(WaitTime);
        TALLY:CastStWait,INT(WaitTime);
        TALLY:NS+(NumAlloy*17),CoilWeight:NEXT(IntSheet);
SS2     TALLY:NS+(NumAlloy*14),INT(WaitTime);
        TALLY:NS+(NumAlloy*15),CoilWeight:NEXT(IntSheet);

Sta2    ASSIGN:SheetDemQue=SheetDemQue-1;
        TALLY:AINT(NS/100)+(NumAlloy*10),INT(TimeIn);
        TALLY:SheetDemWait,INT(TimeIn);
        TALLY:AINT(NS/100)+(NumAlloy*11),(AINT(Amount/CoilWeight)+1)*1000:DISPOSE;
```

;The cast coils are allocated to the customer orders and are sent to cold-mill and annealing furnace stations to be processed OR they are sent to cast coil stock to be allocated to the forthcoming order.

```
Trans   DELAY:CastCooling;
        IF:NQ(NS+NumAlloy).NE.0.AND.NQ(NS).NE.0.AND.FC.EQ.2;
            BRANCH,1:
                IF,AQUE(NS+NumAlloy,1,5).LE.AQUE(NS,1,5),Int2:
                ELSE,Int1;
        ENDIF;
```

```
          IF:NQ(NS+NumAlloy).NE.0;
Int2      ASSIGN:NCoil=AINT(AQUE((NS+NumAlloy),1,2)/CoilWeight)+1:
                  AmountTotal=1*CoilWeight;
          IF:1+NQ(NS+(NumAlloy*2))+NQ(NS+(NumAlloy*3)).GE.NCoil;
                  WHILE:AmountTotal.LT.NCoil*CoilWeight;
                  IF:NQ(NS+(NumAlloy*2)).NE.0;
                          ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                                  CastStock=CastStock-1;
                          REMOVE:1,NS+(NumAlloy*2),SS1;
                  ELSEIF:NQ(NS+(NumAlloy*3)).NE.0;
                          ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                                  CoilStock=CoilStock-1;
                          REMOVE:1,NS+(NumAlloy*3),SS2;
                  ENDIF;
                  ENDWHILE:NEXT(IntSheet);
          ENDIF:NEXT(Stock);
IntSheet  ASSIGN:NCoil=AINT(AQUE((NS+NumAlloy),1,2)/CoilWeight)+1;
          QUEUE,IntQue2:MARK(WaitTime);
          COMBINE,NS:NCoil,First;
          ASSIGN:NS=NSQUE((NS+NumAlloy),1):
                  TimeIn=AQUE((AINT(NS/100)+NumAlloy),1,1):
                  Amount=AQUE((AINT(NS/100)+NumAlloy),1,2):
                  DueDate=AQUE((AINT(NS/100)+NumAlloy),1,3):
                  Priority=AQUE((AINT(NS/100)+NumAlloy),1,5);
          TALLY:AINT(NS/100)+(NumAlloy*19),INT(WaitTime);
          REMOVE:1,(AINT(NS/100)+NumAlloy),Sta2;
          DELAY:Transfer;
          ROUTE:,SEQ;
ELSEIF:NQ(NS).NE.0.AND.FC.EQ.2;
Int1      ASSIGN:NCoil=AINT(AQUE(NS,1,2)/CoilWeight)+1:
                  AmountTotal=1*CoilWeight:
                  AmountFin=0;
          IF:1+NQ(NS+(NumAlloy*2))*(FC.EQ.2)+NQ(NS+(NumAlloy*3))+NQ(NS+(NumAlloy*4)).GE.NCoil;
          WHILE:AmountTotal.LT.NCoil*CoilWeight;
          IF:NQ(NS+(NumAlloy*4)).NE.0;
                  ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                          AmountFin=AmountFin+CoilWeight:
                          FoilStock=FoilStock-1;
                  REMOVE:1,NS+(NumAlloy*4),FoilFin;
          ELSEIF:NQ(NS+(NumAlloy*3)).NE.0;
                  ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                          CoilStock=CoilStock-1;
                  REMOVE:1,NS+(NumAlloy*3),FF1;
          ELSEIF:NQ(NS+(NumAlloy*2)).NE.0.AND.FC.EQ.2;
                  ASSIGN:AmountTotal=AmountTotal+CoilWeight:
                          CastStock=CastStock-1;
                  REMOVE:1,NS+(NumAlloy*2),FF2;
          ENDIF;
          ENDWHILE:NEXT(IntFoil);
          ENDIF:NEXT(Stock);
IntFoil   ASSIGN:NCoil=AINT((AQUE(NS,1,2)-AmountFin)/CoilWeight)+1;
          QUEUE,IntQue1:MARK(WaitTime);
          COMBINE,NS:NCoil,First;
          ASSIGN:NS=NSQUE(NS,1):
                  TimeIn=AQUE(AINT(NS/100),1,1):
                  Amount=AQUE(AINT(NS/100),1,2)-AmountFin:
                  DueDate=AQUE(AINT(NS/100),1,3):
                  Priority=AQUE(AINT(NS/100),1,5);
          TALLY:AINT(NS/100)+(NumAlloy*18),INT(WaitTime);
          REMOVE:1,AINT(NS/100),Sta1;
          DELAY:Transfer;
          ROUTE:,SEQ;
          ENDIF:NEXT(Stock);

Stock     DELAY:Transfer;
          ASSIGN:CastStock=CastStock+1;
          QUEUE,NS+(NumAlloy*2):MARK(WaitTime):DETACH;
```

;The amount of each Al alloy that will be cast in the subsequent cast cycle is determined and the amount of each Al alloy that will be cast in the current cast cycle is updated.

```
Cast      ASSIGN:CastDemand(AINT(NS/100))=CastDemand(AINT(NS/100))+Weight:
                  CastDemandT=CastDemandT+Weight:
```

```
            Alloy=AINT(NS/100);
        IF:CastDemand(AINT(NS/100)).GT.AveCast(AINT(NS/100),FC);
        IF:CastTotal+Weight.LE.MaxCast*CL;
             SEARCH,CastBuffer:AINT(NS/100).EQ.Alloy;
             IF:J.NE.0.OR.CastType.EQ.(AINT(NS/100));
                  ASSIGN:Cast(AINT(NS/100))=Cast(AINT(NS/100))+Weight:
                       CastTotal=CastTotal+Weight:DISPOSE;
             ENDIF;
        ENDIF;
        ASSIGN:WaitOrder(AINT(NS/100))=WaitOrder(AINT(NS/100))+Weight:
            WaitOrderT=WaitOrderT+Weight:DISPOSE;
        ENDIF:DISPOSE;
```

;Cast cycle is renewed. (The amounts of Al alloys that will be cast in subsequent cast cycle is set.)

```
RenewCast       ASSIGN:Num=0:
                     CastTotal=0:
                     CastDemandT=0:
                     WaitOrderT=0;
Con             WHILE:Num.LT.NumAlloy;
                ASSIGN:Num=Num+1:
                     CastDemand(Num)=WaitOrder(Num)*(WaitOrder(Num).LE.AveCast(Num,FC))+
                     AveCast(Num,FC)*(WaitOrder(Num).GT.AveCast(Num,FC)):
                     CastDemandT=CastDemandT+Weight:
                     WaitOrder(Num)=MX(0,WaitOrder(Num)-CastDemand(Num)):
                     Cast(Num)=AveCast(Num,FC):
                     NS=Num:
                     CastTotal=CastTotal+Cast(Num);
                IF:Cast(Num).NE.0;
                      DUPLICATE:1,Con:NEXT(Schedule);
                ENDIF;
                ENDWHILE;
                ASSIGN:Num=0;
                WHILE:Num.LT.NumAlloy;
                ASSIGN:Num=Num+1;
                IF:WaitOrder(Num).LE.MaxCast*CL-CastTotal;
                      ASSIGN:CastDemand(Num)=CastDemand(Num)+WaitOrder(Num):
                           CastDemandT=CastDemandT+WaitOrder(Num):
                           Cast(Num)=Cast(Num)+WaitOrder(Num):
                           CastTotal=CastTotal+WaitOrder(Num):
                           WaitOrder(Num)=0;
                ELSEIF:WaitOrder(Num).GT.MaxCast*CL-CastTotal;
                      ASSIGN:CastDemand(Num)=CastDemand(Num)+(MaxCast*CL-CastTotal):
                           Cast(Num)=Cast(Num)+(MaxCast*CL-CastTotal):
                           CastTotal=MaxCast*CL:
                           WaitOrder(Num)=WaitOrder(Num)-(MaxCast*CL-CastTotal):
                           WaitOrderT=WaitOrderT+WaitOrder(Num);
                ENDIF;
                ENDWHILE:DISPOSE;
```

;Continuous Casting Station and Continuous Casting Process.

```
STATION,ConCasting;

Schedule  QUEUE,CastBuffer;
          SEIZE:SELECT(Caster,RAN,Index);
          ASSIGN:CastType=NS:
               CastNo(Index)=CastNo(Index)+1:

STATE(Caster(Index))=MFSetup*(CastNo(Index).EQ.1)+Setup*(CastNo(Index).GT.1):MARK(WaitTime);
          DELAY:MFSetupTime(FC)*(CastNo(Index).EQ.1);
          IF:NQ(CastBuffer).EQ.0;
               ASSIGN:NCast=1;
               WHILE:NCast.LE.NumCaster;
               ASSIGN:CastNo(NCast)=0:
                    NCast=NCast+1;
               ENDWHILE;
          ENDIF;
          ASSIGN:STATE(Caster(Index))=Setup;
          DELAY:SetupTime(NS,FC);
          TALLY:NS+(NumAlloy*20),INT(WaitTime);
          ASSIGN:CastAmount(NS)=0:
               STATE(Caster(Index))=Casting:MARK(WaitTime);
```

```
WHILE:CastAmount(NS).LE.Cast(NS);
        DELAY:CastTime(NS,FC);
        ASSIGN:CastAmount(NS)=CastAmount(NS)+CoilWeight;
        TALLY:NS+(NumAlloy*22),CoilWeight;
        DUPLICATE:1,Trans;
ENDWHILE;
TALLY:NS+(NumAlloy*21),(TNOW-WaitTime)/(CastAmount(NS)/CoilWeight);
RELEASE:Caster(Index);
IF:NQ(CastBuffer).NE.0;
        DISPOSE;
ENDIF:NEXT(RenewCast);
```

;Cold-Mill and Cold-Rolling Process.

```
STATION,ColdMill:MARK(WaitTime);

ASSIGN:NPro=0:
        NumMillOpr=0;
WHILE:NPro.LT.IS;
ASSIGN:NPro=NPro+1:
        NumMillOpr=NumMillOpr+1*(MSQ(NS,NPro).EQ.ColdMill);
ENDWHILE;
IF:SeqRuleMill.LT.5;
        ASSIGN:ThickRange=1*(ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.5)+
                        2*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.5
                        .AND.ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.1)+
                        3*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.1
                        .AND.ExpThickness(NumMillOpr,AINT(NS/100)).GE.ThickCri(AINT(NS/100)))+
                        4*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.ThickCri(AINT(NS/100))):
                Length=CoilWeight/(density*Width(1)*ExpThickness(NumMillOpr,AINT(NS/100))):
                ProcessTime=ExpLoadingMill+ExpCoilSetting+(ExpPreRun(1)*(ThickRange.LE.2)+
                        ExpPreRun(2)*(ThickRange.GT.2))+ExpSampleTaking*(MSQ(NS,IS+1).EQ.
                        (FinishFoil.OR.FinishSheet).OR.(MSQ(NS,IS+1).EQ.AnnealFur.AND.MSQ(NS,IS+2).EQ.
                        (FinishFoil.OR.FinishSheet)))+ExpCoilRemoving*(IS.NE.1)+
                        Length/ExpMillRate(AINT(NS/100),ThickRange):

Priority=WaitTime*(SeqRuleMill.EQ.1)+DueDate*(SeqRuleMill.EQ.2)+ProcessTime*(SeqRuleMill.EQ.3)+
                (NumOprSeq((NS-AINT(NS/10)*10),(AINT(NS/10)-(AINT(NS/100)*10)))-
                (IS-1))*(SeqRuleMill.EQ.4);
ELSEIF:SeqRuleMill.GE.5.AND.SeqRuleMill.LE.8;
        ASSIGN:NPro=IS-1:
                NumMillOpr=NumMillOpr-1:
                RemProTime=0;
        WHILE:NPro.LT.NumOprSeq((NS-AINT(NS/10)*10),(AINT(NS/10)-(AINT(NS/100)*10)));
        ASSIGN:NPro=NPro+1:
                NumMillOpr=NumMillOpr+1*(MSQ(NS,NPro).EQ.ColdMill):
                ThickRange=1*(ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.5)+
                        2*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.5
                        .AND.ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.1)+
                        3*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.1
                        .AND.ExpThickness(NumMillOpr,AINT(NS/100)).GE.ThickCri(AINT(NS/100)))+
                        4*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.ThickCri(AINT(NS/100))):
                RemProTime=(RemProTime+ExpLoadingMill+ExpCoilSetting+ExpPreRun(1)*(ThickRange.LE.2)+
                        ExpPreRun(2)*(ThickRange.GT.2)+ExpSampleTaking*(MSQ(NS,NPro+1).EQ.
                        (FinishFoil.OR.FinishSheet).OR.(MSQ(NS,NPro+1).EQ.AnnealFur.AND.
                        MSQ(NS,NPro+2).EQ.(FinishFoil.OR.FinishSheet)))+ExpCoilRemoving*(NPro.NE.1)+
                        (CoilWeight/(density*Width(1)*ExpThickness(NumMillOpr,AINT(NS/100))))
                        /ExpMillRate(AINT(NS/100),ThickRange))*(MSQ(NS,NPro).EQ.ColdMill)+
                        (ExpSetupFurnace+ExpAnnCoilRemove+Anneal) *(MSQ(NS,NPro).EQ.AnnealFur);
        ENDWHILE;
        ASSIGN:Priority=RemProTime*(SeqRuleMill.EQ.5)+(DueDate-TNOW-RemProTime)*(SeqRuleMill.EQ.6)+
                ((DueDate-TNOW)/RemProTime)*(SeqRuleMill.EQ.7)+
                ProcessTime*(DueDate.GT.(TNOW+RemProTime)) *(SeqRuleMill.EQ.8);
ELSEIF:SeqRuleMill.EQ.9;
        IF:(IS-1).EQ.0;
                ASSIGN:Priority=(AINT(DueDate/1440.0)*1000+AINT((1/(IS))*99)*10+AINT(NS/100));
        ELSEIF:(IS-1).EQ.1;
                ASSIGN:Priority=(AINT(DueDate/1440.0)*1000+AINT((1/(IS-1))*98)*10+AINT(NS/100));
        ELSE;
                ASSIGN:Priority=(AINT(DueDate/1440.0)*1000+AINT((1/(IS-1))*100)*10+AINT(NS/100));
        ENDIF;
ENDIF;
```

```
ASSIGN:NumRollQue=NumRollQue+(AINT(Amount/CoilWeight)+1);
QUEUE,RollBuffer;
SEIZE:SELECT(Mill,RAN,Index);
ASSIGN:NumRollQue=NumRollQue-(AINT(Amount/CoilWeight)+1);
ASSIGN:NPro=0:
        NumMillOpr=0:
        Thickness=1.0*(AINT(NS/100).NE.8)+0.85*(AINT(NS/100).EQ.8);
WHILE:NPro.LT.IS;
        ASSIGN:NPro=NPro+1:
                NumMillOpr=NumMillOpr+1*(MSQ(NS,NPro).EQ.ColdMill):
                Thickness=Thickness-Thickness*RollRatio(AINT(NS/100));
ENDWHILE;
ASSIGN:ThickRange=1*(Thickness.GE.0.5)+2*(Thickness.LT.0.5.AND.Thickness.GE.0.1)+
                3*(Thickness.LT.0.1.AND.Thickness.GE.ThickCri(AINT(NS/100)))+
                4*(Thickness.LT.ThickCri(AINT(NS/100))):
        MillThickRange=ThickRange:
        MillThickness=Thickness;
ASSIGN:STATE(Mill(Index))=Loading;
DELAY:LoadingMill;
ASSIGN:STATE(Mill(Index))=Setup;
DELAY:CoilSetting;
DELAY:PreRun(1)*(MillThickRange.LE.2)+PreRun(2)*(MillThickRange.GT.2);
WHILE:NCoilMill(Index).LE.AINT(Amount/CoilWeight)+1;
        ASSIGN:STATE(Mill(Index))=Milling:
                Length=CoilWeight/(density*MillThickness*Width(1));
        DELAY:Length/MillRate(AINT(NS/100),MillThickRange);
        ASSIGN:NCoilMill(Index)=NCoilMill(Index)+1;
ENDWHILE;
DELAY:SampleTaking*(MSQ(NS,IS+1).EQ.(FinishFoil.OR.FinishSheet)
        .OR.(MSQ(NS,IS+1).EQ.AnnealFur.AND.MSQ(NS,IS+2).EQ.(FinishFoil.OR.FinishSheet)));
DELAY:CoilRemoving*(IS.NE.1);
ASSIGN:NCoilMill(Index)=0;
RELEASE:Mill(Index);
TALLY:AINT(NS/100)+(NumAlloy*23),(TNOW-WaitTime)/(AINT(Amount/CoilWeight)+1);
TALLY:RollTimeCoil,(TNOW-WaitTime)/(AINT(Amount/CoilWeight)+1);
TALLY:AINT(NS/100)+(NumAlloy*24),TNOW-WaitTime;
TALLY:RollTime,TNOW-WaitTime;
TALLY:AINT(NS/100)+(NumAlloy*25),AINT(Amount/CoilWeight)+1;
TALLY:RollAmount,AINT(Amount/CoilWeight)+1;
IF:MSQ(NS,IS+1).EQ.FinishSheet.OR.MSQ(NS,IS+2).EQ.FinishFoil;
        TALLY:AINT(NS/100)+(NumAlloy*26),AINT(Amount/CoilWeight)+1;
        TALLY:RollEndAmount,AINT(Amount/CoilWeight)+1;
TALLY:AINT((NS-AINT(NS/100)*100)/10)+(NumAlloy*42),(AINT(Amount/CoilWeight)+1)*CoilWeight;
ENDIF;
DELAY:RollCooling;
DELAY:Transfer;
ROUTE:,SEQ;
```

;Annealing Furnace and Annealing Process.

