University of Alberta

Reliability Models of the Rosario Automotive Paint Shop Plant in Argentina

by

Ariel Hernan Malanot ©

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To Edi and Alberto

ABSTRACT

This thesis presents an analysis of the car manufacturing industry process and designs a methodology to study its reliability. A car manufacturing process is a very difficult process to model for reliability purposes since there are no computational tools available or previous methodologies developed for that purpose. This industrial process cannot be analyzed by applying the series-parallel topologies that are used for power systems analysis and other system configuration because its behavior is sequential and cannot be represented by series–parallel reliability models. The proposed methodology is capable of modelling the vast number of elements present in a manufacturing process and their different failure modes, the effect of automation, power system and industrial processes, as well as the alternative and emergency plant operative modes. The methodology developed was successfully applied to the Phosphate-Elpo process of the General Motors Rosario Paint Shop Plant, in Rosario, Argentina.

PREFACE

This work is motivated by the need to develop a tool to analyze the reliability of sequential manufacturing systems, particularly for the car manufacturing industry. I observed and studied the behavior of these systems for some years during my professional work with General Motors Argentina in the Rosario Plant.

The objective of this Master of Science Thesis is to develop a reliability methodology to perform a detailed analysis of a car manufacturing production line. The method allows the prediction of the down time of the production line, its up time and the number of expected scrap cars as a result of failures in some critical process stages. The methodology also provides a way to discriminate in which way the different elements of the system (power system, conveyors, processes, etc,) are responsible for the downtime and failures per year of the production line. How the reliability of the plant changes when the number of cars produced per hour changes is included in the analysis. It is expected that this work will provide a strategic analytical tool to perform accurate financial analysis in order to determine the optimal production rate (cars/hour), to decide on new investment projects and proposed production line improvements and to improve the plant maintenance programs.

The methodology developed is applied to the actual Phosphate – Elpo process of the GM Rosario Plant, in Rosario, Argentina. This stage of the Paint Shop plant is one of the more critical stages in the car manufacturing industry, being fully automated and composed of many different subsystems, including conveyors, chemical processes, heating systems and complex electrical power and control systems. This industrial process was one of the main motives of inspiration to begin this work.

AKNOWLEDGMENT

This thesis is the result of my stay at the University of Alberta. During this period many people have contributed to my learning and, at the same time, to having a good time. But who deserves my major acknowledgement is my supervisor Dr. Don O. Koval. He was involved in this project further more than anymore could expect from a supervisor and many times beyond the academic limits. His uninterrupted advise, contributions, attention to every detail and tracking made it possible to complete the program in so a short period of time.

My mother Edi, my wife Eugenia and my daughter Karen, of course, were sources of unconditional support since the very beginning of this project.

Guillermo Zoratti has been a permanent source of ideas and made big contributions by collecting data, building models and providing the necessary feedback from the plant, and many times sacrificing his personal time in favor of this project. Without his contribution this thesis could have not been properly completed. In fact the idea to perform the study done in this thesis was the result of three years of analysis of the GM Rosario Paint Shop Plant that Guillermo Zoratti and the author performed sharing the responsibility of the Paint Shop Plant Maintenance Department

Ricardo Chanquía as my former supervisor at the Universidad Nacional de Rosario, Rosario, Argentina was always a invaluable source of advice and knowledge contributing generously always he was required.

Mrs. Vivian Koval, Catalin Slatineanu, Guillermo Zoratti, my brother Flavio Malanot and my wife Eugenia who helped me in the review of the writing were also a very important members of the team that supported me permanently.

José Luis Karkovich, responsible for the process engineering of the Phosphate – Elpo process representing Henkel Argentina, contributed generously to perform the modelling of this process by sharing all the necessary technical field data and professional knowledge.

I gratefully acknowledge the General Motors Rosario Plant, Human Resources and Paint Shop Plant Departments Represented by Silvia Catañy and Eduardo Palmisano respectively for providing unrestricted support for this work.

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LIST OF NOMENCLATURE AND ABBREVIATIONS

Elpo: Electro Deposition

PLC: Programmable Logic Controller

CPU: Central Process Unit

HMI: Human Man Interface

SCADA: Supervisory Control and Data Adquisition

CMMS: Computerized Management Maintenance System

DC: Direct Current

AC: Alternated Current

HVAC: Heating, Ventilation and Air Conditioning

Skid P: Process Skid

Skid B: Body Skid

PRB: Power Roll Bed Conveyor

DI Water: Deionized water

UF Solvent: Ultrafiltered Solvent

kV: kiloVolt

kVA: kilo Volt-Ampere

CHAPTER 1. INTRODUCTION AND DESCRIPTION OF GENERAL MOTORS ROSARIO PLANT

1.0. INTRODUCTION

In order to perform an accurate and useful reliability analysis, the nature of the productive process, including sequential conveyors, alternative systems and the emergency operation modes will be analyzed and modelled. The most commonly used reliability analysis methods for the analysis of industrial power systems defined in IEEE Std 493-1997(Gold Book) are minimal cut set, state space and network reduction. These methods are perfectly suitable for systems in which the operation modes can be reduced to serial and parallel combinations of elements like power systems. But there are fundamental differences between the nature of the power systems and manufacturing systems. Although the car manufacturing system appears to be a series – parallel system, similar to a power system, it is not, and the way in which a fault in one component affects the behavior of another in the production line is totally different. An extensive literature review was undertaken for this Master of Science Thesis and it was concluded that the existing reliability models cannot provide an integral solution to the GM plant.

A manufacturing sequential system is described in Chapter 1 and a new reliability analysis methodology was developed and is described in Chapter 2. To include the influence of the power distribution system in the manufacturing sequential system, the proposed method for reliability calculation is also capable of performing power systems reliability calculations.

Some maintenance and reliability software are able to calculate the reliability of a system if the logic of operation of the system (with electrical and mechanical components) is based on series and parallel configurations, or their combinations. Those software packages include a database with only main components or whole subsystems.

But they do not include particular components such as sensors, valves, control systems and conveyor systems, that are present in each stage of the car manufacturing industry and are responsible for a significant number of failures or machine malfunctions.

Existing reliability models cannot analyze the impact of particular elements on a system. These components are also included in the proposed reliability study method developed in this thesis. The use of traditional parallel-serial classical reliability systems theory is not suitable for manufacturing systems and can lead to totally incorrect results. Existing databases containing reliability data of equipment and components cannot account for the effect of aging or work cycles. A method to account the mentioned aging effects on the reliability indices is also proposed.

A very important aspect to be considered is the huge amount of elements that affect the reliability of the entire system. The proposed method for reliability analysis of a manufacturing process was designed to be practical and provide a way to reproduce and repeat quickly elements that are common to many sub-systems, and, when it is required to perform some specific analysis, to change the reliability parameters of all the elements repeated in the system at the same time. It is important also to provide a way to represent the system under study in such a way that it would be possible to introduce changes in the systems and sub-systems easily as well as to obtain the reliability parameters of particular sub-systems if necessary (e.g. accounting for aging effect on components).

A detailed description of the very complex Paint Shop Plant processes is essential for understanding and constructing accurate reliability models.

1.1. General Overview of GM Rosario Plant

The GM Rosario Plant is located 20 km from Rosario, Argentina and is dedicated to the production of small cars, Sport Utility Vehicles and engines. A picture of the GM Rosario Plant with the identification of the productive facilities is shown in Figure 1.1. In the same picture, the production flow is also indicated.