```
STATION,AnnealFur:MARK(WaitTime);

IF:SeqRuleAnn.LT.5;
        ASSIGN:ProcessTime=ExpSetupFurnace+ExpAnnCoilRemove+Anneal:
                Priority=WaitTime*(SeqRuleAnn.EQ.1)+DueDate*(SeqRuleAnn.EQ.2)+
                        ProcessTime*(SeqRuleAnn.EQ.3)+(NumOprSeq((NS-AINT(NS/10)*10),
                        (AINT(NS/10)-(AINT(NS/100)*10)))-(IS-1))*(SeqRuleAnn.EQ.4);
ELSEIF:SeqRuleAnn.GE.5.AND.SeqRuleAnn.LE.8;
        ASSIGN:NPro=0:
                NumMillOpr=0:
                RemProTime=0;
        WHILE:NPro.LT.IS-1;
                ASSIGN:NPro=NPro+1:
                        NumMillOpr=NumMillOpr+1*(MSQ(NS,NPro).EQ.ColdMill);
        ENDWHILE;
        WHILE:NPro.LT.NumOprSeq((NS-AINT(NS/10)*10),(AINT(NS/10)-(AINT(NS/100)*10)));
        ASSIGN:NPro=NPro+1:
                NumMillOpr=NumMillOpr+1*(MSQ(NS,NPro).EQ.ColdMill):
                ThickRange=1*(ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.5)+
                        2*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.5
                        .AND.ExpThickness(NumMillOpr,AINT(NS/100)).GE.0.1)+
                        3*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.0.1
                        .AND.ExpThickness(NumMillOpr,AINT(NS/100)).GE.ThickCri(AINT(NS/100)))+
                        4*(ExpThickness(NumMillOpr,AINT(NS/100)).LT.ThickCri(AINT(NS/100))):
```

```
                RemProTime=(RemProTime+ExpLoadingMill+ExpCoilSetting+
                        ExpPreRun(1)*(ThickRange.LE.2)+ExpPreRun(2)*(ThickRange.GT.2)+
                        ExpSampleTaking*(MSQ(NS,NPro+1).EQ.(FinishFoil.OR.FinishSheet).OR.
                        (MSQ(NS,NPro+1).EQ.AnnealFur.AND.MSQ(NS,NPro+2).EQ.
                        (FinishFoil.OR.FinishSheet)))+ ExpCoilRemoving*(NPro.NE.1)+
                        (CoilWeight/(density*Width(1)*ExpThickness(NumMillOpr,AINT(NS/100))))
                        /ExpMillRate(AINT(NS/100),ThickRange))*(MSQ(NS,NPro).EQ.ColdMill)+
                        (ExpSetupFurnace+ExpAnnCoilRemove+Anneal) *(MSQ(NS,NPro).EQ.AnnealFur);
        ENDWHILE;
        ASSIGN:Priority=RemProTime*(SeqRuleAnn.EQ.5)+(DueDate-TNOW-RemProTime)*(SeqRuleAnn.EQ.6)+
                    ((DueDate-TNOW)/RemProTime)*(SeqRuleAnn.EQ.7)+
                    ProcessTime*(DueDate.GT.(TNOW+RemProTime)) *(SeqRuleAnn.EQ.8);
ELSEIF:SeqRuleAnn.EQ.9;
        IF:(IS-1).EQ.0;
                ASSIGN:Priority=(AINT(DueDate/1440.0)*1000+AINT((1/(IS))*99)*10+AINT(NS/100));
        ELSEIF:(IS-1).EQ.1;
                ASSIGN:Priority=(AINT(DueDate/1440.0)*1000+AINT((1/(IS-1))*98)*10+AINT(NS/100));
        ELSE;
                ASSIGN:Priority=(AINT(DueDate/1440.0)*1000+AINT((1/(IS-1))*100)*10+AINT(NS/100));
        ENDIF;
ENDIF;

        ASSIGN:NumAnnQue=NumAnnQue+(AINT(Amount/CoilWeight)+1);
        QUEUE,AnnealBuffer;
        SEIZE:SELECT(Furnace,RAN,Index);
        ASSIGN:FurnaceNo=Index:
                NumCoil=AINT(Amount/CoilWeight)+1:
                NAnnCoil=NumCoil:
                AlloyType=AINT(NS/100):
                NumAnnQue=NumAnnQue-(AINT(Amount/CoilWeight)+1);
A1      WHILE:NumCoil.LE.AnnCap-AvgCoil;
        SEARCH,AnnealBuffer:SearchType(AINT(NS/100),AlloyType).EQ.AlloyType;
        IF:J.NE.0;
                ASSIGN:NumCoil=NumCoil+AINT(AQUE(AnnealBuffer,J,2)/CoilWeight)+1;
                IF:NumCoil.LE.AnnCap+AvgCoil;
                        ASSIGN:NAnnCoil=NumCoil;
                        REMOVE:J,AnnealBuffer,A2;
                ENDIF:NEXT(A1);
        ENDIF:NEXT(Ann);
        ENDWHILE;
Ann     ASSIGN:NCoilAnn(Index)=NAnnCoil:
                STATE(Furnace(Index))=Loading;
        DELAY:SetupFurnace;
        ASSIGN:STATE(Furnace(Index))=Annealing;
        DELAY:Anneal;
        ASSIGN:STATE(Furnace(Index))=Unloading;
        DELAY:AnnCoilRemove;
        TALLY:AINT(NS/100)+(NumAlloy*29),NCoilAnn(Index);
        TALLY:AnnCount,NCoilAnn(Index);
        SIGNAL:Index;
        ASSIGN:NCoilAnn(Index)=0;
        RELEASE:Furnace(Index):NEXT(A3);
A2      ASSIGN:Index=FurnaceNo:
                NumAnnQue=NumAnnQue-(AINT(Amount/CoilWeight)+1);
        QUEUE,AnnInt;
        WAIT:Index;
A3      TALLY:AINT(NS/100)+(NumAlloy*27),(TNOW-WaitTime);
        TALLY:AnnTime,(TNOW-WaitTime);
        TALLY:AINT(NS/100)+(NumAlloy*28),AINT(Amount/CoilWeight)+1;
        TALLY:AnnAmount,AINT(Amount/CoilWeight)+1;
        DELAY:AnnCooling;
        DELAY:Transfer;
        ROUTE:,SEQ;
```

;Finished products. (They are sent to further processes.)

```
STATION,FinishFoil;

TALLY:AINT(NS/100)+(NumAlloy*30),(AINT(Amount/CoilWeight)+1)*CoilWeight;
TALLY:FoilDemFin,(AINT(Amount/CoilWeight)+1)*CoilWeight;
ASSIGN:FoilFinAmount=FoilFinAmount+(AINT(Amount/CoilWeight)+1)*CoilWeight;
TALLY:FoilFinRatio,FoilFinAmount/FoilDemAmount;
TALLY:AINT(NS/100)+(NumAlloy*31),((AINT(Amount/CoilWeight)+1)*CoilWeight)-Amount;
TALLY:FoilScrap,((AINT(Amount/CoilWeight)+1)*CoilWeight)-Amount;
```

```
TALLY:AINT(NS/100)+(NumAlloy*32),INT(TimeIn);
TALLY:FoilTimeInPro,INT(TimeIn);
TALLY:AINT(NS/100)+(NumAlloy*33),DueDate-TNOW;
TALLY:FoilSlack,DueDate-TNOW;
IF:DueDate-TNOW.LT.0;
        TALLY:AINT(NS/100)+(NumAlloy*34),(AINT(Amount/CoilWeight)+1)*CoilWeight;
        TALLY:FoilTardyAmount,(AINT(Amount/CoilWeight)+1)*CoilWeight;
        TALLY:AINT(NS/100)+(NumAlloy*35),DueDate-TNOW;
        TALLY:FoilTardyTime,DueDate-TNOW;
ENDIF:DISPOSE;

STATION,FinishSheet;

TALLY:AINT(NS/100)+(NumAlloy*36),(AINT(Amount/CoilWeight)+1)*CoilWeight;
TALLY:SheetDemFin,(AINT(Amount/CoilWeight)+1)*CoilWeight;
ASSIGN:SheetFinAmount=SheetFinAmount+(AINT(Amount/CoilWeight)+1)*CoilWeight;
TALLY:SheetFinRatio,SheetFinAmount/SheetDemAmount;
TALLY:AINT(NS/100)+(NumAlloy*37),((AINT(Amount/CoilWeight)+1)*CoilWeight)-Amount;
TALLY:SheetScrap,((AINT(Amount/CoilWeight)+1)*CoilWeight)-Amount;
TALLY:AINT(NS/100)+(NumAlloy*38),INT(TimeIn);
TALLY:SheetTimeInPro,INT(TimeIn);
TALLY:AINT(NS/100)+(NumAlloy*39),DueDate-TNOW;
TALLY:SheetSlack,DueDate-TNOW;
TALLY:AINT((NS-AINT(NS/100)*100)/10)+(NumAlloy*42)+NumFT,(AINT(Amount/CoilWeight)+1)*CoilWeight;
IF:DueDate-TNOW.LT.0;
        TALLY:AINT(NS/100)+(NumAlloy*40),(AINT(Amount/CoilWeight)+1)*CoilWeight;
        TALLY:SheetTardyAmount,(AINT(Amount/CoilWeight)+1)*CoilWeight;
        TALLY:AINT(NS/100)+(NumAlloy*41),DueDate-TNOW;
        TALLY:SheetTardyTime,DueDate-TNOW;
ENDIF:DISPOSE;

END;
```

D.2.2. Experiment Frame (Model 2)

```
BEGIN,Yes,No;

PROJECT,        Tez,ARER;

ATTRIBUTES:     TimeIn:
                Amount:
                DueDate:
                WaitTime:
                Priority:
                Index;

VARIABLES:      F1,0.14585:F2,0.44714:F3,0.60215:F4,1.0:
                L1,0.77495:L2,0.81174:L3,0.83023:L4,1.0:
                ImpPeriodCoil,12819.51:ImpPeriodFoil,30917.65:BatchCoil,280:BatchFoil,127:
                PF1,0.0401:PF2,0.63714:PF3,0.71406:PF4,0.82844:PF5,1.0:
                PL1,0.54381:PL2,0.5618:PL3,0.59474:PL4,0.84606:PL5,1.0:
                M1,562.08:M2,139.13:W1,2974.315:W2,3210.518:
                NumFT,9:FTF,1.0:
                FT1(8),0.01582,0.16709,0.0,0.0,0.97973,0.0,0.00000,0.26740:
                FT2(8),0.04451,0.19624,0.0,0.0,0.97973,0.0,0.00000,0.58160:
                FT3(8),0.23289,0.31490,0.0,0.0,0.97973,0.0,0.01406,0.60794:
                FT4(8),0.50185,0.49536,0.0,0.0,0.97973,0.0,0.12703,0.71428:
                FT5(8),0.57353,0.54363,0.0,0.0,0.97973,0.0,0.20867,0.77626:
                FT6(8),0.67556,0.61635,0.0,0.0,1.00000,0.0,0.95564,0.96762:
                FT7(8),0.71417,0.64106,0.0,0.0,1.00000,0.0,0.95564,0.97933:
                FT8(8),0.79713,0.70023,0.0,0.0,1.00000,0.0,1.00000,0.99170:
                FT9(8),1.00000,1.00000,0.0,0.0,1.00000,0.0,1.00000,1.00000:
                MP1,1.0:MP2,0.5:MP3,1.0:
                FMin,23040.0:FMode,44640.0:FMax,244800.0:
                SMin,5760.0:SMode,43200.0:SMax,283680.0:
                Alloy:FinalThick:MecPerform:RemProTime:NPro:ProcessTime:
                NumOprSeq(3,9),11,10,9,0,8,8,0,8,8,0,7,7,0,7,7,0,6,7,0,6,6,0,6,6,0,5,5:
                FoilDemQue:SheetDemQue:CastStock:CoilStock:FoilStock:NumStock,1:
                AmountTotal:AmountFin:NCoilFoil:NCoilSheet:
                CoilWeight,1000.0:NCoil:Num:NumAlloy,8:Weight:
```

```
                CastDemand(8):CastDemandT:WaitOrder(8):WaitOrderT:
                CastTotal,640000.0:Cast(8):MaxCast,800000.0:CL,1.0:
                CastType:CastAmount(8):CastNo(2):NCast:
                AveCast(8,2),348000,12000,0.0,0.0,21000,0.0,161000,98000,
                        288000,10000,71000,9000,31000,20000,131000,80000:
                NumRollQue:NumMillOpr:density,0.00271:NCoilMill(2):Length:
                ExpThickness(8,8),0.55,0.36,0.22,0.13,0.08,0.05,0.03,0.02,
                                  0.55,0.36,0.22,0.13,0.08,0.05,0.03,0.02,
                                  0.55,0.36,0.22,0.13,0.08,0.05,0.03,0.02,
                                  0.55,0.36,0.22,0.13,0.08,0.05,0.03,0.02,
                                  0.55,0.36,0.22,0.13,0.08,0.05,0.03,0.02,
                                  0.55,0.36,0.22,0.13,0.08,0.05,0.03,0.02,
                                  0.55,0.36,0.22,0.13,0.08,0.05,0.03,0.02,
                                  0.60,0.42,0.25,0.15,0.09,0.05,0.03,0.02:
                Thickness:MillThickness:ThickRange:MillThickRange:
                ThickCri(8),0.03,0.03,0.03,0.03,0.03,0.03,0.03,0.04:
                Width(3),132.0,120.0,110.0:
                NextPro:NumAnnQue:FurnaceNo:NumCoil:NAnnCoil:
                NCoilAnn(2):AlloyType:AnnCap,40:AvgCoil,3:
                AnnealTime(8),720,720,720,720,720,720,720,840:
                SearchType(8,8),1,1,1,1,0,0,0,0,
                                2,2,2,2,0,0,0,0,
                                3,3,3,3,0,0,0,0,
                                4,4,4,4,0,0,0,0,
                                0,0,0,0,5,5,5,0,
                                0,0,0,0,6,6,6,0,
                                0,0,0,0,7,7,7,7,
                                0,0,0,0,0,0,8,8:
                FoilDemAmount:FoilFinAmount:SheetDemAmount:SheetFinAmount:
                FC,2:NumCaster,1:SeqRuleDem,1:SeqRuleMill,1:SeqRuleAnn,1;

EXPRESSIONS:    FoilImp,DISCRETE(F1,3,F2,4,F3,5,F4,6):
                SheetImp,DISCRETE(L1,1,L2,2,L3,5,L4,8):
                FoilIntArr,EXPO(M1):
                SheetIntArr,EXPO(M2):
                FoilAmount,EXPO(W1):
                SheetAmount,EXPO(W2):
                AlloyFoil,DISCRETE(PF1,1,PF2,3,PF3,4,PF4,5,PF5,6):
                AlloySheet,DISCRETE(PL1,1,PL2,2,PL3,5,PL4,7,PL5,8):
                FoilThick,DISCRETE(FTF,1):
                SheetThick,DISCRETE(FT1(Alloy),1,FT2(Alloy),2,FT3(Alloy),3,
                FT4(Alloy),4,FT5(Alloy),5,FT6(Alloy),6,FT7(Alloy),7,FT8(Alloy),8,FT9(Alloy),9):
                FoilMecPerform,DISCRETE(MP1,1):
                SheetMecPerform,DISCRETE(MP2,2,MP3,3):
                FoilDueDate,TRIA(FMin,FMode,FMax):
                SheetDueDate,TRIA(SMin,SMode,SMax):
                MFSetupTime(2),NORM(330.1065,4.572*SQRT(16.51)),
                               NORM(330.0454,5.0847*SQRT(14.9697)):
                SetupTime(8,2),NORM(541.426,8.8491*SQRT(17.5)),
                               NORM(559.1373,13.818*SQRT(17.02)),
                               0.0,0.0,
                               NORM(586.873,8.0265*SQRT(17)),
                               0.0,
                               NORM(561.0393,20.656*SQRT(16.96)),
                               NORM(590.013,13.8707*SQRT(16.68)),
                          NORM(539.6023,8.7985*SQRT(15.9596)),
                          NORM(549.3546,22.479*SQRT(15.0101)),
                          NORM(549.9463,29.3878*SQRT(15.0101)),
                          NORM(346.2038,63.1492*SQRT(15)),
                          NORM(802.3909,62.4650*SQRT(15)),
                          NORM(636.8133,24.1434*SQRT(15)),
                          NORM(673.8173,28.7435*SQRT(15)),
                          NORM(583.4882,14.784*SQRT(15)):
                CastTime(8,2),NORM(36.1318,0.1899*SQRT(17.03)),
                              NORM(39.3623,0.2653*SQRT(17)),
                              0.0,0.0,
                              NORM(45.1833,0.2688*SQRT(16.97)),
                              0.0,
                              NORM(41.5674,0.2668*SQRT(16.69)),
                              NORM(48.64,0.4957*SQRT(16.51)),
                          NORM(36.2349,0.1121*SQRT(15.0101)),
                          NORM(39.4708,0.3882*SQRT(15.0101)),
                          NORM(38.7108,0.217*SQRT(15)),
                          NORM(39.4578,0.2785*SQRT(15)),
```