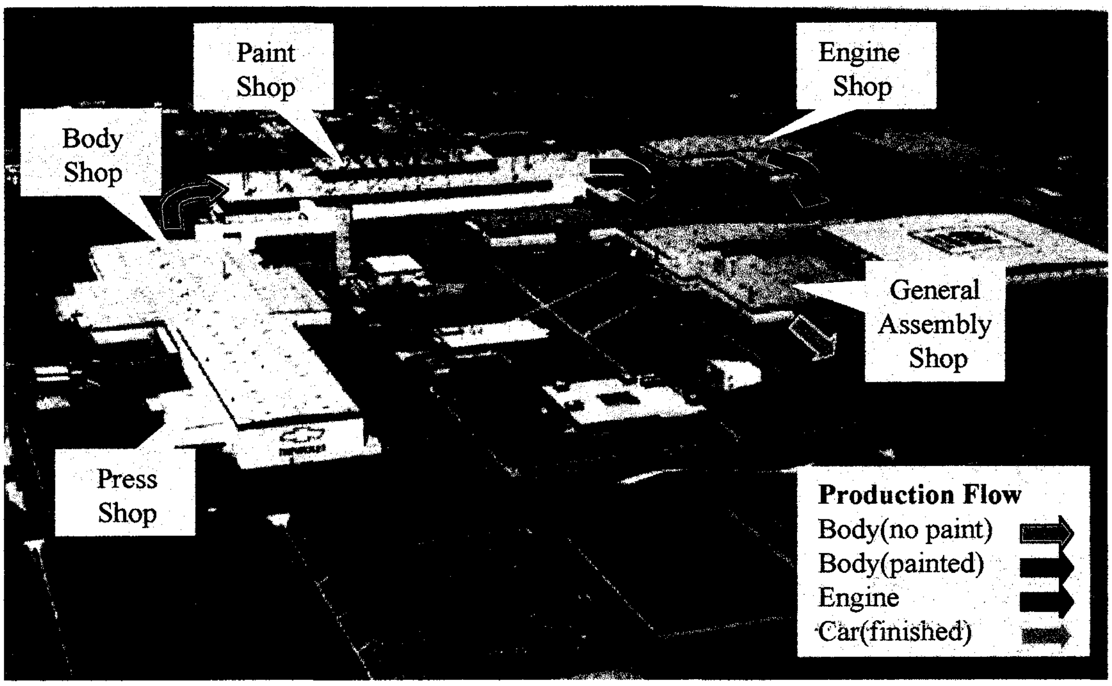


Figure 1.1. General Motors Rosario Plant

It can be observed in Figure 1.1. that the GM Rosario Plant is integrated by:

- Press Shop
- Body Shop
- Paint Shop
- General Assembly Shop
- Engine Shop

The Plant produces the following car models: Chevrolet Corsa Station Wagon, Sedan (3, 4, and 5 doors), and the Sport Utility Vehicles Chevrolet Tracker and Suzuki Grand Vitara. The Rosario Plant is equipped with its own engine plant, producing

- 1.6 liter versions of GM′s family I engines
- 1.4 liter gasoline engines
- 1.7 liter Isuzu diesel engines

1.2. Brief description of the components of the Car Manufacturing Complex

In order to construct a reliability model of the car manufacturing complex, it is essential to have a basic understanding of the parts of the plant and how they are integrated to form an operating system configuration

1.2.1. Press Shop

The Car construction starts in the press shop, where sheets of high quality steel are cut and formed into body panels. Here, 10 machines ‘stamp-out’ high quality pressed steel panels. The two press lines consist of 5 press machines each. Material handling between presses and press process is fully automated. After careful inspection by skilled operators under special lighting, the newly formed steel panels move onto the next stage in the manufacturing process.

1.2.2. Body Shop

The Body Shop is divided in two main components, Sub-assembly and Body Building. The component Sub-assembly area builds the front and rear doors, tailgates, facing panels and roof assemblies on semi-automated production lines.

When the underbody is built, it is mounted on a conveyor skid (device designed to transport the car body to the various assembly and production processes throughout the plant). The completed subassemblies now progress to the computer controlled body framing line where they are welded together to form the complete body. At the end of the framing line, the body receives the doors, bonnet, tailgate and front wings which have been built separately.

1.2.3. Paint Shop

The bodyshell is now transferred to the continuous conveyors that will carry it throughout its journey. The Paint Shop can be divided in two main stages, Phosphate and Electro – deposition (Elpo) coat, and Paint Coats and Finishing. The reliability of the first stage is analyzed in this thesis and is described in Chapter 4.

<u>Paint Shop Stage I</u> - Phosphate and Electro – deposition Processes

The metal surface must be completely clean before any paint can be applied. The bodyshell goes throughout the Phosphate process, the Electro-deposition process (Elpo), and the Elpo oven.

<u>Paint Shop Stage II</u> - Paint Coats and Finishing

The PVC finishing and sealers are applied. The body now moves through a series of spraygun stations where primer, color and clear coat are applied. The Primer and Topcoat Ovens are responsible for the drying processes. At the end of the paint process the body side mouldings and badges are fitted. Before the body leaves the paint shop anticorrosion wax is injected into the underbody box sections.

1.2.4. General Assembly Shop

The components of the general Assembly Plant are Trim and Final Assembly and inspection.

Trim Shop

The body enters the Trim Shop where the doors are removed to improve access for the assembly line team. The exterior components, such as bumpers and lights, are carefully fitted, together with all the interior components including the steering, airbag and electrical systems. The instrument panel and doors are fully assembled and tested off the main car assembly line.

Final Assembly and inspection

It is here that the car unites with major technical assemblies such as the engine and transmission unit, suspension, wheels and brakes. The car progresses through final assembly where fully prepared road wheels and tires are added. At this point, the exhaust system is also installed. The doors are re-attached, fully trimmed and tested. With oil, water and fuel added, the car is finally capable of moving under its own power. A series of comprehensive checks and final adjustments are completed before the car is released.

1.2.5. Engine Shop

The Engine Shop is an independent production and business unit, divided in 4 main components, Block, Crankshaft, Rod, and Engine Assembly Line. Block, Crankshaft and Rod are arrangements of machines that perform independently operations (for example, drilling) on basic metal pieces, which are transported through the different machines to perform the required operations. Once the pieces are finished and approved, they are stored, and when required are transported to the Engine Assembly Line.

In the Engine Assembly Line the different pieces are assembled to build the engine and in the last stage, each engine is tested. The engines are then stored and sent to the General Assembly Shop on the production schedule.

1.3. Conveyor Systems

The sequential transport of the bodyshell among the process stages is done automatically by the "Conveyor Systems". There are 19 Conveyor Systems in the Rosario Industrial Complex and 14 of them are located in Paint Shop. A Programmable Logic Controller (PLC) commands each Conveyor System which is named according to the name assigned to the PLC Central Process Unit (CPU). These names will be respected in the present study. Example: the Conveyor System that commands the 3 Inter – shop Tunnel Conveyors (Paint Shop – General Assembly and General Assembly – Body Shop) is called Conveyor System CPU12.

1.4. Paint Shop Plant Stages

A bodyshell, mounted on a skid, arrives at the Paint Shop Plant via a conveyor tunnel. It is covered with a film of grease and oil as a result of the stamping and body welding stages. Some particles of metal and dust are also found in the bodyshell as a result of the welding process. The Paint Shop Plant delivers the bodyshell painted, waxed, with mouldings and badges fitted.

The process carried out in the Paint Shop Plant involves several sequential stages. They are:

- Anti corrosion protection Elpo dip (Phosphate –Elpo process)
- Elpo Paint Sanding
- Sealing 1
- Undercoat
- Sealing 2

- Primer Coat
- Primer Coat Sanding
- Base Coat
- Clear Coat
- Finesse
- Emblems fixing
- Wax filling

The production stages combine manual and automatic operations. Overall, for all the process stages and auxiliary systems, more than 50 PLCs are involved. They are responsible for the control of several automatic systems such as Chemical Processes, Paint and Fluids Pumping, Ovens, Elpo DC Power Supply, Air Supply Systems, Waste Water and Sludge and Heating Ventilation and Air Conditioning (HVAC) system.

1.5. Anti – corrosion Phosphate - Elpo Process Description

The Phosphate - Elpo Paint (Electro Paint Deposition or Elpo) Process Layout is shown in Figure 1.2.

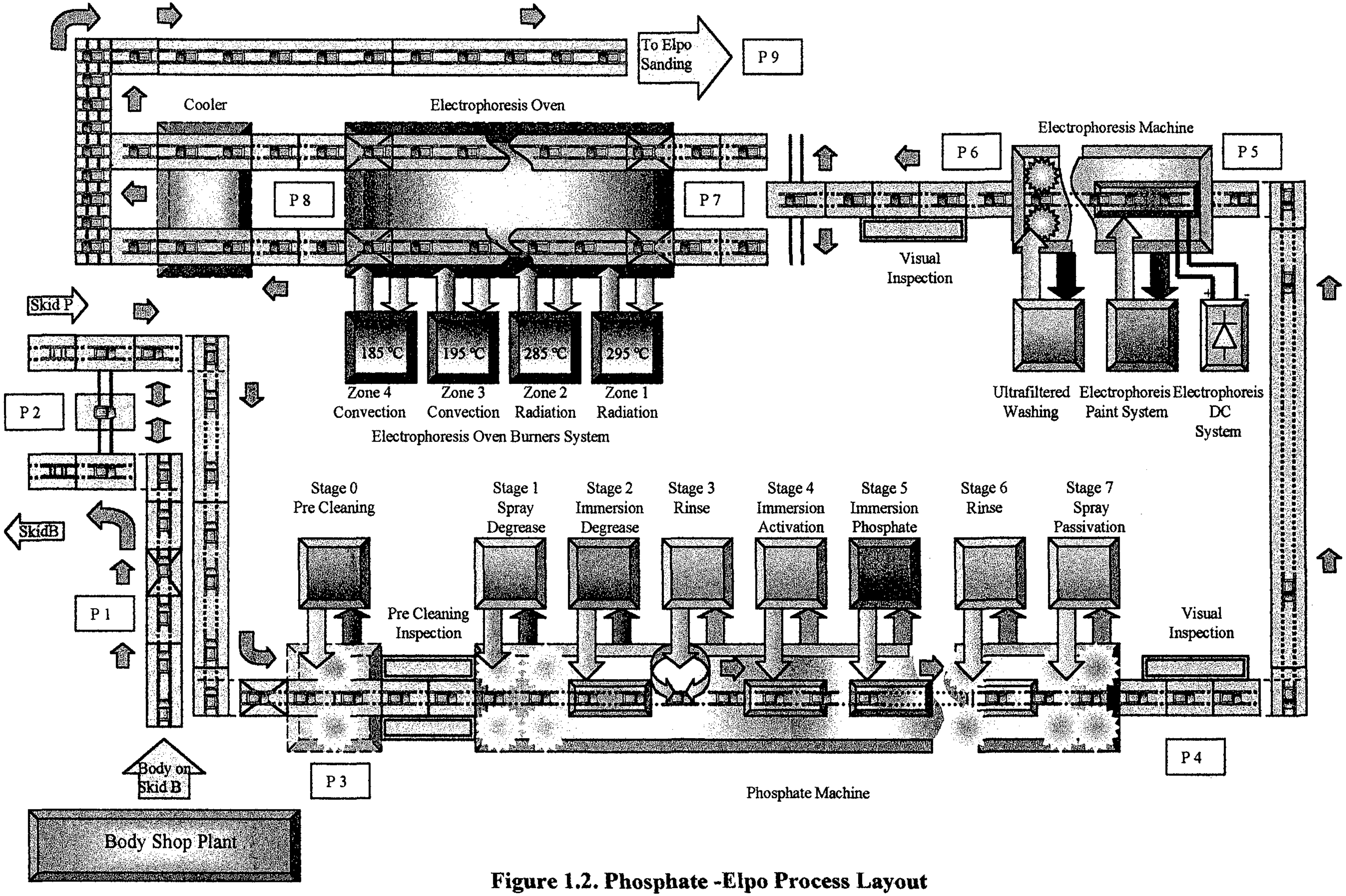


Figure 1.2. Phosphate -Elpo Process Layout

Normally a skid coming from Body Shop Plant transports a bodyshell, but it can also carry spare parts. In order to simplify the description, it will be assumed that the skid always carries a bodyshell. The Elpo process steps are described below according to the numbers assigned in Figure 1.2.

1.5.1. P1 - P2. Loaded skid arrival at Paint Shop Plant to skid switching

In Figure 1.3. a layout of stages P1-P2 and P2-P3 is shown, including the conveyors identification according to the GM Paint Shop Plant mnemonics, that are explained in Chapter 4.

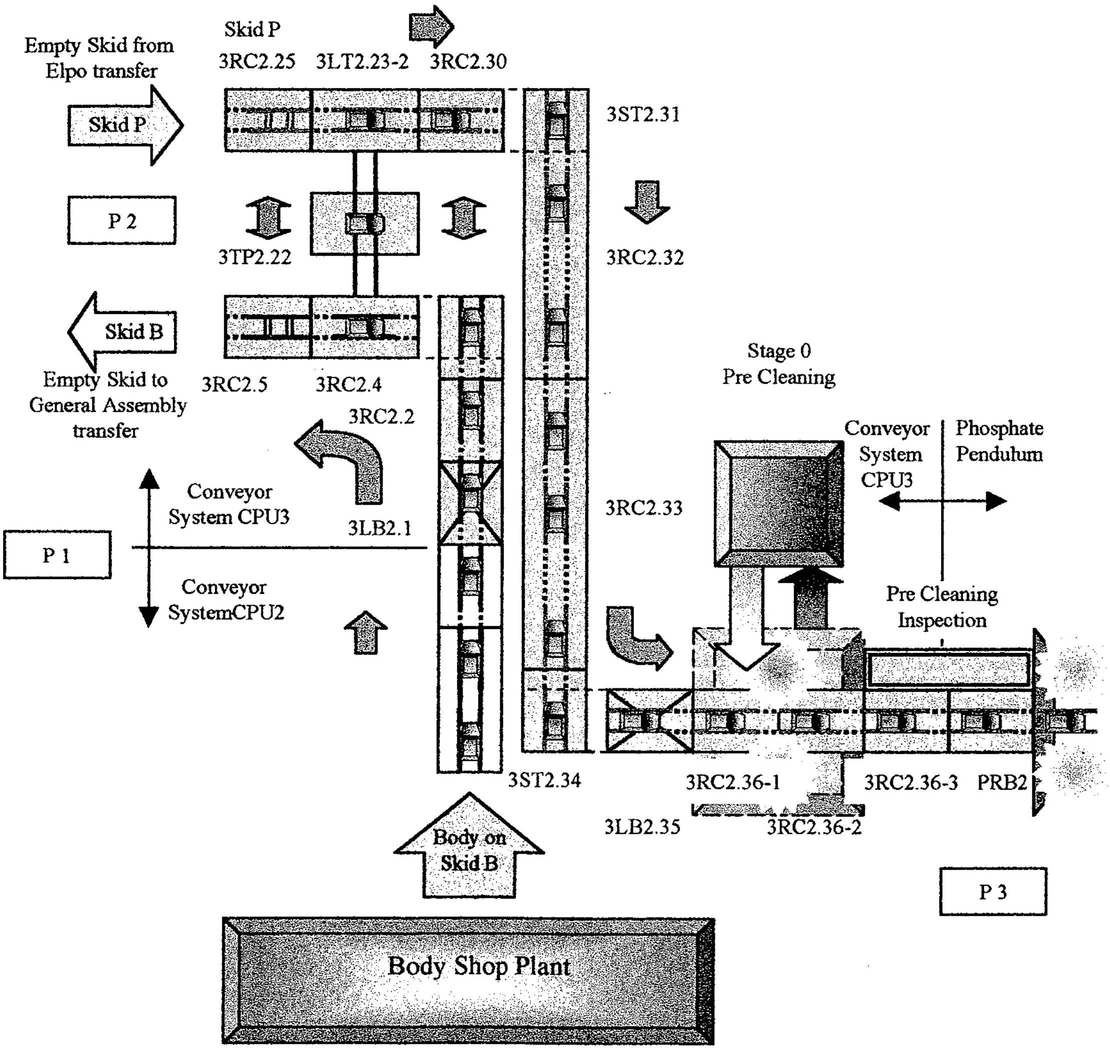


Figure 1.3. Process stages P1 to P3

The “body skid” loaded with a bodyshell, coming from the Body Shop Plant arrives at the end of the conveyor tunnel that connects Body Shop Plant and Paint Shop Plant (Conveyor System CPU2). This loaded skid goes through the paint shop entrance gate and is transferred to the Conveyor System CPU3. The conveyors in the Conveyor System CPU2 contain 51 different conveyor types (e. g. Belt Bed, Elevators, Telescope, and Rotating Power Roll Beds). The Conveyor System CPU3 includes 57 conveyors of different types, including Elevators, Power Roll Beds, Rotating Power Roll Beds, Scissors Lifters, a Scissors – telescope Lifter and Transversal Belt Beds.

1.5.2. P2 – P3. Skid Switching to Phosphate Conveyor Loading

The scissors telescope lifter (see 3.TP2.22 in Figure 1.3.) releases the bodyshell from the “body skid” and loads it on a “process skid”. The “process skid” is heavier than the “body skid” because it needs a stronger structure to stand the stress suffered when it hangs on the pendulum conveyor. The empty “body skid” continues on its way to the other station where it is loaded with a ready painted bodyshell. This is carried to General Assembly Plant in order to start the car assembly.

The “process skid” loaded with the body car continues (Conveyor System CPU3) its way to the Phosphate Machine. As is shown in Figure 1.3, the last conveyor of the Conveyor System CPU3 is the Power Roll Bed 3RC2.36-3, which transfers the skid loaded with the bodyshell to the Power Roll Bed PRB2 of the Phosphate Pendulum Conveyor System. A visual inspection, quality control and unit identification is performed before the unit is loaded in the Phosphate pendulum. This point is identified “P3” in Figure 1.3.