```
                    NORM(44.998,0.3272*SQRT(15)),
                    NORM(45.2791,0.3925*SQRT(15)),
                    NORM(41.552,0.256*SQRT(15)),
                    NORM(48.6711,0.5692*SQRT(14.9697)):
                Cooling(3),2880,UNIF(90,120),2880:
                CastCooling,Cooling(1):
                MillRate(8,4),UNIF(4000,8000),UNIF(4000,8000),UNIF(4000,8000),UNIF(4000,8000),
                      UNIF(4000,8000),UNIF(4000,8000),UNIF(4000,8000),UNIF(1000,4000),
                      UNIF(8000,12000),UNIF(8000,12000),UNIF(8000,12000),UNIF(8000,12000),
                      UNIF(8000,11000),UNIF(8000,11000),UNIF(8000,11000),UNIF(8000,10000),
                      UNIF(30000,36000),UNIF(30000,36000),UNIF(30000,36000),UNIF(30000,36000),
                      UNIF(30000,34000),UNIF(30000,34000), UNIF(30000,34000),UNIF(27000,30000),
                      UNIF(30000,34000),UNIF(30000,34000),UNIF(30000,34000),UNIF(30000,34000),
                      UNIF(27000,32000),UNIF(27000,32000),UNIF(27000,32000),UNIF(24000,27000):
                ExpMillRate(8,4),6000,6000,6000,6000,6000,6000,6000,2500,10000,10000,10000,10000,
                        9500,9500,9500,9000,33000,33000,33000,33000,32000,32000,32000,28500,
                        32000,32000,32000,32000,29500,29500,29500,25500:
                RollRatio(8),UNIF(0.35,0.50),UNIF(0.35,0.50),UNIF(0.35,0.50),
                     UNIF(0.35,0.50),UNIF(0.35,0.45),UNIF(0.35,0.45),UNIF(0.35,0.45),UNIF(0.35,0.40):
                Transfer,0.0:
                LoadingMill,NORM(0.635,0.184):
                ExpLoadingMill,0.635:
                CoilSetting,NORM(1.533,.605):
                ExpCoilSetting,1.533:
                PreRun(2),NORM(0.772,0.284),NORM(1.899,0.476):
                ExpPreRun(2),0.772,1.899:
                SampleTaking,NORM(0.943,0.457):
                ExpSampleTaking,0.943:
                CoilRemoving,NORM(0.852,0.295):
                ExpCoilRemoving,0.852:
                RollCooling,Cooling(2):
                SetupFurnace,UNIF(7.5,12.5):
                ExpSetupFurnace,10.0:
                AnnCoilRemove,UNIF(7.5,12.5):
                ExpAnnCoilRemove,10.0:
                Anneal,AnnealTime(AINT(NS/100)):
                MaxAnnCap,AnnCap+AvgCoil:
                AnnCooling,Cooling(3);

QUEUES:         FoilDemQue1,LVF(Priority):FoilDemQue2,LVF(Priority):
                FoilDemQue3,LVF(Priority):FoilDemQue4,LVF(Priority):
                FoilDemQue5,LVF(Priority):FoilDemQue6,LVF(Priority):
                FoilDemQue7,LVF(Priority):FoilDemQue8,LVF(Priority):
                SheetDemQue1,LVF(Priority):SheetDemQue2,LVF(Priority):
                SheetDemQue3,LVF(Priority):SheetDemQue4,LVF(Priority):
                SheetDemQue5,LVF(Priority):SheetDemQue6,LVF(Priority):
                SheetDemQue7,LVF(Priority):SheetDemQue8,LVF(Priority):
                CastStock1:CastStock2:CastStock3:CastStock4:CastStock5:CastStock6:CastStock7:CastStock8:
                CoilStock1:CoilStock2:CoilStock3:CoilStock4:CoilStock5:CoilStock6:CoilStock7:CoilStock8:
                FoilStock1:FoilStock2:FoilStock3:FoilStock4:FoilStock5:FoilStock6:FoilStock7:FoilStock8:
                IntQue1:IntQue2:CastBuffer:RollBuffer,LVF(Priority):AnnealBuffer,LVF(Priority):AnnInt;

STATIONS:       ConCasting:
                ColdMill:
                AnnealFur:
                FinishFoil:
                FinishSheet;

STATESETS:      CasterStates,MFSetup,Setup,Casting(BUSY),IDLE:
                MillStates,Loading,Setup,Milling(BUSY),IDLE:
                FurnaceStates,Loading,Annealing(BUSY),Unloading,IDLE;

RESOURCES:      REPEAT(Caster,2),CAPACITY(1),CasterStates:
                REPEAT(Mill,2),CAPACITY(1),MillStates:
                REPEAT(Furnace,2),CAPACITY(1),FurnaceStates;

SETS:     Caster,Caster1:
          Mill,Mill1:
          Furnace,Furnace1;

FREQUENCIES:    STATE(Caster1):
                STATE(Caster2):
                STATE(Mill1):
```

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        STATE(Mill2):
        STATE(Furnace1):
        STATE(Furnace2):
        NQ(FoilDemQue1),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(FoilDemQue3),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(FoilDemQue4),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(FoilDemQue5),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(FoilDemQue6),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        FoilDemQue,,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(SheetDemQue1),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(SheetDemQue2),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(SheetDemQue5),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(SheetDemQue7),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(SheetDemQue8),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                   RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        SheetDemQue,,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(CastStock1),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                 RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(CastStock2),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                 RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(CastStock3),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                 RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(CastStock4),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                 RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(CastStock5),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                 RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(CastStock6),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                 RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(CastStock7),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                 RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(CastStock8),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                 RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        CastStock,,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
              RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        CoilStock,,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
              RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        FoilStock,,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
              RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(RollBuffer),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                 RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100):
        NQ(AnnealBuffer),,,,0 & RANGE(0,2) & RANGE(2,5) & RANGE(5,10) &
                  RANGE(10,15) & RANGE(15,25) & RANGE(25,50) & RANGE(50,100);

SEQUENCES:  111,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill
              ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & AnnealFur & FinishFoil:
            112,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill &
              ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
            113,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
              AnnealFur & ColdMill & ColdMill & ColdMill & FinishSheet:
            122,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
              ColdMill & AnnealFur & ColdMill & FinishSheet:
            123,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
              ColdMill & ColdMill & ColdMill & FinishSheet:
            132,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
              ColdMill & AnnealFur & ColdMill & FinishSheet:
            133,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
              AnnealFur & ColdMill & ColdMill & FinishSheet:
            142,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &AnnealFur & ColdMill & FinishSheet:
            143,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
              ColdMill & ColdMill & FinishSheet:
            152,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
              AnnealFur & ColdMill & FinishSheet:
            153,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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ColdMill & ColdMill & FinishSheet:
162,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
163,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
ColdMill & ColdMill & FinishSheet:
172,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
173,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet:
182,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
183,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet:
192,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
193,,ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet:
212,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill &
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213,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
AnnealFur & ColdMill & ColdMill & ColdMill & FinishSheet:
222,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
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223,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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232,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
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233,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
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242,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
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243,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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252,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
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253,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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262,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
263,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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272,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
273,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet:
282,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
283,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet:
292,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
293,,ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet:
311,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill &
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411,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill &
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511,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill &
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512,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill &
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513,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
AnnealFur & ColdMill & ColdMill & ColdMill & FinishSheet:
562,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
563,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
ColdMill & ColdMill & FinishSheet:
611,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill &
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732,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
ColdMill & AnnealFur & ColdMill & FinishSheet:
733,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
AnnealFur & ColdMill & ColdMill & FinishSheet:
742,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &AnnealFur & ColdMill & FinishSheet:
743,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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752,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
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753,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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762,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
763,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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782,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
783,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet:
812,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill &
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813,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
AnnealFur & ColdMill & ColdMill & ColdMill & FinishSheet:

822,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
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823,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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832,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
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833,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
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842,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &AnnealFur & ColdMill & FinishSheet:
843,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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852,,ColdMill & ColdMill & ColdMill & ColdMill & ColdMill &
AnnealFur & ColdMill & FinishSheet:
853,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
ColdMill & ColdMill & FinishSheet:
862,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
863,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur &
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872,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
873,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet:
882,,ColdMill & ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
883,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet:
892,,ColdMill & ColdMill & ColdMill & AnnealFur & ColdMill & FinishSheet:
893,,ColdMill & ColdMill & AnnealFur & ColdMill & ColdMill & FinishSheet;

TALLIES:

FoilDemand1:FoilDemand2:FoilDemand3:FoilDemand4:
FoilDemand5:FoilDemand6:FoilDemand7:FoilDemand8:
FoilAmount1:FoilAmount2:FoilAmount3:FoilAmount4:
FoilAmount5:FoilAmount6:FoilAmount7:FoilAmount8:
FoilSat1:FoilSat2:FoilSat3:FoilSat4:FoilSat5:FoilSat6:FoilSat7:FoilSat8:
FoilCastDem1:FoilCastDem2:FoilCastDem3:FoilCastDem4:
FoilCastDem5:FoilCastDem6:FoilCastDem7:FoilCastDem8:
FoilDemWait1:FoilDemWait2:FoilDemWait3:FoilDemWait4:
FoilDemWait5:FoilDemWait6:FoilDemWait7:FoilDemWait8:
FoilInPro1:FoilInPro2:FoilInPro3:FoilInPro4:FoilInPro5:FoilInPro6:FoilInPro7:FoilInPro8:
SheetDemand1:SheetDemand2:SheetDemand3:SheetDemand4:
SheetDemand5:SheetDemand6:SheetDemand7:SheetDemand8:
SheetAmount1:SheetAmount2:SheetAmount3:SheetAmount4:
SheetAmount5:SheetAmount6:SheetAmount7:SheetAmount8:
SheetSat1:SheetSat2:SheetSat3:SheetSat4:SheetSat5:SheetSat6:SheetSat7:SheetSat8:
SheetCastDem1:SheetCastDem2:SheetCastDem3:SheetCastDem4:
SheetCastDem5:SheetCastDem6:SheetCastDem7:SheetCastDem8:
SheetDemWait1:SheetDemWait2:SheetDemWait3:SheetDemWait4:
SheetDemWait5:SheetDemWait6:SheetDemWait7:SheetDemWait8:
SheetInPro1:SheetInPro2:SheetInPro3:SheetInPro4:SheetInPro5:SheetInPro6:SheetInPro7:SheetInPro8:
FoilStWait1:FoilStWait2:FoilStWait3:FoilStWait4:FoilStWait5:FoilStWait6:FoilStWait7:FoilStWait8:
FoilStAmount1:FoilStAmount2:FoilStAmount3:FoilStAmount4:
FoilStAmount5:FoilStAmount6:FoilStAmount7:FoilStAmount8:
CoilStockWait1:CoilStockWait2:CoilStockWait3:CoilStockWait4:
CoilStockWait5:CoilStockWait6:CoilStockWait7:CoilStockWait8:
CoilStAmount1:CoilStAmount2:CoilStAmount3:CoilStAmount4:
CoilStAmount5:CoilStAmount6:CoilStAmount7:CoilStAmount8:
CastStWait1:CastStWait2:CastStWait3:CastStWait4:
CastStWait5:CastStWait6:CastStWait7:CastStWait8:
CastStAmount1:CastStAmount2:CastStAmount3:CastStAmount4:
CastStAmount5:CastStAmount6:CastStAmount7:CastStAmount8:
IntQue1Wait1:IntQue1Wait2:IntQue1Wait3:IntQue1Wait4:
IntQue1Wait5:IntQue1Wait6:IntQue1Wait7:IntQue1Wait8:
IntQue2Wait1:IntQue2Wait2:IntQue2Wait3:IntQue2Wait4:
IntQue2Wait5:IntQue2Wait6:IntQue2Wait7:IntQue2Wait8:
SetupTime1:SetupTime2:SetupTime3:SetupTime4:SetupTime5:SetupTime6:SetupTime7:SetupTime8:
CastTime1:CastTime2:CastTime3:CastTime4:CastTime5:CastTime6:CastTime7:CastTime8:
Cast1:Cast2:Cast3:Cast4:Cast5:Cast6:Cast7:Cast8:
RollTimeCoil1:RollTimeCoil2:RollTimeCoil3:RollTimeCoil4:
RollTimeCoil5:RollTimeCoil6:RollTimeCoil7:RollTimeCoil8:
RollTime1:RollTime2:RollTime3:RollTime4:RollTime5:RollTime6:RollTime7:RollTime8:
RollAmount1:RollAmount2:RollAmount3:RollAmount4:
RollAmount5:RollAmount6:RollAmount7:RollAmount8:
RollEndAmount1:RollEndAmount2:RollEndAmount3:RollEndAmount4:
RollEndAmount5:RollEndAmount6:RollEndAmount7:RollEndAmount8:
AnnTime1:AnnTime2:AnnTime3:AnnTime4:AnnTime5:AnnTime6:AnnTime7:AnnTime8:
AnnAmount1:AnnAmount2:AnnAmount3:AnnAmount4:
AnnAmount5:AnnAmount6:AnnAmount7:AnnAmount8:
AnnCount1:AnnCount2:AnnCount3:AnnCount4:AnnCount5:AnnCount6:AnnCount7:AnnCount8:

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                FoilDemandFin1:FoilDemandFin2:FoilDemandFin3:FoilDemandFin4:
                FoilDemandFin5:FoilDemandFin6:FoilDemandFin7:FoilDemandFin8:
                FoilScrap1:FoilScrap2:FoilScrap3:FoilScrap4:FoilScrap5:FoilScrap6:FoilScrap7:FoilScrap8:
                FoilTimeInPro1:FoilTimeInPro2:FoilTimeInPro3:FoilTimeInPro4:
                FoilTimeInPro5:FoilTimeInPro6:FoilTimeInPro7:FoilTimeInPro8:
                FoilSlack1:FoilSlack2:FoilSlack3:FoilSlack4:FoilSlack5:FoilSlack6:FoilSlack7:FoilSlack8:
                FoilTardyAmount1:FoilTardyAmount2:FoilTardyAmount3:FoilTardyAmount4:
                FoilTardyAmount5:FoilTardyAmount6:FoilTardyAmount7:FoilTardyAmount8:
                FoilTardyTime1:FoilTardyTime2:FoilTardyTime3:FoilTardyTime4:
                FoilTardyTime5:FoilTardyTime6:FoilTardyTime7:FoilTardyTime8:
                SheetDemandFin1:SheetDemandFin2:SheetDemandFin3:SheetDemandFin4:
                SheetDemandFin5:SheetDemandFin6:SheetDemandFin7:SheetDemandFin8:
                SheetScrap1:SheetScrap2:SheetScrap3:SheetScrap4:
                SheetScrap5:SheetScrap6:SheetScrap7:SheetScrap8:
                SheetTimeInPro1:SheetTimeInPro2:SheetTimeInPro3:SheetTimeInPro4:
                SheetTimeInPro5:SheetTimeInPro6:SheetTimeInPro7:SheetTimeInPro8:
                SheetSlack1:SheetSlack2:SheetSlack3:SheetSlack4:
                SheetSlack5:SheetSlack6:SheetSlack7:SheetSlack8:
                SheetTardyAmount1:SheetTardyAmount2:SheetTardyAmount3:SheetTardyAmount4:
                SheetTardyAmount5:SheetTardyAmount6:SheetTardyAmount7:SheetTardyAmount8:
                SheetTardyTime1:SheetTardyTime2:SheetTardyTime3:SheetTardyTime4:
                SheetTardyTime5:SheetTardyTime6:SheetTardyTime7:SheetTardyTime8:
                RollFinThick1:RollFinThick2:RollFinThick3:RollFinThick4:
                RollFinThick5:RollFinThick6:RollFinThick7:RollFinThick8:RollFinThick9:
                SheetFinThick1:SheetFinThick2:SheetFinThick3:SheetFinThick4:
                SheetFinThick5:SheetFinThick6:SheetFinThick7:SheetFinThick8:SheetFinThick9:
                FoilAmountDem:FoilDemWait:SheetAmountDem:SheetDemWait:CastStWait:
                RollTimeCoil:RollTime:RollAmount:RollEndAmount:
                AnnTime:AnnAmount:AnnCount:
                FoilDemFin:FoilFinRatio:FoilScrap:FoilTimeInPro:FoilSlack:
                FoilTardyAmount:FoilTardyTime:
                SheetDemFin:SheetFinRatio:SheetScrap:SheetTimeInPro:SheetSlack:
                SheetTardyAmount:SheetTardyTime;

DSTATS:         NQ(FoilDemQue1):NQ(FoilDemQue2):NQ(FoilDemQue3):NQ(FoilDemQue4):
                NQ(FoilDemQue5):NQ(FoilDemQue6):NQ(FoilDemQue7):NQ(FoilDemQue8):
                NQ(SheetDemQue1):NQ(SheetDemQue2):NQ(SheetDemQue3):NQ(SheetDemQue4):
                NQ(SheetDemQue5):NQ(SheetDemQue6):NQ(SheetDemQue7):NQ(SheetDemQue8):
                NQ(CastStock1):NQ(CastStock2):NQ(CastStock3):NQ(CastStock4):
                NQ(CastStock5):NQ(CastStock6):NQ(CastStock7):NQ(CastStock8):
                NQ(CoilStock1):NQ(CoilStock2):NQ(CoilStock3):NQ(CoilStock4):
                NQ(CoilStock5):NQ(CoilStock6):NQ(CoilStock7):NQ(CoilStock8):
                NQ(FoilStock1):NQ(FoilStock2):NQ(FoilStock3):NQ(FoilStock4):
                NQ(FoilStock5):NQ(FoilStock6):NQ(FoilStock7):NQ(FoilStock8):
                FoilDemQue,FoilDemandQue:
                SheetDemQue,SheetDemandQue:
                CastStock,CastStockQue:
                CoilStock,CoilStockQue:
                FoilStock,FoilStockQue:
                NQ(IntQue1):NQ(IntQue2):NQ(CastBuffer):
                NQ(RollBuffer),RollBufferQue:
                NumRollQue,NumMillQue:
                NQ(AnnealBuffer),AnnealBufferQue:
                NumAnnQue,NumAnnealQue:NQ(AnnInt):
                Cast(1):Cast(2):Cast(3):Cast(4):Cast(5):Cast(6):Cast(7):Cast(8):
                CastDemand(1):CastDemand(2):CastDemand(3):CastDemand(4):
                CastDemand(5):CastDemand(6):CastDemand(7):CastDemand(8):
                WaitOrder(1):WaitOrder(2):WaitOrder(3):WaitOrder(4):
                WaitOrder(5):WaitOrder(6):WaitOrder(7):WaitOrder(8):
                CastTotal,CastT:
                CastDemandT,CastDemandTotal:
                WaitOrderT,WaitOrderTotal:
                NR(Caster1):
                NR(Caster2):
                NR(Mill1),Mill1Uti:
                NR(Mill2),Mill2Uti:
                NR(Furnace1),Furnace1Uti:
                NR(Furnace2),Furnace2Uti:
                NCoilAnn(1)/MaxAnnCap,Furnace1AvgLoad:
                NCoilAnn(2)/MaxAnnCap,Furnace2AvgLoad;

OUTPUTS:        TAVG(FoilAmountDem)*TNUM(FoilAmountDem),,FoilAmountDem:
                TAVG(FoilDemWait),,FoilDemWait:
                TAVG(SheetAmountDem)*TNUM(SheetAmountDem),,SheetAmountDem:
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                    TAVG(SheetDemWait),,SheetDemWait:
                    TAVG(CastStWait),,CastStWait:
                    TAVG(RollTimeCoil),,RollTimeCoil:
                    TAVG(RollTime),,RollTime:
                    TAVG(RollAmount)*TNUM(RollAmount)*1000,,RollAmount:
                    TAVG(RollEndAmount)*TNUM(RollEndAmount)*1000,,RollEndAmount:
                    TAVG(AnnTime),,AnnTime:
                    TAVG(AnnAmount)*TNUM(AnnAmount)*1000,,AnnAmount:
                    TNUM(AnnCount),,AnnCount:
                    TAVG(FoilDemFin)*TNUM(FoilDemFin),,FoilDemFin:
                    TAVG(FoilFinRatio),,FoilFinRatio:
                    TAVG(FoilTimeInPro),,FoilTimeInPro:
                    TAVG(FoilSlack),,FoilSlack:
                    TAVG(FoilTardyAmount),,FoilTardyAmount:
                    TAVG(FoilTardyTime),,FoilTardyTime:
                    TAVG(SheetDemFin)*TNUM(SheetDemFin),,SheetDemFin:
                    TAVG(SheetFinRatio),,SheetFinRatio:
                    TAVG(SheetTimeInPro),,SheetTimeInPro:
                    TAVG(SheetSlack),,SheetSlack:
                    TAVG(SheetTardyAmount),,SheetTardyAmount:
                    TAVG(SheetTardyTime),,SheetTardyTime:
                    DAVG(FoilDemandQue),,FoilDemQue:
                    DAVG(SheetDemandQue),,SheetDemQue:
                    DAVG(CastStockQue),,CastStock:
                    DAVG(CoilStockQue),,CoilStock:
                    DAVG(FoilStockQue),,FoilStock:
                    DAVG(CastT),,CastTotal:
                    DAVG(CastDemandTotal),,CastDemandT:
                    DAVG(WaitOrderTotal),,WaitOrderT:
                    DAVG(RollBufferQue),,RollBuffer:
                    DAVG(NumMillQue),,NumMillQue:
                    DAVG(AnnealBufferQue),,AnnealBuffer:
                    DAVG(NumAnnealQue),,NumAnnealQue:
                    DAVG(Mill1Uti),,MillUti1:
                    DAVG(Mill2Uti),,MillUti2:
                    DAVG(Furnace1Uti),,FurnaceUti1:
                    DAVG(Furnace2Uti),,FurnaceUti2:
                    DAVG(Furnace1AvgLoad),,FurnaceAvgLoad1:
                    DAVG(Furnace2AvgLoad),,FurnaceAvgLoad2;

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END;
```