1.5.3. P3 – P4. Phosphate Process

The purpose of the Phosphate Process is to provide anticorrosion protection to the car body. This anticorrosion operation pre-treats the metal body parts preparing them for the subsequent operations (Elpo Paint), by applying a protective coating. Three steps are included in the anticorrosion operation: aqueous washing, zinc phosphating, and a pacifying rinse. A water rinse step follows the zinc phosphating and pacifying rinse steps. A layout of the Phosphate Process is shown in Figure 1.4.

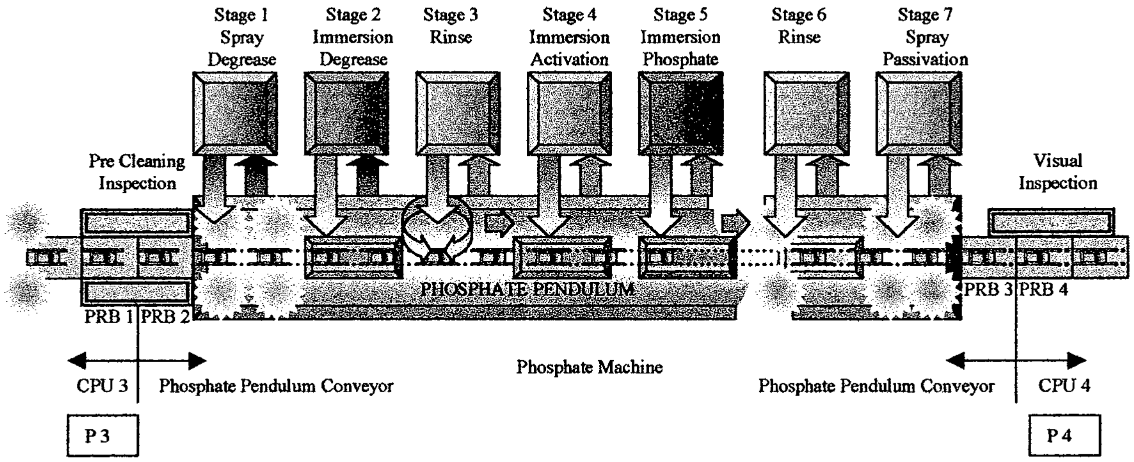


Figure 1.4 . Phosphate Process and Phosphate Pendulum Conveyor

1.5.4. Phosphate conveyor

The phosphate conveyor is able to hold up to 35 body cars at a time. Overall the machine length is close to 200 m. In order to submerse the body car into the 4 tanks a special conveyor has been developed. The so-called "Pendulum Conveyor" consists of two parallel chains with links designed to hold the pendulums. The pendulums are "U" shaped and the "process skid" is designed to fit over a pair of pendulums. The chains are driven by 2 motors which are pulling simultaneously. One of the motors is located at the end of the machine while the other is at its middle point.

1.5.5. Phosphate Stages

- **Stage #0 - Pre cleaning**

This stage shown in Figure 1.3 is designed to provide a pre-wash mist halo, and hand wiping of a cleaning material on each body. The pumping system is equipped with a backpressure regulator to allow the pumps to operate continuously and provide a constant pressure to the halo and hand wipe stations. There is a fresh water make-up and a chemical feed from the bulk storage. At this point the body car is transferred from the CPU3 Conveyor System to the Phosphate Pendulum conveyor.

Once the skid is loaded on the pendulum it is not possible to back up. That skid has to complete the phosphate, elpo and elpo oven steps in the time programmed in order not to compromise the quality of the product. The stages that start here are totally automatic and generally takes about two hours to get the car body painted with the hardened elpo paint.

- Stage #1 – Spray Degrease

This stage is a heated spray cleaner. The first rinse is pump fed from stage #3A with this spray going to the drain. This stage includes two sets of pumps; one set provides circulation through the bag filters, to the heat exchanger, and then to the spray/bypass; the other set provides circulation through the bag filters to the deluge spray. The deluge spray is started after initial heatup. There is no spray valve associated with these pumps. There is a counterflow/make-up from stage 3A. The chemical feed is from a day tank that is shared between stages 1 & 2. This stage also has a filtration circulation loop that is separately controlled.

- Stage #2 – Immersion Degrease

This stage is a heated immersion wash stage. The single set of pumps circulate solution through the bag filters, to the heat exchanger and to the tank eductors. The tank has continuous circulation but there are also entry and exit sprays that are controlled based on production. There is a counterflow/make-up from stage 3A. The chemical feed is from a day tank that is shared with stages 1 & 2.

-Stage #3 – Rinse

As the car body leaves the cleaning stage, it carries the out spent cleaner, emulsified soils and other contaminants. If it's not immediately rinsed, these contaminants could deposit on the surface and become very difficult to remove. The rinse must remove these unwanted materials and not interfere with subsequent operations. In this case a multi stage rinse is used to ensure all contaminants have been removed.

This stage is divided in two sub-stages, 3A and 3B.

- Stage #3 A - Spray Rinse

This stage is an un-heated spray rinse stage. The single set of pumps circulate solution through the bag filters to the spray risers as well as the counterflows to stages 1 & 2. The water make-up is through gravity overflow from stage 3B. The drain valve is opened based on conductivity of the tank.

- Stage #3 B - Spray Rinse

This stage also is an un-heated spray rinse stage. The single set of pumps circulate solution through the bag filters to the spray risers. The water make-up is through fresh water. This stage overflows to stage #3 A for makeup. Stage #4 overflows into this stage.

- Stage #4 – Immersion Activation

The function of this stage is to activate the metal surface by the action of Titanium Salts. It prepares the metallic surface to obtain a dense, uniform and microcrystalline phosphate deposition layer. This stage is an un-heated immersion rinse stage with conditioner rinse riser. The single set of pumps circulate solution through the bag filters to the tank circulation and spray risers.

The sprays operate continuously so as to provide tank circulation. The final rinse halo is the conditioner rinse. This rinse riser has a conditioner chemical injection tee. The water make-up for this stage can be provided by either de-ionized (DI) water make-up of fresh water make-up as selected by manual valves and the chemical provider. The chemical feed is by direct injection to the final rinse riser or by manual addition to the bath.

- Stage #5 – Immersion Phosphate

The bodyshell is submerged in a solution of phosphoric acid salts. The objective of this stage is to deposit a dense, uniform and microcrystalline layer of phosphate guaranteeing excellent adhesion and protection against corrosion combined with the applied paint. It is a heated stage with two sets of pumps; one set provides circulation to the dual heat exchangers and back to the tank eductor circulation system and the other exit spray risers. The exit spray valve is controlled by the production level of the system.

Water make-up is from fresh water. The chemical feed is from both an accelerator day tank and from a replenisher day tank. This stage also has a filtration circulation loop that is separately controlled.

The heat exchanger loop is provided with dual heat exchangers to facilitate on-line cleaning while providing a back up heat exchanger. The heat exchangers for the process solution are fed with hot water. The temperature of the solution is controlled by varying the temperature setpoint of the hot water control loop through a cascaded control arrangement.

- Stage #6 – Rinse

The bodyshell arrives at this stage covered with acid residues and subproducts resulted from the phosphate stage reactions. In order to remove them from the metallic surfaces the body car is sprayed and then submerged in a water base solution.

This stage consists of two sub-stages, 6A and 6B

- Stage #6 A & 6 B - Spray & Dip Rinse

With a single set of pumps the solution is circulated through bag filters, to both stage #6A pre-rinse and to stage #6B with both immersion tank eductors and pre/post rinse risers. The pre-rinse riser is controlled based on production and all of the drainage from this riser goes to drain. There is an additional riser at the exit of the stage that is supplied from fresh water. It is controlled based on production and the run off from the spray drains back to the stage 6 tank. The water make-up is through run off from the fresh rinse riser or from a fresh water make-up if required. This tank overflows to the process waste trench.

- Stage # 7 – Spray Passivation and Deionized water(D I) rinse

In this stage the car body is conducted through a multi stage spray station.
This stage consists of four sub-stages, 7A, 7B, 7C and 7D.

- Stage #7 A Acidulated spray

This stage is an un-heated, acid rinse stage. The single set of pumps circulate solution through bag filters to the spray risers. The acidulated chemical is injected to the tank based on production. The water make-up is from fresh water. This tank overflows to the process waste trench.

- Stage #7 B – Recirc D.I. Spray Rinse

This stage is an unheated, recirculated DI water rinse stage. The single set of pumps circulate solution through bag filters to the spray risers.

- Stage #7 C – Recirc D.I. Spray Rinse

This stage is an unheated, recirculated DI water rinse stage. The single set of pumps circulate solution through bag filters to the spray risers. The water make-up is through run off from the stage #7D fresh DI rinse riser or fresh D.I.

makeup line. This tank overflows to stage #7B.

- Stage #7 D – Fresh D.I. Spray

This stage is actually an exit riser in stage #7C. This rinse riser is supplied with fresh DI water and is controlled based on production. The run off from this riser causes stage #7C to overflow to stage #7B. Stage #7B then overflows to the drain.

1.5.6. Bulk Storage

Chemical solution is pumped from the Bulk Storage area to chemical day tanks on stages: Prep, #1, #2, and #5. Chemical is added based on the level of the day tanks. Air transfer pumps are started when a low level on the day tank is enunciated and continues until the chemical reaches a high level.

1.5.7. P4 - P5. Visual inspection and transport to the Elpo Pendulum

This process stage is shown in Figure 1.5.

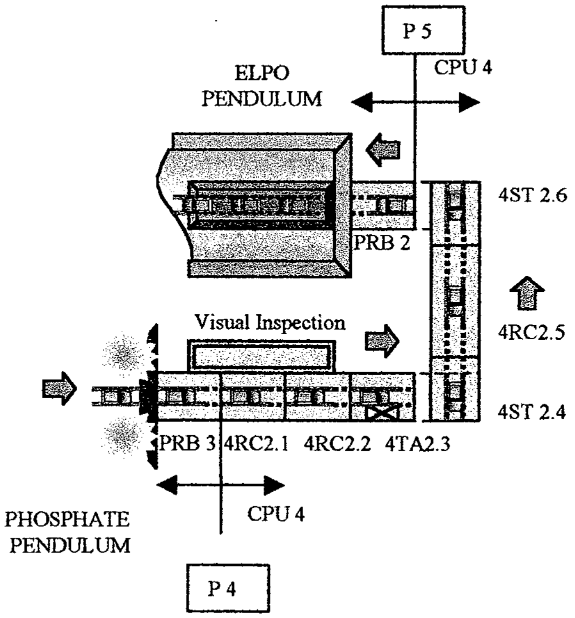


Figure 1.5. P4 -P5. Conveyor System CPU 4

From the Phosphate Pendulum the bodyshell is transferred on the Power Roll Bed 3 conveyor (PRB3). The PRB3 transfers the body car to the Power Roll Bed 4RC2.1 that belongs to the Conveyor Transport System CPU 4. The CPU 4 PLC controls the conveyors between the output gate of the Phosphate machine and the input gate of the Elpo Machine (P5). In that sector the conveyors are Power Roll Bed, Rotating Power Roll Bed and Shaking Power Roll Bed. The CPU 4 Conveyor System also controls 44 conveyors of the paint shop Plant. At P4 a visual inspection is performed to control the Phosphate Process quality.

1.5.8. P5 - Elpo Process

A layout of the Elpo Process, including the Elpo Pendulum and the Elpo Rectifier is shown in Figure 1.6.

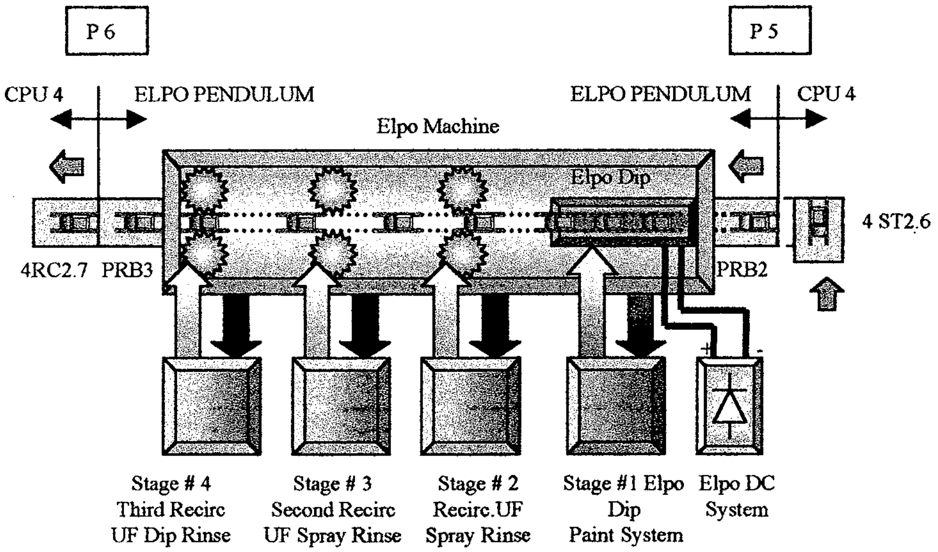


Figure 1.6. Elpo Process, Elpo Pendulum and Elpo Rectifier

The Elpo Paint is applied by a method called Cathaphoretic Dipping Painting System. This is a dipping painting system where the transport of the paint particles takes place by an electrical effect. The car body is submerged in a tank full of elpo paint. The car body acts as a cathode (positive charged) attracting the paint. The system allows penetration and total coverage, including the recesses, with a uniform thickness of paint. The layer of paint obtained is proportional to the amount of electric charge that passes through the car body. After that, the car body has to be rinsed and dried to obtain the specified paint hardness.

The stage by stage operation is described as follows

- Stage # 1 – Elpo Dip

This stage is the electrodeposition paint coating stage. This tank submerges the vehicle in a paint solution and grounds the carrier and vehicle. The anodes plates placed on the sides of the tank are given a positive D.C. charge causing the paint to be attracted to the bare steel of the vehicle.

The paint is circulated by two sets of pumps. The entrance end pumps circulate the paint by drawing it from the bottom of the entrance end, through bag filters and feeding the eductors on the right side of the dip tank. The exit end circulation pumps draw paint from the exit of the elpo tank, through bag filters, through the heat exchanger and back to the tank feeding the eductor system on the left side of the dip tank.

At the exit end of the dip tank, over the weir, is a spray riser that knocks the heavy solids of paint off the vehicle and back into the dip tank. This spray riser is the first recirculation UF rinse and also is the end of the ultra filtrate counterflow loop.

- Stage # 2 – First Recirculation UF Spray Rinse (over the weir)

This stage is actually a riser fed with solution from the circulation pumps from the next stage. These risers complete the ultra filtration counterflow loop. This is the most concentrated of the spray risers and drains completely into the elpo weir tank. If the second recirculation pump did overflow, it would overflow back to the elpo dip tank.

- Stage # 3 – Second Recirculation UF Spray Rinse

This stage has two pumps that both run to supply solution from the recirculation tank through bag filters to the spray risers. The spray riser has a valve to bypass the spray back to the tank when there are no vehicles in the stage thus reducing foaming in the recirc tank.

- Stage # 4 – Third Recirculation UF Dip Rinse

The dip rinse stage two pumps that both run to draw solution from both the entrance end weir and the bottom of the exit end. The solution is fed through the bag filters to the eductor header.

This stage is fed with solution from the run off the continuously spraying entrance riser of the next stage and the excess solution is normally overflowing into the previous stage.

1.5.9. Elpo Machine

A pendulum conveyor similar to that described for the phosphate machine carries the car body through the different stages of the elpo machine. This conveyor has room to carry 12-car bodies simultaneously.

1.5.10. Elpo Paint System

The paint consists of two components. Compound and ultrafiltered solvent (U F Water base). The balance between both components is carefully and continuously controlled.

It was said previously, that the paint is continuously recirculated and filtered. If the recirculating process stops, the paint will start to harden in the pipelines. After the recirculating process stops, the system has to be started within 120 minutes. Elsewhere, some parts of the pipelines could be blocked. Once a pipeline is blocked with Elpo paint, there is no way to clean it out, it has to be disassembled or cut. The damage to installations, in such a case, could reach several millions of US$ in installation and in weeks of down time of production. Because of that, the pumping system of this stage has an Emergency / Stand by Power Supply. It is a 250 kVA Diesel generator with automatic switching and start control.

The UF solvent is also continuously recirculated by a system of two parallel pumps, one of them operating continuously up and the other as a backup. There is also a system of pumps that feeds the hydraulic seals fluid to UF recirculating pumps. Both pumping systems have to be up continuously to keep the elpo system on and are also connected to the Emergency / Stand by Power Supply.