APPENDIX E

EXAMPLE ANOVA TABLES AND PLOTS OF RESIDUAL ANALYSIS

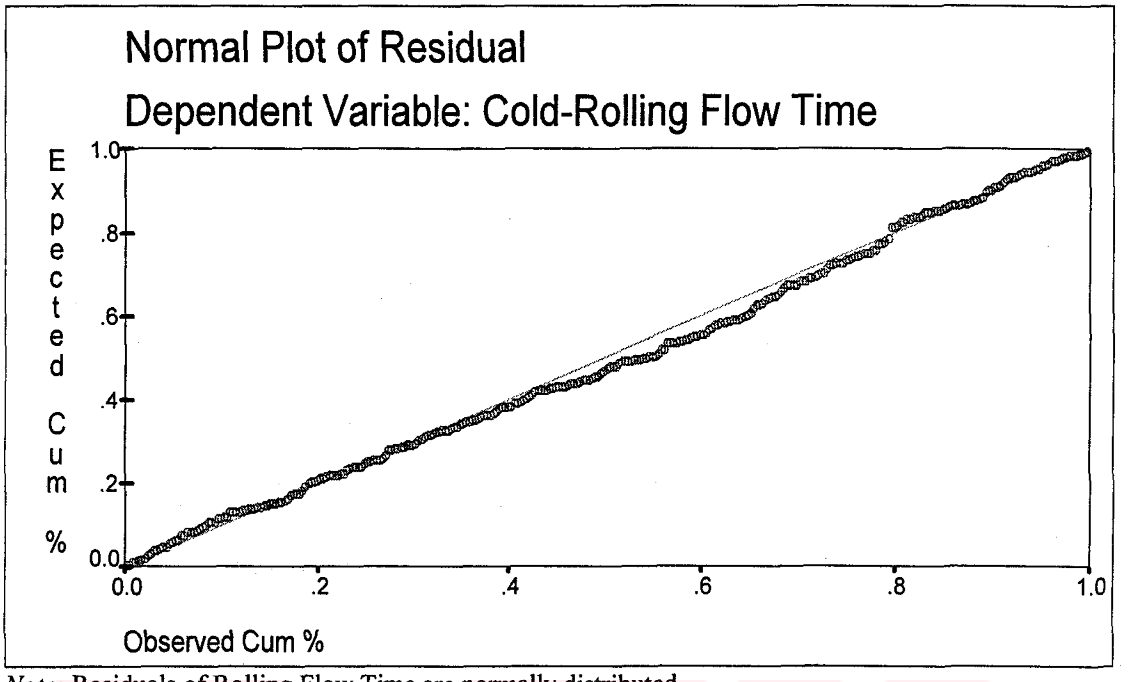
In Appendix E, examples of ANOVA Tables and Plots of Residual Analysis for capacity alternative **BCMA** are given.

Table E.1. ANOVA Table for Cold-Rolling Flow Time

SUMMARY	*Count*	*Sum*	*Average*	*Variance*		
FIFO	40	1494.82	37.37049	1.289356		
EDD	40	1410.1	35.25251	1.482269		
SPT	40	1298.594	32.46485	0.906461		
SRNO	40	1533.222	38.33054	1.548876		
MST	40	1392.496	34.8124	0.925729		
CR	40	1409.72	35.243	1.2438		
HYBRID	40	1481.62	37.04049	1.179674		
USER	40	1408.535	35.21338	1.033279		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Random # Stream	38.9995	39	0.999987	0.813049	0.779453	1.443928
Sequencing Rule	936.2031	7	133.7433	108.7412	3.5E-75	2.043205
Error	335.7688	273	1.229923			
Total	1310.971	319				$R^2 = 0.744$

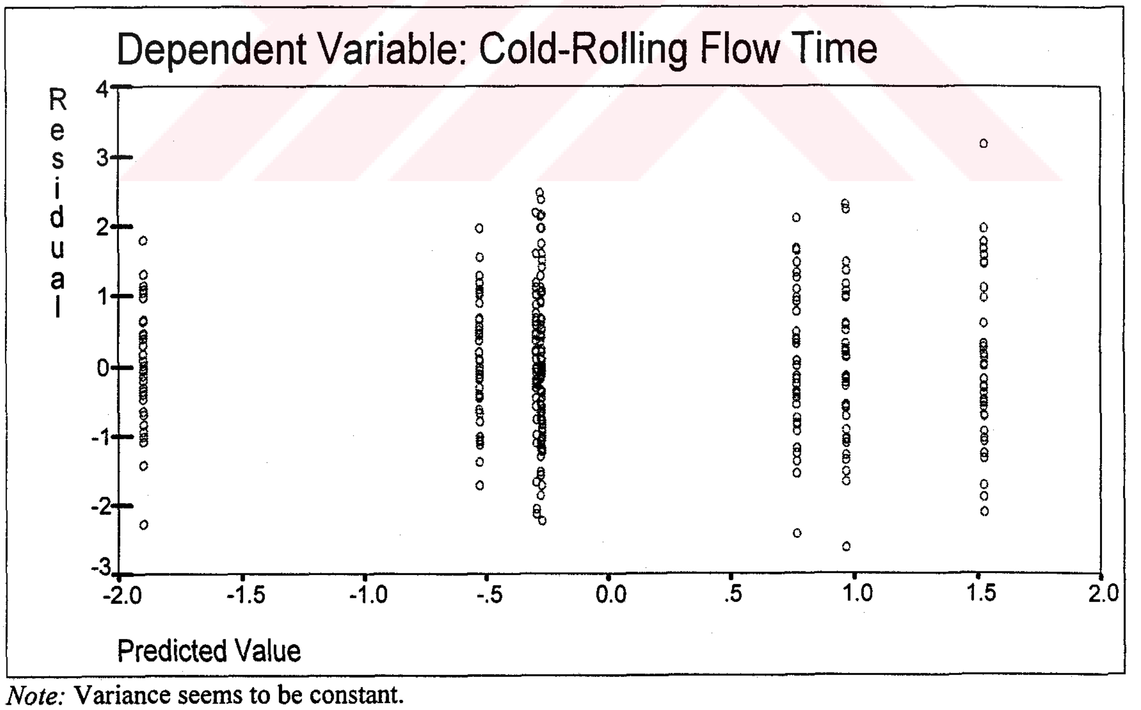
Note: Sequencing rules are significantly different.

Figure E.1. Normal Probability Plot of Residuals for Cold-Rolling Flow Time



Note: Residuals of Rolling Flow Time are normally distributed.

Figure E.2. Plot of Residuals vs. Predicted Values of Cold-Rolling Flow Time



Note: Variance seems to be constant.

Table E.1. ANOVA Table for Foil Order Flow Time

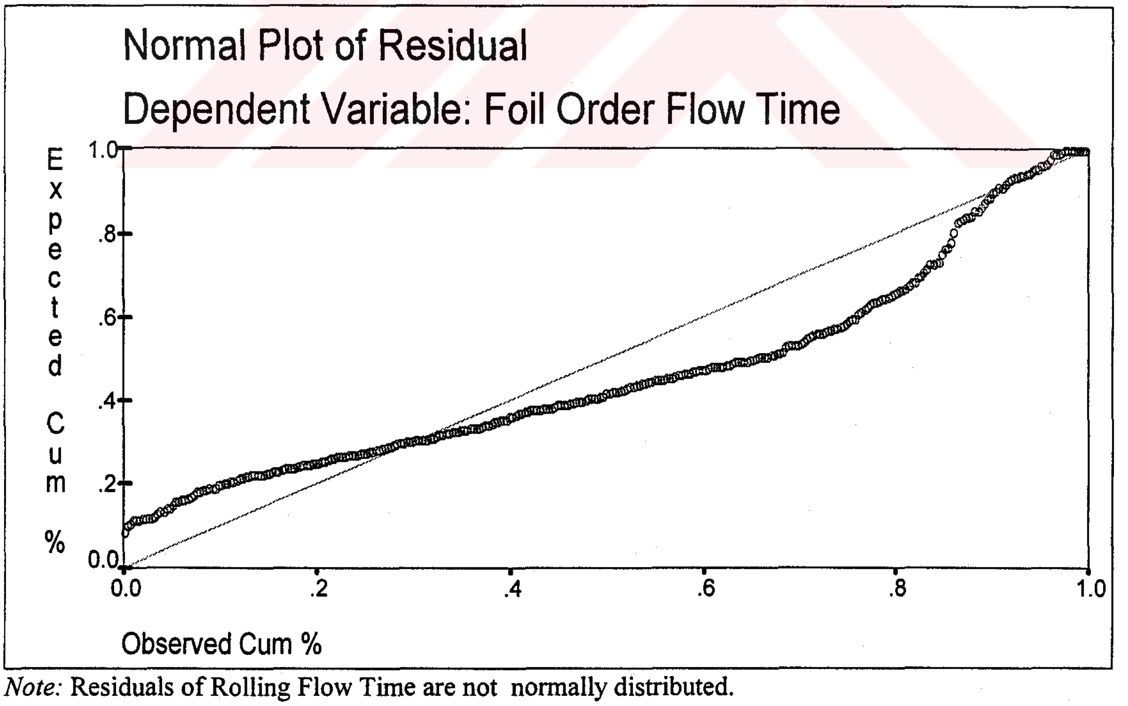
SUMMARY	*Count*	*Sum*	*Average*	*Variance*
FIFO	40	544295.9	13607.4	21830.83
EDD	40	541952.1	13548.8	9950.187
SPT	40	544057	13601.42	8067.755
SRNO	40	543521	13588.02	6245.538
MST	40	542636.5	13565.91	23711.44
CR	40	542911	13572.78	8283.982
HYBRID	40	543234.6	13580.87	7745.962
USER	40	540660.9	13516.52	2952.2

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Random # Stream	263107.4	39	6746.343	0.575616	0.980469	1.443928
Scheduling Rule	244143.1	7	34877.59	2.975847	0.005041	2.043205
Error	3199620	272	11720.22			
Total	3706871	318				$R^2 = 0.137$

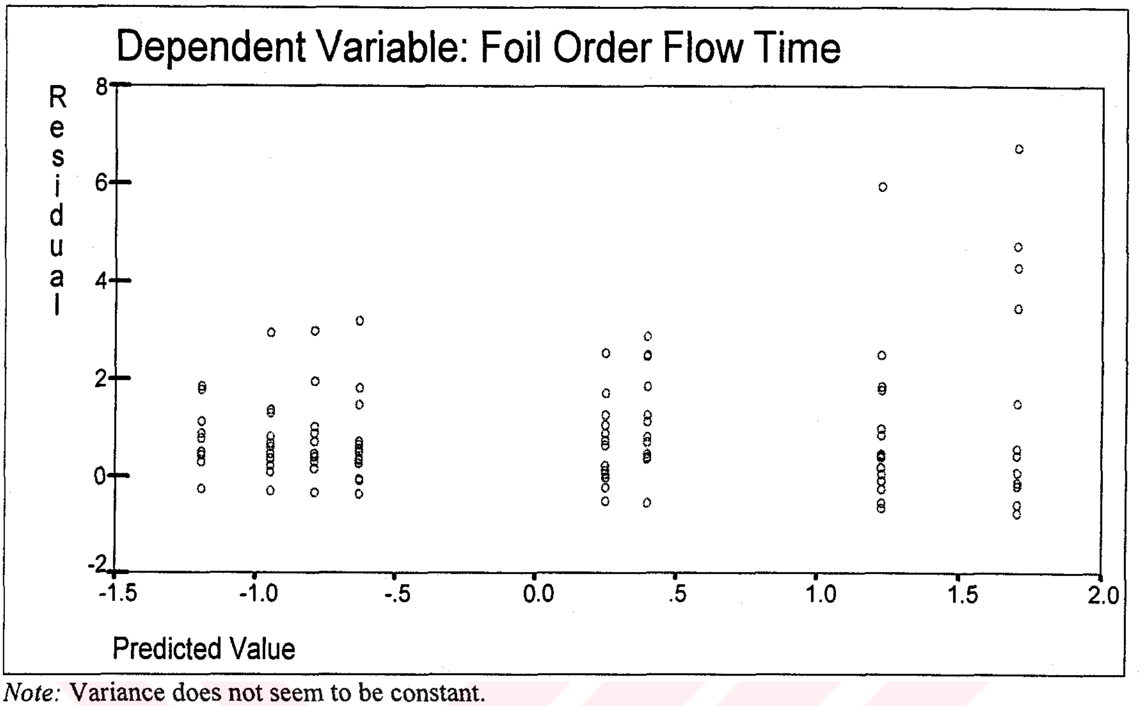
Note: ANOVA has been applied to transformed data.
Sequencing rules are significantly different.

Figure E.3. Normal Probability Plot of Residuals for Foil Order Flow Time



Note: Residuals of Rolling Flow Time are not normally distributed.

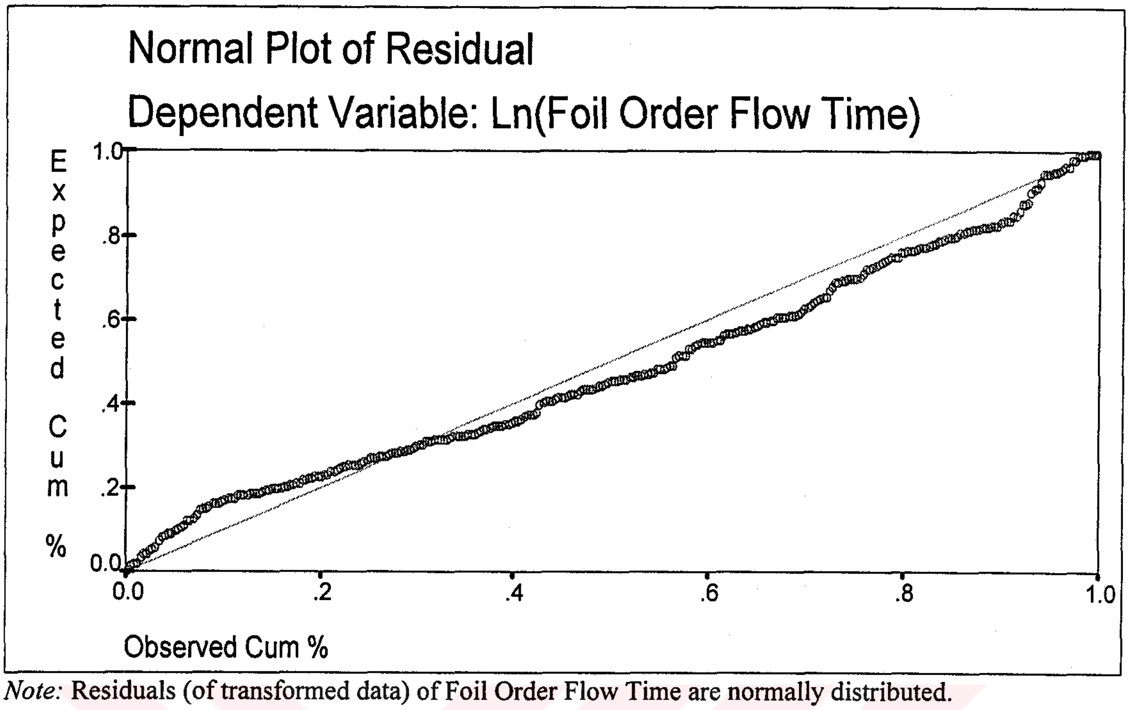
Figure E.4. Plot of Residuals vs. Predicted Values of Foil Order Flow Time



Note: Variance does not seem to be constant.