1.5.11. DC Power Supply

The DC Power Supply is a system of three 6 phase full bridge thyristor rectifiers. Each rectifier feeds a zone of the elpo tank. The Elpo tank has three main zones for paint application:

- Zone 1: Side (First stage)
- Zone 2: Side (Second Stage)
- Zone 3: Roof

Each zone operates with an independent AC/DC converter. For each zone there are over 15 electrodes used to obtain a homogeneous current distribution from which results a continuous thickness of paint film. The thickness of the resulting paint film depends on the amount of charge (current x time) that pass through the bodyshell surface.

1.5.11. P6 – P7 . Elpo Paint inspection and rinse water drain

When the bodyshell leaves the Elpo Pendulum it is wet because of the rinse stages. It will be drained and then continue on its way to the Elpo Oven. This Stage P6 – P7 is shown in Figure 1.7.

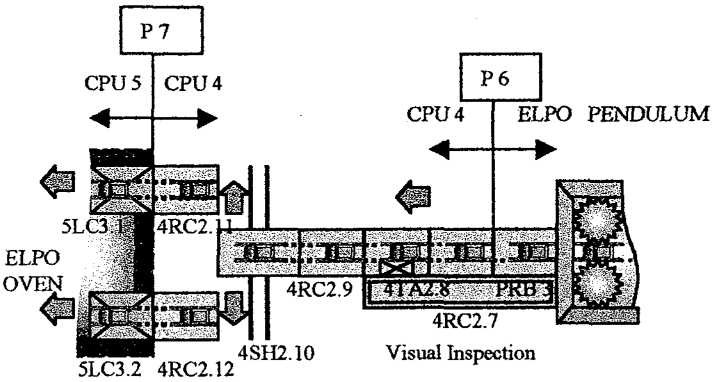


Figure 1.7. P6 - P7. Conveyor System CPU 4 R2

The Elpo Pendulum conveyor transfers the bodyshell to the PRB3 conveyor, and then to the CPU 4 Remote 2 (or CPU4 R2) Conveyor System. After being drained in the Shaking Power Roll Bed 4TA2.8 the car is transferred to the Lateral Transfer conveyor 4SH2.10. This conveyor alternatively selects directions in order to transfer the bodyshells in two parallel lanes. Each lane leads to one of 2 oven gates. It is the first time in the described process that it is possible to select between two options. That the lateral transfer conveyor "alternatively selects" means "once each lane", when both are available. If one of the lanes is down the bodyshells will be transferred to the only available lane. At this stage the CPU4R2 Conveyor System consists of Power Roll Beds, Shaking Power Roll Bed and Lateral Transfer conveyors. Then at point P7 shown in Figure 1.7 the bodyshells are transferred to Conveyor System CPU5 which will carry them through the Elpo oven.

1.5.13. P7. Elpo Oven

The car is baked into the Elpo oven in order to cure the elpo paint. To cure the elpo paint, the bodyshell is heated to a certain temperature for a period of time according to the paint provider specification. A basic lay out of the Elpo oven is shown in Figure 1.8.

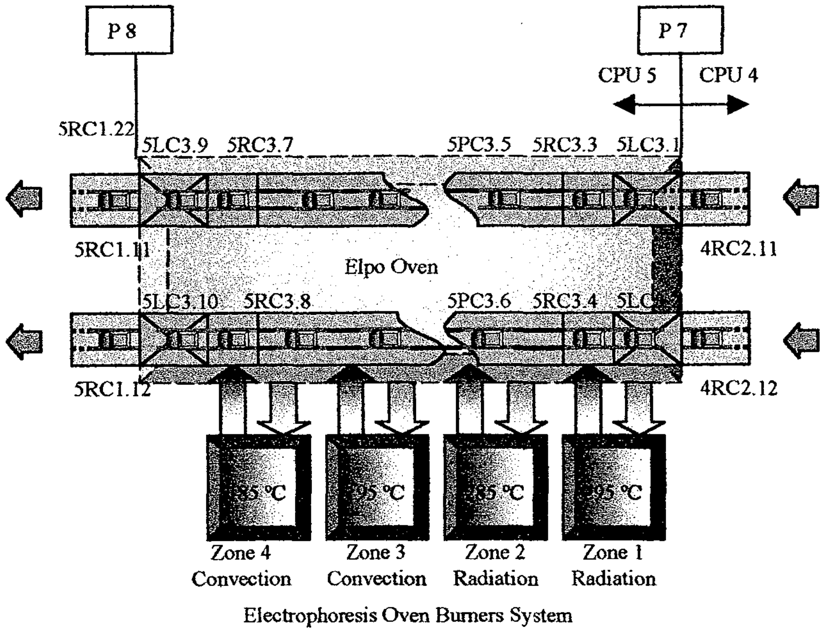


Figure 1.8. Elpo Oven and Conveyor SystemCPU5(partial)

The Elpo oven is a continuous process, two level, four zones oven. Two zones operate with different principles, the first two by radiation and the last two by convection. The four zones are natural gas fired and they are:

- Zone # 1 Radiation I	+ 295 ° C
- Zone # 2 Radiation II	+ 285 ° C
- Zone # 3 Convection I	+ 195 ° C
- Zone # 4 Convection II	+ 190 ° C

Although the oven gates are open type, a complex system of heated air fans, air exhausters, and recycle fans are precisely balanced so not as to have an exchange of heated air with the environment. The radiation zones operate by heating the interior oven walls. These walls are heated by a closed circuit of preheated air that is forced to go towards them. This preheated air circuit avoids the contact with the air that surrounds the bodyshells. Although the efficiency of heat exchanging of this method is poor, the contact with potentially contaminated air coming from the gas burners is avoided. This is particularly important at these first two oven zones because the paint is not cured yet.

When the car arrives to the first convection zone (Zone 3), the most superficial layer of elpo paint is totally dried. The convection zones operate by directing a homogeneous heated air current to the bodyshell surface. A system of over 2000 blast tewels guarantees that the elpo paint will be cured over the entire bodyshell surface.

1.5.14. Oven Conveyor System

The oven conveyor system shown in Figure 1.8 is controlled by the Conveyor System CPU5 PLC and consists of two independent conveyor lanes. Each lane has a chain conveyor of about 40 meters long, two Power Roll Bed and two 2 level Elevators. Due to the high temperatures involved, the mechanical and electrical drives are placed outside the oven. This is particularly more complicated for the elevators, due to the movements involved. For these conveyors the elevation and forward movements are carried out with special transmission chains. There are also proximity inductive sensors that operate in the oven with temperatures close to 300 ° C.

If some of the Oven Conveyor components installed inside the oven fail, it is not possible to repair it in the production shift. It is necessary to cool down the oven in order to enable the maintenance crew to perform the repair job. This operation takes at least 8 hours.

Although there are two parallel alternative lanes, the above mentioned characteristics make this stage particularly sensitive to component failure, and hence, this stage is one of the most critical in the Paint Shop Process. We want to note, at this point, that each oven lane can handle only 13 cars per hour. Normally the production line is running at 20 cars per hour. Hence, it is possible to operate in an emergency mode with one lane up and the other lane down, but it is not possible to process the scheduled production rate with one lane down. This particularity is carefully considered in this thesis to determine the reliability of the Elpo oven and the entire system.

1.5.15. P8 – P9 Cooler, Inspection and Transport to Elpo Sanding Stage

When the bodyshells leave the Elpo Oven their temperature is about 200 °C. Due to the high temperature it is not possible to perform any operation on the bodyshells. The cars are cooled down when they go through the Elpo Cooler shown in Figure 1.9.