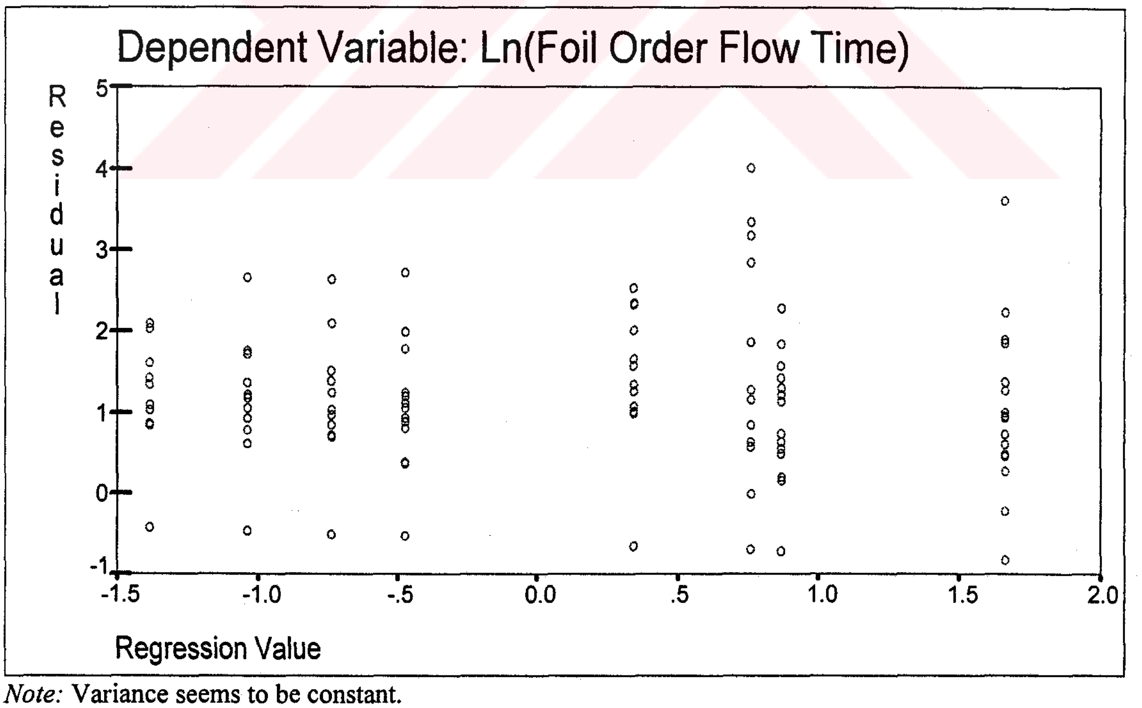
Since assumptions of normality and constant variance of residuals are not satisfied (Tables E.3 and E.4), variance-stabilizing transformation applied to the data.

Figure E.5. Normal Probability Plot of Residuals for Foil Order Flow Time



Note: Residuals (of transformed data) of Foil Order Flow Time are normally distributed.

Figure E.6. Plot of Residuals vs. Predicted Values of Foil Order Flow Time



Note: Variance seems to be constant.

APPENDIX F

Table F.1. Results for Capacity Expansion Alternative **S**

Capacity Alternative **S**	Only Sheet			1 caster, 1 cold-mill, 1 annealing furnace						Avg.	Trans.	Sig.
Performance Measures	*Sequencing Rules*										Used	
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER			
Foil Order Waiting Time												
(min/order)												
Sheet Order Waiting Time	52372	51379	51260	38815	32328	20813	20748	52372	52485	42530	Ln	**
(min/order)	6322.8	6295.9	6149.0	3845.3	3949.1	3168.7	2309.3	6322.8	6600.4			
Cast Coil Waiting Time	975.7	889.2	1075.7	820.1	673.6	671.6	647.7	975.7	906.0	870.2	1/Sqrt	**
(min/order)	274.6	446.4	343.9	426.0	206.4	343.0	225.5	274.6	504.0			
Cold-Rolling Flow Time	42.8	44.3	36.7	40.1	42.4	42.1	41.8	42.8	44.2	41.9	-	**
(min/order)	0.98	1.32	1.05	1.24	1.05	1.04	0.93	0.98	1.06			
Annealing Flow Time	1219.5	1324.5	1231.5	1222.8	1638.8	1312.0	1319.0	1219.5	1333.4	1272.8	Ln	**
(min/order)	27.58	38.47	38.35	38.18	69.55	35.55	32.95	27.58	51.35			
Foil Order Flow Time												
(min/order)												
Sheet Order Flow Time	57334	56176	56252	43696	37604	25903	25940	57334	57324	47495	Ln	**
(min/order)	6325.1	6369.3	6146.7	3873.3	4240.9	3217.6	2289.8	6325.1	6687.8			
Foil Order Queue												
(time averaged #)												
Sheet Order Queue	411.0	408.9	400.3	429.9	423.9	411.6	414.6	411.0	415.7	412.9	-	InSig.
(time averaged #)	56.4	56.9	50.6	51.4	57.5	55.9	50.4	56.4	55.1			
Cast Coil Queue	16.9	15.9	18.7	14.9	12.0	12.0	11.5	16.9	16.4	15.4	Recip.	**
(time averaged #)	5.2	8.0	6.8	8.9	3.9	5.8	4.4	5.2	9.6			
Cold-Rolling Queue	1.06	1.11	0.83	0.96	1.03	1.04	1.02	1.06	1.10	1.02	-	**
(time averaged #)	0.05	0.05	0.04	0.05	0.05	0.05	0.04	0.05	0.04			
Annealing Queue	3.00	3.67	3.09	2.98	5.85	3.61	3.64	3.00	3.72	3.34	Ln	**
(time averaged #)	0.19	0.26	0.26	0.24	0.50	0.24	0.22	0.19	0.34			
Mill 1 Utilization	51.20	51.36	51.31	48.10	48.87	51.30	51.25	51.20	51.22	50.87	-	**
(time averaged %)	0.54	0.50	0.55	0.82	0.64	0.54	0.52	0.54	0.45			
Mill 2 Utilization												
(time averaged %)												
Annealing Furnace 1 Load	42.76	42.72	42.86	41.67	42.97	42.69	42.72	42.76	42.67	42.61	-	**
(time averaged %)	0.21	0.25	0.21	0.19	0.28	0.28	0.19	0.21	0.22			
Annealing Furnace 2 Load												
(time averaged %)												
% Foil Order Satisfied												
% Sheet Order Satisfied	83.85	83.77	84.10	83.19	83.24	83.51	83.27	83.85	83.56	83.64	-	InSig.
	1.89	1.81	1.65	1.71	1.76	1.89	1.72	1.89	1.85			
Slack Time of Foil Order												
(min/order)												
Slack Time of Sheet Order	53693	49822	54700	67563	73256	69744	69896	53693	48604	58464	-	**
(min/order)	6090.1	6591.3	6436.4	3919.2	4482.7	3873.3	2759.2	6090.1	6401.8			
Number of Tardy Foil Orders												
(#/year)												
Average Tardiness of Foil Order												
(min/tardy order)												
Number of Tardy Sheet Orders	723.6	302.0	710.2	530.0	370.0	104.5	105.1	723.6	287.7	435.8	Sqrt	**
(#/year)	108.8	162.5	109.6	56.9	57.2	31.0	26.0	108.8	140.6			
Average Tardiness of Sheet Order	37867	22599	36937	71086	92839	58925	63961	37867	23643	44111	Sqrt	**
(min/tardy order)	7286.1	11542.7	6309.1	11785.3	19176.5	23904	22131.5	7286.1	10807.5			

(Avg. symbol): SRPT Rule is excluded in calculation of average values.
(Sig. symbol): SRPT Rule is excluded in ANOVA calculations.

* Significant at $\alpha = 0.05$
** Significant at $\alpha = 0.01$
! : Normality and constant variance assumptions to apply ANOVA are violated.

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

Table F.2. Duncan's Multiple Range Test Results for Capacity Expansion Alternative **S**

Capacity Alternative **S**	Ranking of Sequencing Rules According to Duncan's Test									
Performance Measures	*Sequencing Rules*									Note
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER	
Foil Order Waiting Time (min/order)										-
Sheet Order Waiting Time (min/order)	3	3	3	2		1	1	3	3	
Cast Coil Waiting Time (min/order)	3	2	3	2		1	1	3	2	
Cold-Rolling Flow Time (min/order)	4	5	1	2		3	3	4	5	
Annealing Flow Time (min/order)	1	2, 3	1	1		2	2, 3	1	3	
Foil Order Flow Time (min/order)										-
Sheet Order Flow Time (min/order)	3	3	3	2		1	1	3	3	
Foil Order Queue (time averaged #)										-
Sheet Order Queue (time averaged #)										InSig.
Cast Coil Queue (time averaged #)	3, 4	2, 3	4	2		1	1	3, 4	2, 3	
Cold-Rolling Queue (time averaged #)	4	5	1	2		3, 4	3	4	5	
Annealing Queue (time averaged #)	1, 2	3	2	1		3	3	1, 2	3	
Mill 1 Utilization (time averaged %)	1	1	1	2		1	1	1	1	
Mill 2 Utilization (time averaged %)										-
Annealing Furnace 1 Load (time averaged %)	2	2	1	3		2	2	2	2	
Annealing Furnace 2 Load (time averaged %)										-
% Foil Order Satisfied										-
% Sheet Order Satisfied										InSig.
Slack Time of Foil Order (min/order)										-
Slack Time of Sheet Order (min/order)	2	3	2	1		1	1	2	3	
Number of Tardy Foil Orders (#/year)										-
Average Tardiness of Foil Order (min/tardy order)										-
Number of Tardy Sheet Orders (#/year)	4	2	4	3		1	1	4	2	
Average Tardiness of Sheet Order (min/tardy order)	2	1	2	4		3	3	2	1	

: SRPT Rule is not included in Duncan's Test

Table F.3. Results for Capacity Expansion Alternative **B**

Capacity Alternative **B**	Both foil and sheet			1 caster, 1 cold-mill, 1 annealing furnace						Avg.	Trans.	Sig.
Performance Measures	*Sequencing Rules*										Used	
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER			
Foil Order Waiting Time	162891	158825	168752	169878	129850	29032	29899	168498	159420	130899	Sqrt	**
(min/order)	11663	13516	11898	15249	12663	4356	4851	12667	12025			
Sheet Order Waiting Time	116612	116447	109469	46956	41895	22610	22106	109219	115275	82337	Sqrt	**
(min/order)	6314.1	8344.7	7981.3	5198.9	4526.2	2916.5	2328.5	7100.2	7594.6			
Cast Coil Waiting Time	1316.3	1233.1	1273.7	1059.0	1017.0	789.4	781.8	1308.1	1202.1	1120.4	-	**
(min/order)	133.2	120.0	176.6	125.9	113.0	177.0	103.6	113.8	140.1			
Cold-Rolling Flow Time	113.1	96.6	79.1	91.9	109.6	94.0	96.5	113.4	96.3	97.6	-	**
(min/order)	5.73	7.10	3.39	6.24	5.94	4.37	4.22	5.33	6.93			
Annealing Flow Time	1432.4	1868.9	1409.3	1915.7	4372.0	1690.4	1703.3	1405.0	1871.2	1662.0	1/Sqrt	**
(min/order)	19.4	229.9	16.7	94.1	962.0	50.7	49.4	20.7	220.4		!	
Foil Order Flow Time	169238	165519	173816	175552	138612	44811	45671	173962	165292	139232	Ln	**
(min/order)	11754	13471	11885	16414	12591	3997	4421	12781	11868			
Sheet Order Flow Time	120445	120634	113401	52261	49977	28317	27981	112990	119401	86929	Ln	**
(min/order)	6082.2	7994.6	7724.4	5227.9	4816.7	2918.2	2341.5	6843.2	7320.9			
Foil Order Queue	290.8	288.7	336.4	342.3	259.7	279.4	278.9	340.4	292.3	306.1	-	**
(time averaged #)	24.74	25.03	21.77	28.50	28.35	23.76	30.06	22.18	24.44			
Sheet Order Queue	900.4	917.1	853.9	867.5	946.6	907.6	901.4	856.5	906.8	888.9	-	**
(time averaged #)	49.36	61.14	61.15	53.77	48.90	62.98	46.21	56.91	61.62			
Cast Coil Queue	21.2	20.1	20.5	17.6	16.8	13.4	13.3	21.0	19.7	18.3	-	**
(time averaged #)	2.14	1.95	2.91	2.25	1.71	2.86	1.62	1.80	2.30			
Cold-Rolling Queue	3.58	2.95	2.32	2.68	3.33	2.89	2.97	3.58	2.95	2.99	-	**
(time averaged #)	0.23	0.26	0.14	0.23	0.23	0.18	0.17	0.22	0.27			
Annealing Queue	5.59	9.17	5.24	9.20	59.06	7.74	7.81	5.21	9.18	7.39	Recip.	**
(time averaged #)	0.17	2.01	0.19	0.70	17.39	0.44	0.40	0.20	1.79		!	
Mill 1 Utilization	61.93	61.80	60.90	55.34	58.16	62.30	62.22	61.04	61.73	60.91	-	**
(time averaged %)	0.69	0.71	0.65	0.87	0.91	0.70	0.58	0.65	0.63			
Mill 2 Utilization												
(time averaged %)												
Annealing Furnace 1 Load	51.89	52.17	50.40	49.82	52.44	52.49	52.44	50.45	52.08	51.47	-	**
(time averaged %)	0.32	0.32	0.33	0.39	0.73	0.40	0.36	0.39	0.43			
Annealing Furnace 2 Load												
(time averaged %)												
% Foil Order Satisfied	56.13	56.55	50.17	49.79	60.82	57.14	56.77	49.61	56.31	54.06	-	**
	2.67	2.51	2.55	3.35	3.08	2.72	2.99	2.60	2.83			
% Sheet Order Satisfied	66.58	65.98	68.17	67.42	63.01	66.09	66.29	68.02	66.22	66.85	-	**
	1.33	1.54	1.55	1.50	1.44	1.78	1.32	1.61	1.55			
Slack Time of Foil Order	-64860	-64978	-69874	-71026	-34089	25533	24500	-69748	-64790	-44405	-	**
(min/order)	12025	13252	11649	16668	12104	5108	5494	12411	11051		!	
Slack Time of Sheet Order	-9251	-14591	-2575	58568	60734	51436	51859	-2326	-12758	15045	-	**
(min/order)	6204.5	7717.6	7488.7	5564.6	5242.5	3211.9	2689.4	7031.2	7097.1			
Number of Tardy Foil Orders	396.6	400.8	345.7	350.7	343.6	67.9	67.8	346.5	391.9	296.0	Sqrt	**
(#/year)	23.20	30.02	21.02	24.75	19.70	14.10	15.44	23.77	27.13			
Average Tardiness of Foil Order	102919	94487	106548	107978	103609	51083	54122	106366	95487	89874	-	**
(min/tardy order)	9867.9	9311.9	8959.8	11442.4	12124.5	15254.9	17363.4	9101.6	9686.0			
Number of Tardy Sheet Orders	1408.5	1246.0	1364.8	383.3	420.8	150.6	148.0	1347.6	1186.5	904.4	Ln	**
(#/year)	69.7	247.2	98.3	57.6	41.0	29.1	24.4	97.0	229.4			
Average Tardiness of Sheet Order	72604	63631	70450	153896	102424	61840	58877	71311	64599	77151	Sqrt	**
(min/tardy order)	3524.8	10170.1	4932.1	19241.2	21862.1	19074.5	17325.0	3847.8	10369.5			

: SRPT Rule is excluded in calculation of average values. * Significant at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

: SRPT Rule is excluded in ANOVA calculations. ! : Normality and constant variance assumptions to apply ANOVA are violated.

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

Table F.4. Duncan's Multiple Range Test Results for Capacity Expansion Alternative **B**

Capacity Alternative **B**	Ranking of Sequencing Rules According to Duncan's Test									
Performance Measures	*Sequencing Rules*									Note
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER	
Foil Order Waiting Time (min/order)	2	2	3	3		1	1	3	2	
Sheet Order Waiting Time (min/order)	4	4	3	2		1	1	3	4	
Cast Coil Waiting Time (min/order)	4	2, 3	3, 4	2		1	1	4	2	
Cold-Rolling Flow Time (min/order)	4	3	1	2		2, 3	3	4	3	
Annealing Flow Time (min/order)	1	3	1	4		2	2	1	3	
Foil Order Flow Time (min/order)	2, 3	2	3	3		1	1	3	2	
Sheet Order Flow Time (min/order)	4	4	3	2		1	1	3	4	
Foil Order Queue (time averaged #)	1, 2	1, 2	3	3		1	1	3	2	
Sheet Order Queue (time averaged #)	2	2	1	1		2	2	1	2	
Cast Coil Queue (time averaged #)	5	3, 4	3, 4, 5	2		1	1	4, 5	3	
Cold-Rolling Queue (time averaged #)	4	3	1	2		3	3	4	3	
Annealing Queue (time averaged #)	2	4	1	4		3	3	1	4	
Mill 1 Utilization (time averaged %)	2, 3	3	4	5		1	1, 2	4	3	
Mill 2 Utilization (time averaged %)										-
Annealing Furnace 1 Load (time averaged %)	3	2	4	5		1	1	4	2	
Annealing Furnace 2 Load (time averaged %)										-
% Foil Order Satisfied	1	1	2	2		1	1	2	1	
% Sheet Order Satisfied	3	3	1	2		3	3	1, 2	3	
Slack Time of Foil Order (min/order)	2	2	2, 3	3		1	1	2, 3	2	
Slack Time of Sheet Order (min/order)	4	5	3	1		2	2	3	5	
Number of Tardy Foil Orders (#/year)	3	3	2	2		1	1	2	3	
Average Tardiness of Foil Order (min/tardy order)	3	2	3	3		1	1	3	2	
Number of Tardy Sheet Orders (#/year)	4	3	4	2		1	1	4	3	
Average Tardiness of Sheet Order (min/tardy order)	3	2	3	4		1, 2	1	3	2	

▮ : SRPT Rule is not included in Duncan's Test

Table F.5. Results for Capacity Expansion Alternative **SC**

Capacity Alternative **SC**	Only sheet				2 casters, 1 cold-mill, 1 annealing furnace					Avg.	Trans.	Sig.
Performance Measures	*Sequencing Rules*										Used	
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER			
Foil Order Waiting Time (min/order)												
Sheet Order Waiting Time (min/order)										0.03	-	InSig.
Cast Coil Waiting Time (min/order)	157548	155710	157459	155983	156866	157217	158174	157548	156957	157075	-	InSig.
	6382.0	5791.8	5338.6	4328.9	5530.4	4567.1	4814.2	6382.0	6062.2			
Cold-Rolling Flow Time (min/order)	49.2	50.4	42.9	53.0	53.9	50.4	50.6	49.2	50.2	49.5	-	**
	1.88	1.69	1.26	1.57	2.31	1.80	2.06	1.88	1.68			
Annealing Flow Time (min/order)	1677.2	1852.2	1678.1	1652.7	2097.0	1858.3	1886.2	1677.2	1861.9	1768.0	Ln	**
	23.47	53.28	25.26	23.85	173.77	50.79	54.16	23.47	67.25			
Foil Order Flow Time (min/order)												
Sheet Order Flow Time (min/order)	5656.7	5850.4	5623.7	5657.5	6127.1	5857.1	5886.2	5656.7	5857.5	5755.7	Ln	**
	39.80	67.16	40.61	32.53	197.85	61.12	69.56	39.80	81.48			
Foil Order Queue (time averaged #)												
Sheet Order Queue (time averaged #)										0.0	-	InSig.
Cast Coil Queue (time averaged #)	7152.5	7072.1	7120.7	7071.2	7110.6	7124.5	7171.9	7152.5	7108.1	7121.7	-	InSig.
	252.6	232.9	216.4	182.8	230.8	181.1	191.0	252.6	250.2			
Cold-Rolling Queue (time averaged #)	1.48	1.55	1.23	1.66	1.69	1.54	1.55	1.48	1.54	1.50	-	**
	0.09	0.09	0.06	0.08	0.11	0.09	0.10	0.09	0.08			
Annealing Queue (time averaged #)	6.79	8.22	6.86	6.72	10.19	8.24	8.37	6.79	8.28	7.54	-	**
	0.23	0.44	0.25	0.23	1.33	0.42	0.46	0.23	0.56			
Mill 1 Utilization (time averaged %)	58.77	59.64	59.55	59.67	59.37	59.49	59.01	58.77	59.33	59.28	-	**
	1.17	1.12	1.02	0.98	1.19	1.16	1.10	1.17	1.02			
Mill 2 Utilization (time averaged %)												
Annealing Furnace 1 Load (time averaged %)	49.24	49.74	49.78	49.66	48.22	49.65	49.33	49.24	49.49	49.52	-	*
	1.04	0.97	0.96	0.91	1.18	0.99	1.01	1.04	0.93			
Annealing Furnace 2 Load (time averaged %)												
% Foil Order Satisfied												
% Sheet Order Satisfied	98.27	98.19	98.27	98.26	98.11	98.19	98.19	98.27	98.20	98.23	-	**
	0.06	0.04	0.05	0.05	0.09	0.06	0.06	0.06	0.06			
Slack Time of Foil Order (min/order)												
Slack Time of Sheet Order (min/order)	105283	105230	105224	105255	104869	105139	104771	105283	105044	105154	-	InSig.
	992.2	954.2	1026.9	818.8	914.8	1077.1	935.6	992.2	1028.7			
Number of Tardy Foil Orders (#/year)												
Average Tardiness of Foil Order (min/tardy order)												
Number of Tardy Sheet Orders (#/year)	0.35	0.18	0.55	0.53	3.45	0.23	0.18	0.35	0.23	0.32	-	*
	0.58	0.45	0.78	0.85	2.46	0.58	0.45	0.58	0.48			
Average Tardiness of Sheet Order (min/tardy order)	582.6	226.5	570.0	910.4	5455.5	265.0	211.6	582.6	265.3	451.7	Sqrt	*
	1074.1	680.9	1135.9	1711.7	4502.6	721.5	543.6	1074.1	615.1			

: SRPT Rule is excluded in calculation of average values.
: SRPT Rule is excluded in ANOVA calculations.

* Significant at $\alpha = 0.05$
** Significant at $\alpha = 0.01$
! : Normality and constant variance assumptions to apply ANOVA are violated.

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

Table F.6. Duncan's Multiple Range Test Results for Capacity Expansion Alternative **SC**

Capacity Alternative **SC**	Ranking of Sequencing Rules According to Duncan's Test									
Performance Measures	*Sequencing Rules*									Note
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER	
Foil Order Waiting Time (min/order)										-
Sheet Order Waiting Time (min/order)										InSig.
Cast Coil Waiting Time (min/order)										InSig.
Cold-Rolling Flow Time (min/order)	2	3	1	4		3	3	2	3	
Annealing Flow Time (min/order)	2	3	2	1		3	4	2	3	
Foil Order Flow Time (min/order)										-
Sheet Order Flow Time (min/order)	2	3	1	2		3	4	2	3	
Foil Order Queue (time averaged #)										-
Sheet Order Queue (time averaged #)										InSig.
Cast Coil Queue (time averaged #)										InSig.
Cold-Rolling Queue (time averaged #)	2	3	1	4		3	3	2	3	
Annealing Queue (time averaged #)	1	2	1	1		2	2	1	2	
Mill 1 Utilization (time averaged %)	3	1	1	1		1, 2	2, 3	3	1, 2	
Mill 2 Utilization (time averaged %)										-
Annealing Furnace 1 Load (time averaged %)	2	1	1	1, 2		1, 2	1, 2	2	1, 2	
Annealing Furnace 2 Load (time averaged %)										-
% Foil Order Satisfied										-
% Sheet Order Satisfied	1	2	1	1		2	2	1	2	
Slack Time of Foil Order (min/order)										-
Slack Time of Sheet Order (min/order)										InSig.
Number of Tardy Foil Orders (#/year)										-
Average Tardiness of Foil Order (min/tardy order)										-
Number of Tardy Sheet Orders (#/year)	1, 2	1	2	2		1	1	1, 2	1	
Average Tardiness of Sheet Order (min/tardy order)	1, 2	1	1, 2	2		1	1	1, 2	1	

: SRPT Rule is not included in Duncan's Test

Table F.7. Results for Capacity Expansion Alternative BC

Capacity Alternative **BC**	Both foil and sheet			2 casters, 1 cold-mill, 1 annealing furnace						Avg.	Trans.	Sig.
Performance Measures	*Sequencing Rules*										Used	
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER			
Foil Order Waiting Time	18.3	33.3	17.8	55.2	26.5	58.0	34.2	52.6	18.9	36.0	Sqrt x 2	InSig.
(min/order)	64.1	76.1	40.6	105.5	80.2	107.4	85.7	132.2	59.2		!	
Sheet Order Waiting Time	12.5	5.5	6.8	4.4	3.0	19.4	5.5	4.2	5.3	7.9	Sqrt x 2	InSig.
(min/order)	43.0	17.1	23.4	9.5	14.0	67.5	14.7	12.5	11.6		!	
Cast Coil Waiting Time	85413	82457	82044	83286	83674	82421	85025	84690	82237	83447	-	InSig.
(min/order)	6652.6	8027.6	8010.6	5900.5	6652.6	5555.8	7259.8	6825.1	5719.2			
Cold-Rolling Flow Time	467.7	489.9	718.4	583.4	207.2	457.9	775.1	562.6	507.9	570.3	1 / Sqrt	**
(min/order)	230.5	225.9	658.5	145.3	38.5	170.0	376.2	387.6	202.4			
Annealing Flow Time	3041.7	7430.4	3272.1	5857.0	3756.6	5727.5	6993.8	3103.1	7244.3	5333.7	Recip.	**
(min/order)	211.4	3302.1	314.5	1872.6	1218.0	1642.9	2048.4	172.5	2824.5			
Foil Order Flow Time	22813	25766	27157	53019	14772	23142	24464	23840	25222	28178	Recip.	**
(min/order)	2367.3	4801.0	8782.2	14212.2	120.8	2439.4	3305.8	3531.5	4066.9			
Sheet Order Flow Time	9446	16494	10762	7896	10467	14021	18577	10065	16469	12966	Recip.	**
(min/order)	1536.3	4864.4	3719.5	369.8	2398.4	2853.4	4721.9	2344.4	4259.2			
Foil Order Queue										0.02	-	InSig.
(time averaged #)												
Sheet Order Queue										0.03	-	InSig.
(time averaged #)												
Cast Coil Queue	3635.9	3513.5	3499.8	3550.1	3575.9	3520.2	3616.8	3602.7	3510.3	3556.2		InSig.
(time averaged #)	273.8	324.4	320.0	241.0	265.7	224.6	288.6	268.4	227.3			
Cold-Rolling Queue	25.5	26.7	41.6	33.1	10.2	25.5	44.7	31.0	27.9	32.0	1/ Sqrt	**
(time averaged #)	13.3	13.5	45.4	9.3	2.1	11.1	23.3	22.7	12.2			
Annealing Queue	29.2	91.8	32.4	66.6	455.0	82.5	128.4	30.1	86.2	68.4	Recip.	**
(time averaged #)	3.0	45.1	4.5	23.5	24.3	35.2	54.9	2.4	37.7			
Mill 1 Utilization	96.36	96.19	97.27	95.24	90.31	96.14	95.40	96.79	96.41	96.23	-	**
(time averaged %)	1.67	1.41	1.82	1.52	1.80	1.70	1.64	1.66	1.48			
Mill 2 Utilization												
(time averaged %)												
Annealing Furnace 1 Load	81.54	80.45	82.37	80.00	72.28	80.63	79.87	81.89	80.91	80.96	-	**
(time averaged %)	1.71	1.48	1.91	1.34	1.64	1.71	1.64	1.53	1.58			
Annealing Furnace 2 Load												
(time averaged %)												
% Foil Order Satisfied	93.07	92.27	91.77	85.00	95.49	92.79	92.14	92.78	92.36	91.52	Sqrt	**
	0.76	1.38	2.60	3.51	0.22	0.80	1.33	1.08	1.12			
% Sheet Order Satisfied	97.12	95.10	96.69	97.58	82.19	95.12	93.00	96.93	95.12	95.83	Sqrt	**
	0.50	1.36	1.26	0.12	1.14	1.17	2.06	0.72	1.16			
Slack Time of Foil Order	81673	77635	76954	51007	89001	80327	78351	80665	78052	75583	-	**
(min/order)	2875.5	5103.1	9250.9	14108.5	1595.5	2718.6	3153.2	3654.6	4539.7		!	
Slack Time of Sheet Order	101147	93003	100152	102522	100201	95509	89287	101087	93440	97018	Ln	**
(min/order)	1468.1	5467.0	3568.6	1022.6	2836.7	3696.7	5934.7	2428.9	4840.4			
Number of Tardy Foil Orders	2.48	0.0	26.53	161.48	0.03	2.75	6.93	4.15	0.0	25.54	Sqrt	**
(# / year)	4.9	0.0	44.3	87.7	0.2	5.2	8.2	11.8	0.0		!	
Average Tardiness of Foil Order	1465.2	0.0	16160	21471	15.4	28925	67369	1879.7	0.0	17159	Sqrt	**
(min/tardy order)	1649.0	0.0	18628.0	10033.5	97.3	44663	59527.3	1960.2	0.0		!	
Number of Tardy Sheet Orders	9.15	0.05	55.40	9.83	46.50	13.78	30.75	12.33	0.30	16.45	Sqrt	**
(# / year)	9.23	0.22	51.46	5.12	32.97	20.42	30.12	16.66	0.56		!	
Average Tardiness of Sheet Order	2521.7	28.5	52685	6390.6	64747	35087.0	60008	3077.3	222.4	20003	Sqrt	**
(min/tardy order)	1374.1	155.9	48985	2259.2	45146	43401.5	46024	1306.7	500.4		!	

: SRPT Rule is excluded in calculation of average values. * Significant at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

: SRPT Rule is excluded in ANOVA calculations. ! : Normality and constant variance assumptions to apply ANOVA are violated.

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

Table F.8. Duncan's Multiple Range Test Results for Capacity Expansion Alternative **BC**

Capacity Alternative **BC**	Ranking of Sequencing Rules According to Duncan's Test									
Performance Measures	*Sequencing Rules*									Note
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER	
Foil Order Waiting Time (min/order)										InSig.
Sheet Order Waiting Time (min/order)										InSig.
Cast Coil Waiting Time (min/order)										InSig.
Cold-Rolling Flow Time (min/order)	1	1	2, 3	1, 2		1	3	1, 2	1	
Annealing Flow Time (min/order)	1	3	1	2		2	2	1	3	
Foil Order Flow Time (min/order)	1	1, 2	2	3		1	1, 2	1	1, 2	
Sheet Order Flow Time (min/order)	2	4	2	1		3	5	2	4	
Foil Order Queue (time averaged #)										InSig.
Sheet Order Queue (time averaged #)										InSig.
Cast Coil Queue (time averaged #)										InSig.
Cold-Rolling Queue (time averaged #)	1	1	2, 3	1, 2		1	3	1	1	
Annealing Queue (time averaged #)	1	3	1	2		3	4	1	3	
Mill 1 Utilization (time averaged %)	2	2	1	3		2	3	1, 2	2	
Mill 2 Utilization (time averaged %)										-
Annealing Furnace 1 Load (time averaged %)	2, 3	4, 5	1	5		4, 5	5	1, 2	3, 4	
Annealing Furnace 2 Load (time averaged %)										-
% Foil Order Satisfied	1	1, 2, 3	3	4		1, 2	2, 3	1, 2	1, 2, 3	
% Sheet Order Satisfied	1, 2	3	2	1		3	4	2	3	
Slack Time of Foil Order (min/order)	1	2, 3	3	4		1, 2	2, 3	1, 2	2, 3	
Slack Time of Sheet Order (min/order)	1, 2	4	2	1		3	5	1, 2	4	
Number of Tardy Foil Orders (# / year)	1	1	2	3		1	1	1	1	
Average Tardiness of Foil Order (min/tardy order)	1	1	2	2, 3		3	4	1	1	
Number of Tardy Sheet Orders (# / year)	1, 2	1	4	1, 2		2	3	2	1	
Average Tardiness of Sheet Order (min/tardy order)	1	1	3	1		2	3	1	1	

: SRPT Rule is not included in Duncan's Test

Table F.9. Results for Capacity Expansion Alternative **BCM**

Capacity Alternative **BCM**	Both foil and sheet		2 casters, 2 cold-mills, 1 annealing furnace							Avg.	Trans.	Sig.
Performance Measures	*Sequencing Rules*										Used	
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER			
Foil Order Waiting Time	56.1	30.5	24.9	32.9	33.6	63.9	46.5	19.2	49.1	40.4	Sqrt x 2	InSig.
(min/order)	158.9	62.8	52.0	78.2	77.7	123.6	92.0	34.3	101.7		!	
Sheet Order Waiting Time	6.92	6.47	7.30	6.56	7.88	5.90	2.90	1.28	7.25	5.57	Sqrt x 2	InSig.
(min/order)	20.3	16.5	23.4	15.7	15.8	19.2	7.8	3.6	20.1		!	
Cast Coil Waiting Time	82974	83131	81563	84057	81321	80604	81643	82189	81899	82257	-	InSig.
(min/order)	6102.6	5889.0	5992.6	8571.1	6214.3	4882.3	7735.4	7009.3	6411.2			
Cold-Rolling Flow Time	42.17	40.04	35.95	41.85	38.73	40.40	40.05	41.96	40.10	40.32	-	**
(min/order)	0.98	0.89	0.94	1.78	0.86	1.01	0.97	1.08	0.99			
Annealing Flow Time	3373.7	8557.9	3374.7	8241.5	5102.2	6304.4	7190.8	3428.7	8033.2	6063.1	Recip.	**
(min/order)	343.2	3749.2	370.6	2236.7	1841.1	2087.7	2352.3	571.8	3256.7			
Foil Order Flow Time	20571.7	24959.1	20546.9	62415.8	14105.9	21953.5	24589.1	20706.5	24384.7	27515.9	Recip.	**
(min/order)	1091.4	6400.2	1218.2	18368.1	108.1	2298.8	3303.1	1765.9	4550.2			
Sheet Order Flow Time	7270.8	15283.9	7216.4	6322.4	12244.3	12090.5	13008.3	7303.6	14520.6	10377.1	Recip.	**
(min/order)	373.6	5300.4	387.3	181.0	3545.7	3222.7	3472.5	594.5	4652.1			
Foil Order Queue										0.03	-	InSig.
(time averaged #)												
Sheet Order Queue										0.02	-	InSig.
(time averaged #)												
Cast Coil Queue	3540.2	3551.3	3482.7	3578.6	3470.1	3441.8	3489.1	3509.6	3495.9	3511.1	-	InSig.
(time averaged #)	248.0	238.7	249.7	348.7	253.9	199.1	308.7	291.3	267.7			
Cold-Rolling Queue	1.450	1.325	1.062	1.430	1.215	1.344	1.319	1.438	1.324	1.337	-	**
(time averaged #)	0.06	0.05	0.05	0.09	0.05	0.06	0.06	0.07	0.06			
Annealing Queue	33.65	105.86	33.64	113.22	484.33	118.23	156.65	34.34	98.57	86.77	1/Sqrt	**
(time averaged #)	4.80	51.77	5.16	40.70	40.45	55.76	59.10	8.05	45.74			
Mill 1 Utilization	47.03	46.31	48.70	44.03	44.02	46.84	46.61	46.89	46.37	46.60	-	**
(time averaged %)	1.01	0.72	1.04	0.96	0.61	0.93	0.80	1.12	0.86			
Mill 2 Utilization	47.03	46.31	48.69	43.99	43.97	46.85	46.62	46.82	46.37	46.58	-	**
(time averaged %)	0.93	0.68	1.04	0.94	0.62	0.86	0.74	1.17	0.85			
Annealing Furnace 1 Load	82.42	80.27	82.50	76.94	72.28	80.89	79.85	82.31	80.65	80.73	-	**
(time averaged %)	1.96	1.52	1.96	1.76	1.32	1.96	1.74	2.30	1.54			
Annealing Furnace 2 Load												
(time averaged %)												
% Foil Order Satisfied	93.73	92.45	93.72	82.48	95.69	92.77	91.58	93.60	92.77	91.64	Ln	**
	0.46	1.47	0.51	5.32	0.16	1.21	1.41	0.63	1.23			
% Sheet Order Satisfied	97.76	95.44	97.77	98.03	81.49	94.97	93.98	97.75	95.64	96.42	-	**
	0.14	1.48	0.15	0.09	1.49	1.62	1.71	0.21	1.34			
Slack Time of Foil Order	83623	78333	83539	41642	90302	81554	77806	83941	79167	76200	-	**
(min/order)	2057.7	6171.1	1983.6	18033.5	1445.0	2688.8	3060.5	2403.1	5085.5			
Slack Time of Sheet Order	103415	94422	103667	104517	98704	96218	94109	103382	95126	99357	-	**
(min/order)	915.5	6279.6	849.3	1018.0	3759.3	3783.4	3140.8	1398.8	5480.1			
Number of Tardy Foil Orders	0.58	0.0	0.55	200.70	0.05	3.70	8.63	0.90	0.0	26.88	Sqrt	**
(#/year)	1.03	0.0	1.77	82.32	0.22	4.94	8.43	2.33	0.0			
Average Tardiness of Foil Order	902.3	0.0	697.6	41285	118.6	38205	58865	838.6	0.0	17599	Sqrt	**
(min/tardy order)	1909.7	0.0	2135.5	21920.7	524.7	52336.2	46056.3	2331.3	0.0			
Number of Tardy Sheet Orders	2.40	0.28	1.83	2.08	76.90	20.95	32.78	2.88	0.25	7.93	Sqrt	**
(#/year)	1.72	0.51	1.39	1.85	49.63	29.43	31.20	2.31	0.44			
Average Tardiness of Sheet Order	1513.4	364.5	1465.2	4228.0	70358	53411	60739	1706.2	185.1	15452	Sqrt	**
(min/tardy order)	1357.4	745.1	1308.9	4769.7	29707.7	56271.8	45932.6	1486.2	402.1			

: SRPT Rule is excluded in calculation of average values.