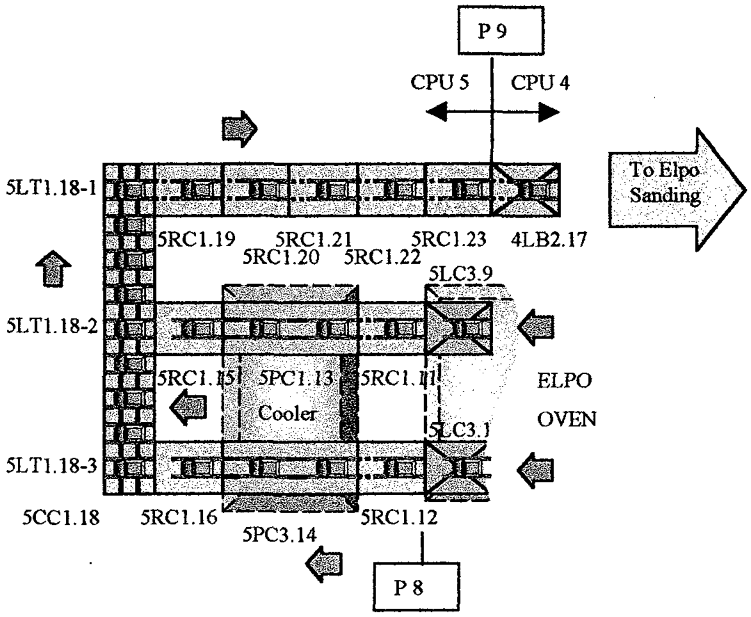


Figure 1.9. P8 -P9. Cooler, Inspection and Transport to Elpo Sanding

After the coolers both lanes merge in Lateral Chain Conveyor 5CC1.18 that finally transfer the bodyshells to a series of Power Roll conveyors (5RC1.19 to 5RC1.23 in Figure 1.9), with capacity for 5 bodyshells, that transport them to the Elpo Sanding Stage. The conveyors at this stage are controlled by the Conveyor System CPU5 PLC.

This Phosphate Elpo process can hold up to 80 bodyshells. The process time is about 2 hours and is the most critical stage of the Car Manufacturing Industrial Complex. At this stage, failures of any system component with an associated downtime for the phosphate pendulum longer than 3 minutes, could produce a scrap bodyshell. This is due to the tight process times, the corrosion exposure, and the impossibility to remove the car body from the production line once this process has started the first step.

CHAPTER 2. SEQUENTIAL MANUFACTURING PROCESS ANALYSIS

2.1. Introduction

The reliability modelling has to be based on how the manufactured cars are carried throughout the various process stages by conveyor systems, as explained in Chapter 1. Each conveyor follows a cyclic sequential process going through process states. For a typical conveyor, the state diagram is shown in Figure 2.1.

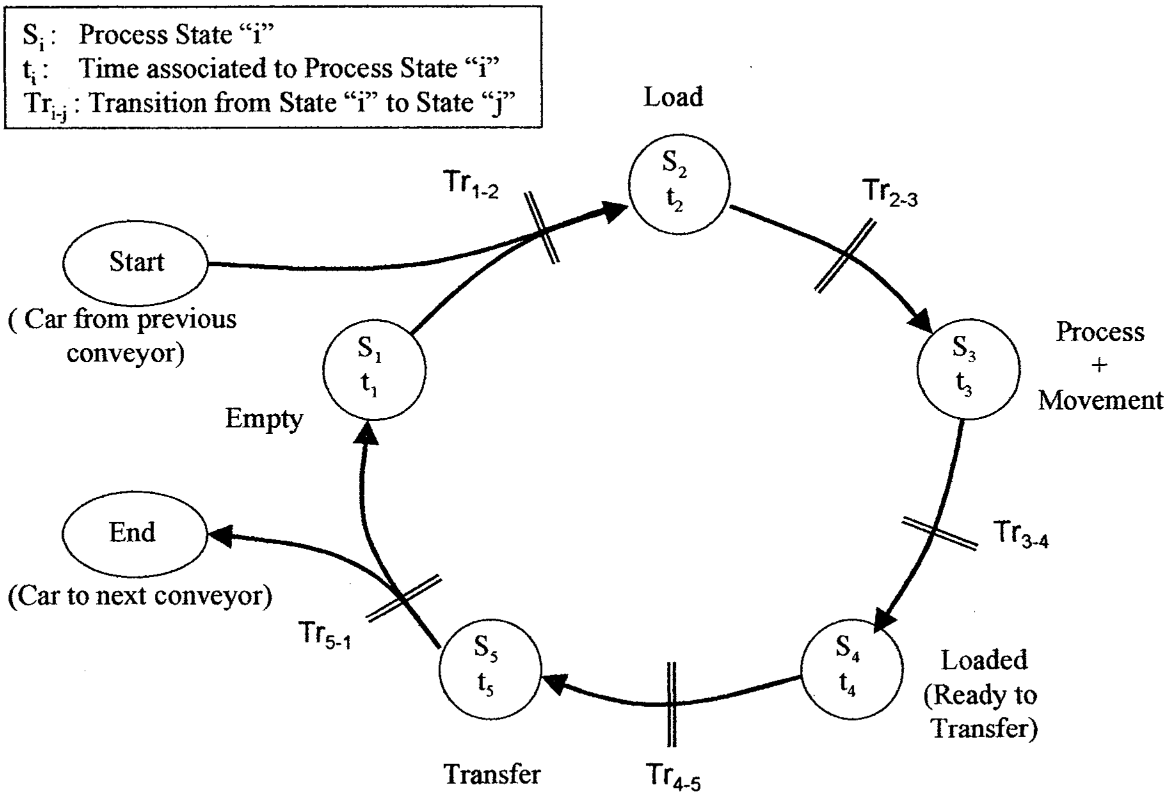


Figure 2.1. State Process Diagram for a Conveyor

In Figure 2.1, the steps to be followed by the process are denoted as $S_1,\ldots,S_5$ with the period of time used in each of these steps as $t_1,\ldots,t_5$. To advance from one state to the following, some specific conditions have to be met. These conditions are called "Transitions", and are noted in Figure 2.1 by Tr_{i-j}, where i and j are subsequent states. In order to analyze and explain the cycle of a conveyor system certain basic assumptions have to be made, (i.e., the conveyor is empty and the previous conveyor has a car ready to be transferred). Based on these assumptions the process states of Figure 2.1 are described:

State 1 (S_1): Conveyor empty (E)

After processing a car, it is transferred, and the conveyor remains empty. It will wait until the previous conveyor is in a "ready to transfer" state. The length of time (t_1) will depend on the difference between cycle times of both conveyors. If the previous conveyor cycle time is smaller than this one, the time t_1 will be zero.

State 2 (S_2): Car load (L)

The first active step is the car loading, i.e., the previous conveyor transfers the car, which is placed in the "load position". The time necessary to complete this step is denoted as t_2 in Figure 2.1.

State 3 (S_3): Car process and internal movement (P)

The car is processed at this stage and then it is transferred to the "ready to transfer" position. The "car process" and "internal transfer" can be done independently or simultaneously. In this step, for some conveyors there are no processes involved (e.g. elevators), while for others there are no movements involved and the process is complete with the car stopped (e.g. the shaking power roll bed). In this case, the "load" and "ready to transfer" positions (denoted as S_3) are the same. A series of internal operations, blocking actions and movements are taken in this step. A total time t_3 is considered for this step in order to simplify the analysis.

State 4 (S_4): Loaded - Wait for the next conveyor ready to load (W)

Once the car is placed in the "ready to transfer" position, the conveyor controller (PLC) has to wait for the signal "conveyor ready to load" from the next conveyor to start the transfer process. The period in this stage, which is represented by the time t_4, depends on the difference of the total cycle time of the next conveyor and the total cycle time of the present conveyor. If the next conveyor is faster than the present one, then the time t_4 is zero.

State 5 (S_5): Transfer and return to ready to load position (T)

When the next conveyor is "ready to load", the transfer process will start. After finishing the transfer, the conveyor returns to the "ready to load position". The time involved summarizing both events is t_5. It must be noted that the transfer time for this conveyor (t_5) is the same as the load time for the next conveyor (t_2).

2.2. Process characteristic times

Based on the example presented in Figure 2.1., two periods of time (cycle time and run time) that characterize each conveyor are defined as follows:

The **cycle time** or $\mathbf{t_{cycle}}$ is the period of time lapsed between the load starting of a car and the load starting of the next one, on the same conveyor. Within this period of time, the car goes throughout all conveyor states, so by definition, this time will be:

$$t_{cycle} = t_1 + t_2 + t_3 + t_4 + t_5$$

where:

t_1 = empty time

t_2 = load time

t_3 = process + internal movement time

t_4 = loaded (waiting next conveyor ready to load) time

t_5 = transfer time

Once the shift production is started, and it is running steadily, this t_{cycle} will be the same for every conveyor that is part of the sequential production system because the feeding of cars to the production line is restricted due to the production schedule. For each conveyor, the "empty time" and the "waiting time" can or cannot be zero. It will depend on the relative speed between two consecutive conveyors.

The variable **run time** or $\mathbf{t_{run}}$ is, for a cycle, the summation of those periods of time when the conveyor is performing an action (loading, transferring, blocking sequence operations, etc) or a process operation that is done on the car while the conveyor is stopped. It is defined as:

$$t_{run} = t_2 + t_3 + t_5$$

where

t_2 = load time

t_3 = process + internal movement time

t_5 = transfer time

The production schedule will change the t_{cycle} depending upon the number of cars to be produced each hour. However, the t_{run} will be always the same for each individual conveyor. From the conveyor system described above it can be concluded that the conveyors will have periods of activity and inactivity. The system behavior can be represented in a time-state diagram shown in the Figure 2.2.