: SRPT Rule is excluded in ANOVA calculations.

* Significant at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

! : Normality and constant variance assumptions to apply ANOVA are violated.

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

Table F.10. Duncan's Multiple Range Test Results for Capacity Expansion Alternative **BCM**

Capacity Alternative **BCM**	Ranking of Sequencing Rules According to Duncan's Test									
Performance Measures	*Sequencing Rules*									Note
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER	
Foil Order Waiting Time (min/order)										InSig.
Sheet Order Waiting Time (min/order)										InSig.
Cast Coil Waiting Time (min/order)										InSig.
Cold-Rolling Flow Time (min/order)	3	2	1	3		2	2	3	2	
Annealing Flow Time (min/order)	1	4	1	4		2	2, 3	1	3, 4	
Foil Order Flow Time (min/order)	1	2	1	3		1, 2	2	1	2	
Sheet Order Flow Time (min/order)	2	4	2	1		3	3	2	4	
Foil Order Queue (time averaged #)										InSig.
Sheet Order Queue (time averaged #)										InSig.
Cast Coil Queue (time averaged #)										InSig.
Cold-Rolling Queue (time averaged #)	3	2	1	3		2	2	3	2	
Annealing Queue (time averaged #)	1	2, 3	1	2, 3		3	4	1	2	
Mill 1 Utilization (time averaged %)	2	3	1	4		2	2, 3	2	3	
Mill 2 Utilization (time averaged %)	2	3	1	4		2	2, 3	2	3	
Annealing Furnace 1 Load (time averaged %)	1	2, 3	1	4		2	3	1	2, 3	
Annealing Furnace 2 Load (time averaged %)										-
% Foil Order Satisfied	1	2, 3	1	4		1, 2	3	1	1, 2	
% Sheet Order Satisfied	2	3, 4	2	1		4	5	2	3	
Slack Time of Foil Order (min/order)	1	2, 3	1	4		1, 2	3	1	2, 3	
Slack Time of Sheet Order (min/order)	1	3	1	1		2	3	1	2, 3	
Number of Tardy Foil Orders (#/year)	1	1	1	3		1, 2	2	1	1	
Average Tardiness of Foil Order (min/tardy order)	2	1	2	3		3	4	2	1	
Number of Tardy Sheet Orders (#/year)	2	1	2	2		3	4	2	1	
Average Tardiness of Sheet Order (min/tardy order)	2	1	2	3		4	5	2	1	

: SRPT Rule is not included in Duncan's Test

Table F.11. Results for Capacity Expansion Alternative **BCA**

Capacity Alternative **BCA**	Both foil and sheet			2 casters, 1 cold-mill, 2 annealing furnaces						Avg.	Trans.	Sig.
Performance Measure	*Sequencing Rules*										Used	
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER			
Foil Order Waiting Time	41.8	48.0	27.4	20.0	21.9	44.1	52.6	50.9	104.5	48.7	Sqrt x 2	InSig.
(min/order)	92.1	133.8	79.5	38.8	46.3	99.3	131.1	107.1	212.3		!	
Sheet Order Waiting Time	4.6	4.0	3.8	8.1	5.0	3.6	8.3	3.0	7.1	5.3	Sqrt x 2	InSig.
(min/order)	10.8	10.2	8.6	25.7	26.1	9.1	40.4	7.9	21.8		!	
Cast Coil Waiting Time	81712	83261	82184	81879	82018	82911	82010	82836	81350	82268	-	InSig.
(min/order)	6828.3	5854.6	6245.8	5884.8	6686.3	5878.1	5709.7	6692.4	6677.1			
Cold-Rolling Flow Time	744.1	531.4	790.0	647.3	527.4	663.9	1724.6	633.3	698.3	804.1	1/ Sqrt	**
(min/order)	491.3	239.0	615.2	203.4	267.1	423.7	1292.6	337.7	461.9			
Annealing Flow Time	1235.8	1247.1	1216.7	1228.6	5581.0	1243.6	1261.6	1233.6	1244.7	1239.0	-	**
(min/order)	9.9	18.1	6.5	12.5	2627.2	12.5	14.2	8.8	11.0			
Foil Order Flow Time	19226.0	15744.2	22326	25098.1	13731.2	15855.4	14135.5	18407.6	16428.5	18403	Recip.	**
(min/order)	3913.6	968.6	7275.8	5056.2	167.2	1134.5	184.6	2756.1	1948.3			
Sheet Order Flow Time	9289.7	8495.1	8827.3	7098.1	15766.6	9551.8	18362.2	8644.4	9692.0	9995.1	Recip.	**
(min/order)	2890.9	1683.0	3201.1	422.5	5614.8	3102.6	10392.7	2022.9	3241.3			
Foil Order Queue										0.04	-	InSig.
(time averaged #)												
Sheet Order Queue										0.01	-	InSig.
(time averaged #)												
Cast Coil Queue	3480.8	3552.8	3503.3	3496.7	3500.5	3541.5	3504.6	3527.8	3471.2	3509.8	-	InSig.
(time averaged #)	280.1	235.8	259.0	241.3	271.9	234.1	220.0	270.7	269.2			
Cold-Rolling Queue	41.4	29.1	46.0	36.0	30.8	37.9	105.0	35.0	38.4	46.1	Ln	**
(time averaged #)	28.5	13.4	40.6	12.0	17.0	28.0	99.2	19.4	26.0			
Annealing Queue	6.17	6.34	5.94	6.12	129.17	6.32	6.52	6.15	6.36	6.24	-	**
(time averaged #)	0.16	0.25	0.15	0.21	57.70	0.21	0.24	0.17	0.18			
Mill 1 Utilization	97.32	96.70	97.11	97.19	94.89	96.97	97.07	97.06	97.32	97.09	-	InSig.
(time averaged %)	1.63	1.62	1.95	1.57	2.17	1.74	1.58	1.72	1.58			
Mill 2 Utilization												
(time averaged %)												
Annealing Furnace 1 Load	41.03	40.43	41.08	40.50	39.12	40.74	41.03	41.05	40.84	40.84	-	InSig.
(time averaged %)	1.08	1.21	1.16	1.07	1.45	1.06	1.37	1.06	0.99			
Annealing Furnace 2 Load	41.14	40.87	40.97	40.91	39.59	40.75	40.61	40.85	40.96	40.88	-	InSig.
(time averaged %)	1.06	1.23	1.31	1.12	1.62	1.49	1.24	0.88	1.11			
% Foil Order Satisfied	94.26	95.19	93.23	92.41	95.81	95.14	95.67	94.46	94.91	94.41	-	**
	0.93	0.45	1.98	1.55	0.19	0.41	0.23	0.80	0.62			
% Sheet Order Satisfied	97.21	97.40	97.19	97.82	92.84	97.06	94.05	97.37	97.07	96.90	Sqrt	**
	0.76	0.53	1.06	0.15	1.98	0.99	3.78	0.64	0.90			
Slack Time of Foil Order	85005	88718	81612	78486	90443	88609	90360	85746	87954	85811	Sqrt	**
(min/order)	3905.4	1744.0	7776.4	5049.1	1606.0	1599.3	1368.3	3382.1	2307.5			
Slack Time of Sheet Order	101715	102610	101921	103569	95170	101476	92530	102127	101513	100932	Sqrt	**
(min/order)	2996.0	1850.4	3367.3	1063.8	5533.0	3155.7	11845.3	2325.4	3062.3			
Number of Tardy Foil Orders	2.78	0.03	29.45	10.55	0.03	0.25	0.00	0.70	0.03	5.47	Sqrt	**
(#/year)	7.99	0.16	40.39	16.76	0.16	0.78	0.00	2.60	0.16		!	
Average Tardiness of Foil Order	1131.3	100.1	21154.6	4079.8	20.4	7607.0	0.0	676.0	62.6	4351.4	Sqrt	**
(min/tardy order)	2224.4	633.0	17033.2	3184.8	129.3	23560.6	0.0	1811.5	396.2		!	
Number of Tardy Sheet Orders	11.83	0.23	55.28	5.13	141.15	7.53	44.28	7.30	0.15	16.46	Sqrt	**
(#/year)	17.16	0.48	49.50	3.24	75.86	17.17	97.69	9.06	0.36		!	
Average Tardiness of Sheet Order	2357.9	226.1	52061.6	4264.2	92176.7	16842.4	18536.8	2373.6	199.8	12107.8	Sqrt	**
(min/tardy order)	1776.1	584.1	39285	2527.4	38688.1	37042.8	31579.3	1441.4	558.2		!	

: SRPT Rule is excluded in calculation of average values.

: SRPT Rule is excluded in ANOVA calculations.

* Significant at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

! : Normality and constant variance assumptions to apply ANOVA are violated.

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

Table F.12. Duncan's Multiple Range Test Results for Capacity Expansion Alternative **BCA**

Capacity Alternative **BCA**	Ranking of Sequencing Rules According to Duncan's Test									
Performance Measure	*Sequencing Rules*									Note
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER	
Foil Order Waiting Time (min/order)										InSig.
Sheet Order Waiting Time (min/order)										InSig.
Cast Coil Waiting Time (min/order)										InSig.
Cold-Rolling Flow Time (min/order)	2	1	2	1, 2		1, 2	3	1, 2	2	
Annealing Flow Time (min/order)	1	1, 2	1	1		1, 2	2	1	1, 2	
Foil Order Flow Time (min/order)	3	1, 2	4	5		2	1	3	2	
Sheet Order Flow Time (min/order)	3	2	2	1		3	4	2	3	
Foil Order Queue (time averaged #)										InSig.
Sheet Order Queue (time averaged #)										InSig.
Cast Coil Queue (time averaged #)										InSig.
Cold-Rolling Queue (time averaged #)	1	1	1	1		1	2	1	1	
Annealing Queue (time averaged #)	2	3	1	2		3	4	2	3	
Mill 1 Utilization (time averaged %)										InSig.
Mill 2 Utilization (time averaged %)										-
Annealing Furnace 1 Load (time averaged %)										InSig.
Annealing Furnace 2 Load (time averaged %)										InSig.
% Foil Order Satisfied	3	2	4	5		2	1	3	2, 3	
% Sheet Order Satisfied	1	1	1	1		1	2	1	1	
Slack Time of Foil Order (min/order)	3	1, 2	4	5		1, 2	1	3	2	
Slack Time of Sheet Order (min/order)	1	1	1	1		1	2	1	1	
Number of Tardy Foil Orders (#/year)	1	1	3	2		1	1	1	1	
Average Tardiness of Foil Order (min/tardy order)	1	1	3	1, 2		2	1	1	1	
Number of Tardy Sheet Orders (#/year)	1	1	2	1		1	2	1	1	
Average Tardiness of Sheet Order (min/tardy order)	1	1	3	1		2	2	1	1	

: SRPT Rule is not included in Duncan's Test

Table F.13. Results for Capacity Expansion Alternative **BCMA**

Capacity Alternative **BCMA**	Both foil and sheet			2 casters, 2 cold-mills, 2 annealing furnaces						Avg.	Trans.	Sig.
Performance Measures	*Sequencing Rules*									(SRPT excluded icon)	Used	(ANOVA excluded icon)
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER			
Foil Order Waiting Time	65.6	23.7	26.3	30.8	28.6	43.0	30.0	24.9	8.5	31.6	Sqrt x 2	*
(min/order)	131.3	54.9	53.2	54.3	50.9	84.9	58.0	63.4	21.5		!	
Sheet Order Waiting Time	8.4	3.8	1.6	14.7	5.2	2.4	2.7	2.2	5.0	5.1	Sqrt x 2	InSig.
(min/order)	30.1	8.3	4.3	45.8	16.0	8.0	9.1	7.5	11.7		!	
Cast Coil Waiting Time	81064	81756	82652	82506	83568	83436	83618	81285	80653	82121	-	InSig.
(min/order)	6827.2	6030.6	6218.5	7138.0	7321.3	5984.3	6030.0	5188.8	6834.9			
Cold-Rolling Flow Time	37.4	35.3	32.5	38.3	33.0	34.8	35.2	37.0	35.2	35.7	-	**
(min/order)	1.14	1.22	0.95	1.24	1.22	0.96	1.12	1.09	1.02			
Annealing Flow Time	1234.1	1261.6	1240.3	1237.0	4203.1	1257.9	1264.1	1236.8	1255.7	1248.4	-	**
(min/order)	9.51	14.39	8.63	9.23	1023.49	13.73	12.71	11.06	11.77			
Foil Order Flow Time	13607.4	13548.8	13601.4	13588.0	13045.1	13565.9	13572.8	13580.9	13516.5	13572.7	Ln	*
(min/order)	147.8	99.8	89.8	79.0	67.7	154.0	91.0	88.0	54.3			
Sheet Order Flow Time	5123.5	5156.0	5079.1	5140.7	10437.3	5148.3	5149.9	5120.9	5150.3	5133.6	Sqrt	**
(min/order)	36.7	29.9	19.2	61.9	1914.0	24.3	31.3	22.2	29.4			
Foil Order Queue										0.01	-	InSig.
(time averaged #)												
Sheet Order Queue										0.02	-	InSig.
(time averaged #)												
Cast Coil Queue	3462.0	3497.1	3524.8	3523.7	3563.8	3558.2	3562.7	3479.2	3450.4	3507.2	-	InSig.
(time averaged #)	278.5	239.6	246.2	287.0	309.2	245.1	254.2	209.1	282.6			
Cold-Rolling Queue	1.176	1.061	0.863	1.236	0.932	1.034	1.054	1.157	1.061	1.080	-	**
(time averaged #)	0.069	0.073	0.051	0.075	0.072	0.053	0.067	0.067	0.066			
Annealing Queue	6.161	6.559	6.193	6.215	175.948	6.491	6.560	6.175	6.502	6.357	-	**
(time averaged #)	0.159	0.253	0.154	0.162	45.894	0.216	0.249	0.200	0.211			
Mill 1 Utilization	47.01	46.86	48.33	46.52	44.66	46.60	46.92	46.72	47.02	47.00	-	**
(time averaged %)	0.88	1.01	0.79	0.94	1.01	0.71	1.01	0.95	0.98			
Mill 2 Utilization	47.00	46.80	48.34	46.51	44.65	46.56	46.85	46.80	47.00	46.98	-	**
(time averaged %)	0.85	1.01	0.83	0.93	1.00	0.74	1.06	0.93	0.98			
Annealing Furnace 1 Load	41.20	40.59	40.73	40.87	38.75	40.72	40.72	40.83	41.28	40.87	-	InSig.
(time averaged %)	1.19	1.36	1.20	1.36	1.22	1.21	1.04	1.00	1.35			
Annealing Furnace 2 Load	41.14	41.01	40.85	40.54	38.56	40.61	40.67	40.99	41.01	40.85	-	InSig.
(time averaged %)	1.16	1.21	1.00	1.44	1.51	0.97	1.37	1.15	1.13			
% Foil Order Satisfied	95.83	95.80	95.88	95.86	96.00	95.85	95.85	95.85	95.79	95.84	-	InSig.
	0.18	0.21	0.19	0.20	0.21	0.16	0.23	0.20	0.17			
% Sheet Order Satisfied	98.41	98.42	98.44	98.42	92.51	98.42	98.41	98.43	98.40	98.42	-	InSig.
	0.05	0.04	0.04	0.04	1.65	0.03	0.04	0.04	0.04			
Slack Time of Foil Order	90825.9	90470.2	90786.0	90659.6	91450.2	90704.9	90467	90529.2	90977.5	90678	-	InSig.
(min/order)	1678.1	1336.1	1698.5	1613.4	1975.1	1440.4	1532.2	1585.5	1445.7			
Slack Time of Sheet Order	105617	105815	105713	105512	100298	105565	105719	105721	105408	105634	-	InSig.
(min/order)	847.8	847.5	971.2	931.9	2156.2	1042.6	919.3	848.4	1026.3			
Number of Tardy Foil Orders										0.0	-	InSig.
(#/year)												
Average Tardiness of Foil Order										0.0	-	InSig.
(min/tardy order)												
Number of Tardy Sheet Orders	0.20	0.23	0.23	0.43	78.73	0.13	0.10	0.35	0.18	0.23	-	*
(#/year)	0.41	0.42	0.48	0.64	26.23	0.33	0.30	0.62	0.38		!	
Average Tardiness of Sheet Order	309.5	212.8	243.9	638.5	88895.3	53.4	21.3	380.8	102.1	245.3	Sqrt	*
(min/tardy order)	729.0	542.6	705.4	1493.0	36408.7	160.2	122.4	756.3	272.1			

(icon) : SRPT Rule is excluded in calculation of average values.

(icon) : SRPT Rule is excluded in ANOVA calculations.

* Significant at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

! : Normality and constant variance assumptions to apply ANOVA are violated.

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

Table F.14. Duncan's Multiple Range Test Results for Capacity Expansion Alternative **BCMA**

Capacity Alternative **BCMA**	Ranking of Sequencing Rules According to Duncan's Test									
Performance Measures	*Sequencing Rules*									Note
	FIFO	EDD	SPT	SRNO	SRPT	MST	CR	HYBRID	USER	
Foil Order Waiting Time (min/order)	2	1, 2	1, 2	1, 2		1, 2	1, 2	1, 2	1	
Sheet Order Waiting Time (min/order)										InSig.
Cast Coil Waiting Time (min/order)										InSig.
Cold-Rolling Flow Time (min/order)	3	2	1	4		2	2	3	2	
Annealing Flow Time (min/order)	1	4, 5	2	1, 2		3, 4	5	1, 2	3	
Foil Order Flow Time (min/order)	3	1, 2	3	2, 3		2, 3	2, 3	2, 3	1	
Sheet Order Flow Time (min/order)	2	2, 3	1	3		3	3	2	3	
Foil Order Queue (time averaged #)										InSig.
Sheet Order Queue (time averaged #)										InSig.
Cast Coil Queue (time averaged #)										InSig.
Cold-Rolling Queue (time averaged #)	3	2	1	4		2	2	3	2	
Annealing Queue (time averaged #)	1	2	1	1		2	2	1	2	
Mill 1 Utilization (time averaged %)	3	3, 4	1	4		3, 4	3, 4	3, 4	2	
Mill 2 Utilization (time averaged %)	3	3, 4	1	4		3, 4	3, 4	3, 4	2	
Annealing Furnace 1 Load (time averaged %)										InSig.
Annealing Furnace 2 Load (time averaged %)										InSig.
% Foil Order Satisfied										InSig.
% Sheet Order Satisfied										InSig.
Slack Time of Foil Order (min/order)										InSig.
Slack Time of Sheet Order (min/order)										InSig.
Number of Tardy Foil Orders (#/year)										InSig.
Average Tardiness of Foil Order (min/tardy order)										InSig.
Number of Tardy Sheet Orders (#/year)	1, 2, 3	1, 2, 3	1, 2, 3	3		1, 2	1	2, 3	1, 2	
Average Tardiness of Sheet Order (min/tardy order)	1, 2, 3	1, 2	1, 2	3		1	1	2, 3	1, 2	

: SRPT Rule is not included in Duncan's Test

Table F.15. Results for Alternative **BCMA** Under 1.25xCurrent Demand

BCMA (Demand*1.25)	2 casters, 2 cold-mills, 2 annealing furnaces					
Performance Measures	*Sequencing Rules* EDD	SPT	SRNO	Avg.	Trans. Used	Sig.
Foil Order Waiting Time (min/order)	1987.1 1553.8	3426.5 2379.0	2967.4 2489.0	2793.7	Sqrtx2 !	*
Sheet Order Waiting Time (min/order)	4096.3 3350.6	4648.8 3459.4	4750.1 3047.2	4498.4	Sqrtx2 !	InSig.
Cast Coil Waiting Time (min/order)	10615.0 3400.6	10737.9 4187.9	10541.5 4272.6	10631.4	-	InSig.
Cold-Rolling Flow Time (min/order)	48.4 2.7	43.5 3.1	55.3 4.4	49.1	-	**
Annealing Flow Time (min/order)	1339.6 28.0	1262.6 22.3	1341.1 47.8	1314.4	-	**
Foil Order Flow Time (min/order)	15867.8 1588.6	17096.4 2235.6	17150.6 2636.8	16705.0	Ln	*
Sheet Order Flow Time (min/order)	9415.2 3322.6	9801.9 3424.0	10038.5 3059.1	9751.9	-	InSig.
Foil Order Queue (time averaged #)	4.5 3.8	8.9 7.1	11.0 11.5	8.1	Sqrt	InSig.
Sheet Order Queue (time averaged #)	37.4 31.3	42.5 32.3	47.6 33.6	42.5	-	InSig.
Cast Coil Queue (time averaged #)	434.3 144.7	425.0 176.8	427.0 182.9	428.8	-	InSig.
Cold-Rolling Queue (time averaged #)	2.24 0.19	1.85 0.22	2.74 0.32	2.28	-	**
Annealing Queue (time averaged #)	9.45 0.45	8.16 0.37	9.41 0.79	9.01	-	**
Mill 1 Utilization (time averaged %)	59.37 0.66	61.82 0.74	58.83 0.90	60.01	-	**
Mill 2 Utilization (time averaged %)	59.32 0.63	61.79 0.68	58.80 0.92	59.97	-	**
Annealing Furnace 1 Load (time averaged %)	51.29 1.19	51.39 1.43	51.20 1.53	51.29	-	InSig.
Annealing Furnace 2 Load (time averaged %)	50.90 1.27	51.61 1.37	51.14 1.57	51.22	-	InSig.
% Foil Order Satisfied	95.04 0.57	94.49 0.86	94.22 1.42	94.58	-	*
% Sheet Order Satisfied	97.02 1.00	96.98 0.97	96.72 0.99	96.90	-	InSig.
Slack Time of Foil Order (min/order)	88552.9 2190.6	87127.8 2558.9	86625.6 3206.1	87435.4	-	*
Slack Time of Sheet Order (min/order)	101255 3644.0	101337 3845.8	100806 2937.8	101132	-	InSig.
Number of Tardy Foil Orders (#/year)	0.08 0.27	7.75 9.69	6.68 9.30	4.83	- !	**
Average Tardiness of Foil Order (min./tardy order)	104.2 473.9	54456 77133.2	37014 64589.6	30525	-	**
Number of Tardy Sheet Orders (#/year)	1.7 1.5	33.7 41.9	63.7 54.8	33.0	- !	**
Average Tardiness of Sheet Order (min./tardy order)	1811.1 1954.1	5504.2 3168.7	31642.8 19899.1	12986.0	Sqrt	**

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

* Significant at a = 0.05
** Significant at a = 0.01
! : Normality and constant variance assumptions to apply ANOVA are violated.

Table F.16. Duncan's Multiple Range Test Results
for Alternative **BCMA** Under 1.25xCurrent Demand

BCMA (Demand*1.25)	Ranking Of Rules According to Duncan's Test			
Performance Measures	*Sequencing Rules*			Note
	EDD	SPT	SRNO	
Foil Order Waiting Time (min/order)	1	2	1, 2	
Sheet Order Waiting Time (min/order)				InSig.
Cast Coil Waiting Time (min/order)				InSig.
Cold-Rolling Flow Time (min/order)	2	1	3	
Annealing Flow Time (min/order)	2	1	2	
Foil Order Flow Time (min/order)	1	2	2	
Sheet Order Flow Time (min/order)				InSig.
Foil Order Queue (time averaged #)				InSig.
Sheet Order Queue (time averaged #)				InSig.
Cast Coil Queue (time averaged #)				InSig.
Cold-Rolling Queue (time averaged #)	2	1	2	
Annealing Queue (time averaged #)	2	1	2	
Mill 1 Utilization (time averaged %)	2	1	3	
Mill 2 Utilization (time averaged %)	2	1	3	
Annealing Furnace 1 Load (time averaged %)				InSig.
Annealing Furnace 2 Load (time averaged %)				InSig.
% Foil Order Satisfied	1	2	2	
% Sheet Order Satisfied				InSig.
Slack Time of Foil Order (min/order)	1	1, 2	2	
Slack Time of Sheet Order (min/order)				InSig.
Number of Tardy Foil Orders (#/year)	1	2	2	
Average Tardiness of Foil Order (min./tardy order)	1	2	2	
Number of Tardy Sheet Orders (#/year)	1	2	3	
Average Tardiness of Sheet Order (min./tardy order)	1	1	2	

Table F.17. Results for Alternative **BCMA** under 1.5xCurrent Demand

BCMA (Demand*1.5)	2 casters, 2 cold-mills, 2 annealing furnaces					
Performance Measures	*Sequencing Rules*			Avg.	Trans. Used	Sig.
	EDD	SPT	SRNO			
Foil Order Waiting Time	43686.2	67356.4	56312.7	55785.1	Sqrt	**
(min/order)	14789.5	18639.0	23750.6			
Sheet Order Waiting Time	45378.2	38610.1	27599.2	37195.8	Sqrt	**
(min/order)	5424.8	3836.0	3423.2			
Cast Coil Waiting Time	3076.2	1523.7	2748.9	2449.6	Sqrt	**
(min/order)	1433.6	940.2	1703.0			
Cold-Rolling Flow Time	68.3	65.0	66.8	66.7	-	InSig.
(min/order)	13.1	9.1	6.3			
Annealing Flow Time	1823.0	1176.2	1425.4	1472.9	Ln	**
(min/order)	309.1	10.8	65.5			
Foil Order Flow Time	56493.5	79328.7	67356.6	67726.2	Sqrt	**
(min/order)	14133.7	17368.0	22563.2			
Sheet Order Flow Time	51017.8	43522.6	32714.8	42418.4	Sqrt	**
(min/order)	5405.6	3949.1	3393.9			
Foil Order Queue	131.0	200.0	180.3	170.4	-	**
(time averaged #)	41.4	48.6	51.3			
Sheet Order Queue	554.4	496.4	503.0	517.9	-	**
(time averaged #)	60.7	52.7	60.1			
Cast Coil Queue	48.2	116.8	53.7	72.9	Sqrt	**
(time averaged #)	39.7	62.5	36.2			
Cold-Rolling Queue	3.85	3.54	3.75	3.72	-	InSig.
(time averaged #)	0.98	0.67	0.48			
Annealing Queue	18.24	7.05	11.13	12.14	Ln	**
(time averaged #)	5.54	0.28	1.20			
Mill 1 Utilization	62.22	65.73	59.90	62.62	-	**
(time averaged %)	1.40	1.66	1.16			
Mill 2 Utilization	62.19	65.70	59.91	62.60	-	**
(time averaged %)	1.42	1.65	1.16			
Annealing Furnace 1 Load	53.02	53.49	52.67	53.06	-	InSig.
(time averaged %)	1.74	2.21	1.93			
Annealing Furnace 2 Load	53.01	53.14	51.83	52.66	-	*
(time averaged %)	1.80	2.11	2.04			
% Foil Order Satisfied	84.30	77.57	80.17	80.68	-	**
	3.21	3.70	4.15			
% Sheet Order Satisfied	84.62	86.49	85.97	85.69	-	**
	1.27	1.14	1.27			
Slack Time of Foil Order	43384.0	24753.9	36666.7	34934.8	Ln	**
(min/order)	14270.8	17585.5	22961.1			
Slack Time of Sheet Order	58469.7	67504.0	78454.3	68142.7	Ln	**
(min/order)	6083.7	4016.1	3763.6			
Number of Tardy Foil Orders	174.8	396.9	294.8	288.8	-	**
(#/year)	127.4	102.2	147.8		!	
Average Tardiness of Foil Order	18285.2	58246.8	50732.5	42421.5	Sqrt	**
(min/tardy order)	9731.1	10064.6	18376.9		!	
Number of Tardy Sheet Orders	525.5	853.3	613.5	664.1	-	**
(#/year)	216.6	95.0	98.3			
Average Tardiness of Sheet Order	25380.9	52839.5	71855.6	50025.4	Sqrt	**
(min/tardy order)	8815.3	6679.0	12122.2		!	

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

* Significant at a = 0.05
** Significant at a = 0.01
! : Normality and constant variance assumptions to apply ANOVA are violated.

Table F.18. Duncan's Multiple Range Test Results for Alternative **BCMA** under 1.5xCurrent Demand

BCMA (Demand*1.5)	Ranking Of Rules According to Duncan's Test			
Performance Measures	*Sequencing Rules*			Note
	EDD	SPT	SRNO	
Foil Order Waiting Time (min/order)	1	3	2	
Sheet Order Waiting Time (min/order)	3	2	1	
Cast Coil Waiting Time (min/order)	2	1	1, 2	
Cold-Rolling Flow Time (min/order)				InSig.
Annealing Flow Time (min/order)	3	1	2	
Foil Order Flow Time (min/order)	1	3	2	
Sheet Order Flow Time (min/order)	3	2	1	
Foil Order Queue (time averaged #)	1	2	2	
Sheet Order Queue (time averaged #)	2	1	1	
Cast Coil Queue (time averaged #)	1	2	1	
Cold-Rolling Queue (time averaged #)				InSig.
Annealing Queue (time averaged #)	3	1	2	
Mill 1 Utilization (time averaged %)	1, 2	1	2	
Mill 2 Utilization (time averaged %)	1, 2	1	2	
Annealing Furnace 1 Load (time averaged %)				InSig.
Annealing Furnace 2 Load (time averaged %)	1	1	2	
% Foil Order Satisfied	1	3	2	
% Sheet Order Satisfied	2	1	1, 2	
Slack Time of Foil Order (min/order)	1	3	2	
Slack Time of Sheet Order (min/order)	3	2	1	
Number of Tardy Foil Orders (#/year)	1	3	2	
Average Tardiness of Foil Order (min/tardy order)	1	2	2	
Number of Tardy Sheet Orders (#/year)	1	2	1	
Average Tardiness of Sheet Order (min/tardy order)	1	2	3	

Table F.19. Results for Alternative **BCMA** Under 2.0xCurrent Demand

BCMA (Demand*2.0)	2 casters, 2 cold-mills, 2 annealing furnaces					
Performance Measures	*Sequencing Rules* EDD	SPT	SRNO	Avg.	Trans. Used	Sig.
Foil Order Waiting Time (min/order)	163374 7507.9	174263 9341.6	173640 10553.9	170426	Sqrt	**
Sheet Order Waiting Time (min/order)	113116 4584.3	105399 5288.5	41750 3628.9	86755	Sqrt	**
Cast Coil Waiting Time (min/order)	638.7 46.6	652.1 45.1	567.2 59.3	619.3	-	**
Cold-Rolling Flow Time (min/order)	67.1 4.9	48.4 1.6	51.3 2.3	55.6	-	**
Annealing Flow Time (min/order)	1913.3 414.0	1141.5 7.1	1336.9 34.6	1467.2	1/Sqrt !	**
Foil Order Flow Time (min/order)	172188 7530.5	182770 9380.2	181946 10030.8	178968	Ln	**
Sheet Order Flow Time (min/order)	117906 4588.3	109082 5200.3	46447 3450.0	91145	Ln	**
Foil Order Queue (time averaged #)	595.9 27.8	721.0 34.4	708.5 37.7	675.1	-	**
Sheet Order Queue (time averaged #)	1807.9 65.3	1676.8 82.2	1699.5 75.7	1728.1	-	**
Cast Coil Queue (time averaged #)	21.0 1.54	21.1 1.46	19.2 2.05	20.4	-	**
Cold-Rolling Queue (time averaged #)	3.79 0.38	2.35 0.13	2.55 0.17	2.89	-	**
Annealing Queue (time averaged #)	19.2 6.87	6.2 0.13	9.1 0.56	11.5	Recip. !	**
Mill 1 Utilization (time averaged %)	60.18 0.69	61.65 0.57	53.24 0.56	58.36	-	**
Mill 2 Utilization (time averaged %)	60.18 0.68	61.68 0.62	53.22 0.48	58.36	-	**
Annealing Furnace 1 Load (time averaged %)	51.93 1.37	50.17 1.60	49.22 1.84	50.44	-	**
Annealing Furnace 2 Load (time averaged %)	51.64 1.46	50.14 1.48	49.58 1.84	50.45	-	**
% Foil Order Satisfied	55.72 1.40	47.60 1.55	48.21 1.92	50.51	-	**
% Sheet Order Satisfied	66.35 0.88	68.83 1.16	68.38 1.06	67.85	-	**
Slack Time of Foil Order (min/order)	-70875 7385.2	-78361 9666.3	-78138 10287.0	-75791	- !	**
Slack Time of Sheet Order (min/order)	-10287 4319.7	2033 5246.1	64442 3341.7	18729	-	**
Number of Tardy Foil Orders (#/year)	806.9 35.8	691.3 28.0	690.1 33.9	729.4	Sqrt	**
Average Tardiness of Foil Order (min/tardy order)	96787 6160.9	108626 7705.0	109644 7760.5	105019	-	**
Number of Tardy Sheet Orders (#/year)	2230.7 360.0	2581.0 157.0	692.0 69.5	1834.5	Ln	**
Average Tardiness of Sheet Order (min/tardy order)	69568 11169.8	72582 3781.7	189949 21051.7	110700	Sqrt	**

Note: In each cell, the average and the standard deviation (gray shaded) of 40 replications are given.

* Significant at a = 0.05
** Significant at a = 0.01
! : Normality and constant variance assumptions to apply ANOVA are violated.

Table F.20. Duncan's Multiple Range Test Results for Alternative **BCMA** Under 2.0xCurrent Demand

BCMA (Demand*2.0)	Ranking of Rules According to Duncan's Test			
Performance Measures	*Sequencing Rules*			Note
	EDD	SPT	SRNO	
Foil Order Waiting Time (min/order)	1	2	2	
Sheet Order Waiting Time (min/order)	2	2	1	
Cast Coil Waiting Time (min/order)	2	2	1	
Cold-Rolling Flow Time (min/order)	2	1	1	
Annealing Flow Time (min/order)	3	1	2	
Foil Order Flow Time (min/order)	1	2	2	
Sheet Order Flow Time (min/order)	2	2	1	
Foil Order Queue (time averaged #)	1	2	2	
Sheet Order Queue (time averaged #)	2	1	1	
Cast Coil Queue (time averaged #)	2	2	1	
Cold-Rolling Queue (time averaged #)	2	1	1	
Annealing Queue (time averaged #)	3	1	2	
Mill 1 Utilization (time averaged %)	1	1	2	
Mill 2 Utilization (time averaged %)	1	1	2	
Annealing Furnace 1 Load (time averaged %)	1	1, 2	2	
Annealing Furnace 2 Load (time averaged %)	1	1, 2	2	
% Foil Order Satisfied	1	2	2	
% Sheet Order Satisfied	2	1	1	
Slack Time of Foil Order (min/order)	1	2	2	
Slack Time of Sheet Order (min/order)	3	2	1	
Number of Tardy Foil Orders (#/year)	2	1	1	
Average Tardiness of Foil Order (min/tardy order)	1	2	2	
Number of Tardy Sheet Orders (#/year)	2	2	1	
Average Tardiness of Sheet Order (min/tardy order)	1	1	2	