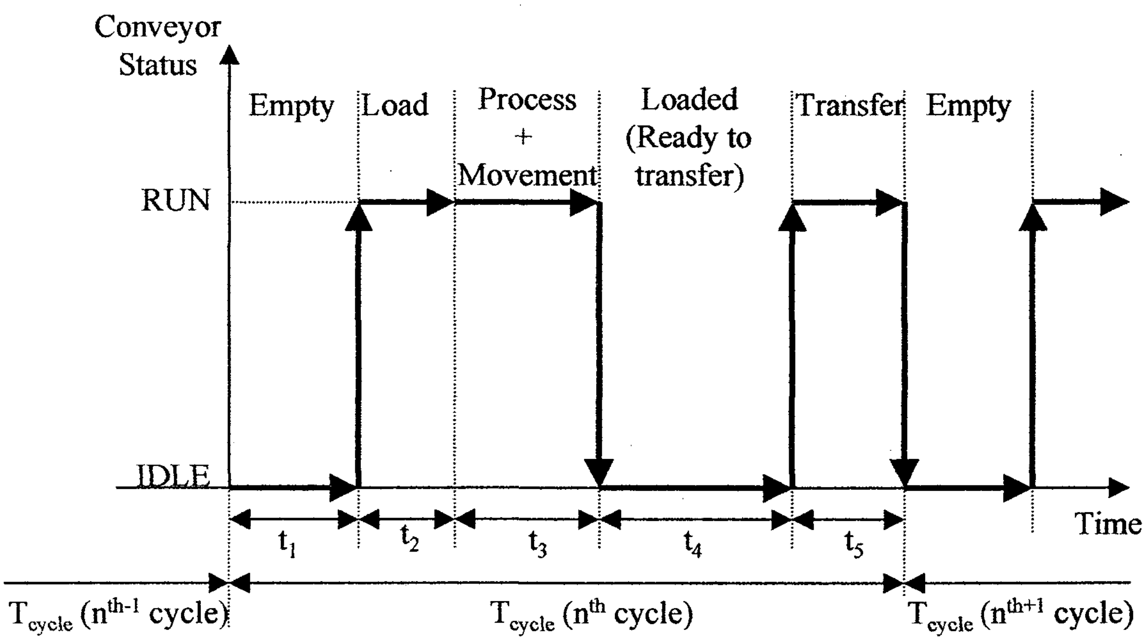


Figure 2.2. Conveyor time - state diagram

It can be concluded that due to the cycle time differences between consecutive conveyors, that either t_1 or t_5 will be equal to zero, if the system is continuously fed with cars. On the other hand, if the system is fed with cars separated by a period of time, then both t_3 and t_5 can coexist. Based on this conclusion the time-state diagram of the system represented in Figure 2.2 can be practically reduced to one of three cycle diagrams shown in Figure 2.3a, 2.3b and 2.3c.

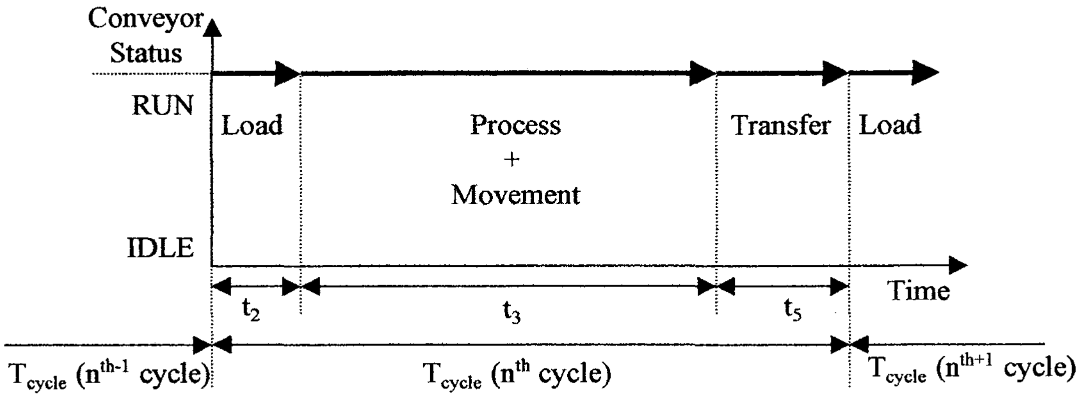


Fig.2.3a. Time-state diagram for a conveyor operating with $t_{cycle} = t_{run}$

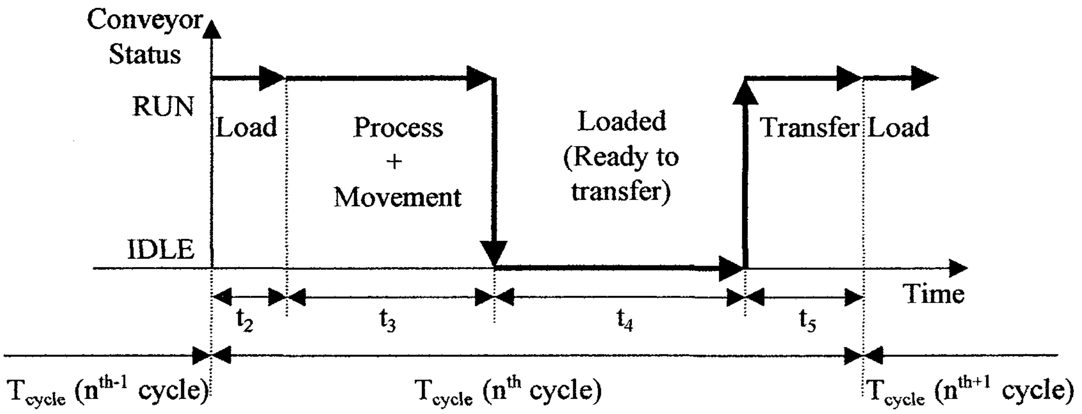


Fig.2.3b. Time-state diagram for a conveyor operating before a process bottle neck

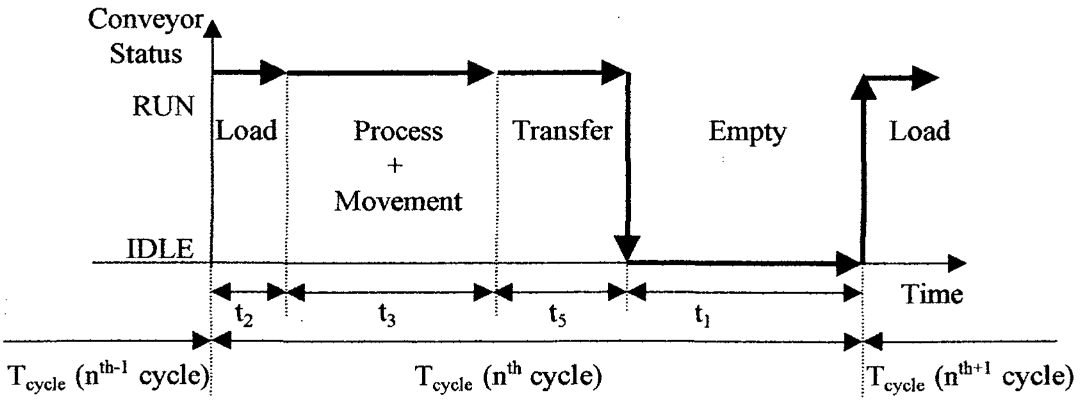


Fig.2.3c. Time-state diagram for a conveyor operating after a process bottle neck

2.3. Example of Conveyor Cycle

In order to understand the manufacturing process, an automatic cycle of a conveyor will be described. The conveyor to be analyzed is the Two Level Elevator "3.LB2.35". This conveyor belongs to the "CPU3 Conveyor System". It was shown in Chapter 1, Figure 1.3 as part of the mentioned Conveyor System and is located before the Phosphate Process Stage 0 "Pre Cleaning". In Figure 1.2., this site is called P3. The conveyor that precedes the Elevator 3.LB2.35, is the Rotating Power Roll Bed 3.ST2.34. The conveyor that follows the 3.LB2.35 is the Power Roll Bed 3.RC2..36. (The short names assigned to the conveyors are the same as those used in the plant). The conveyor 3.LB2.35 is shown in Figure 2.4.

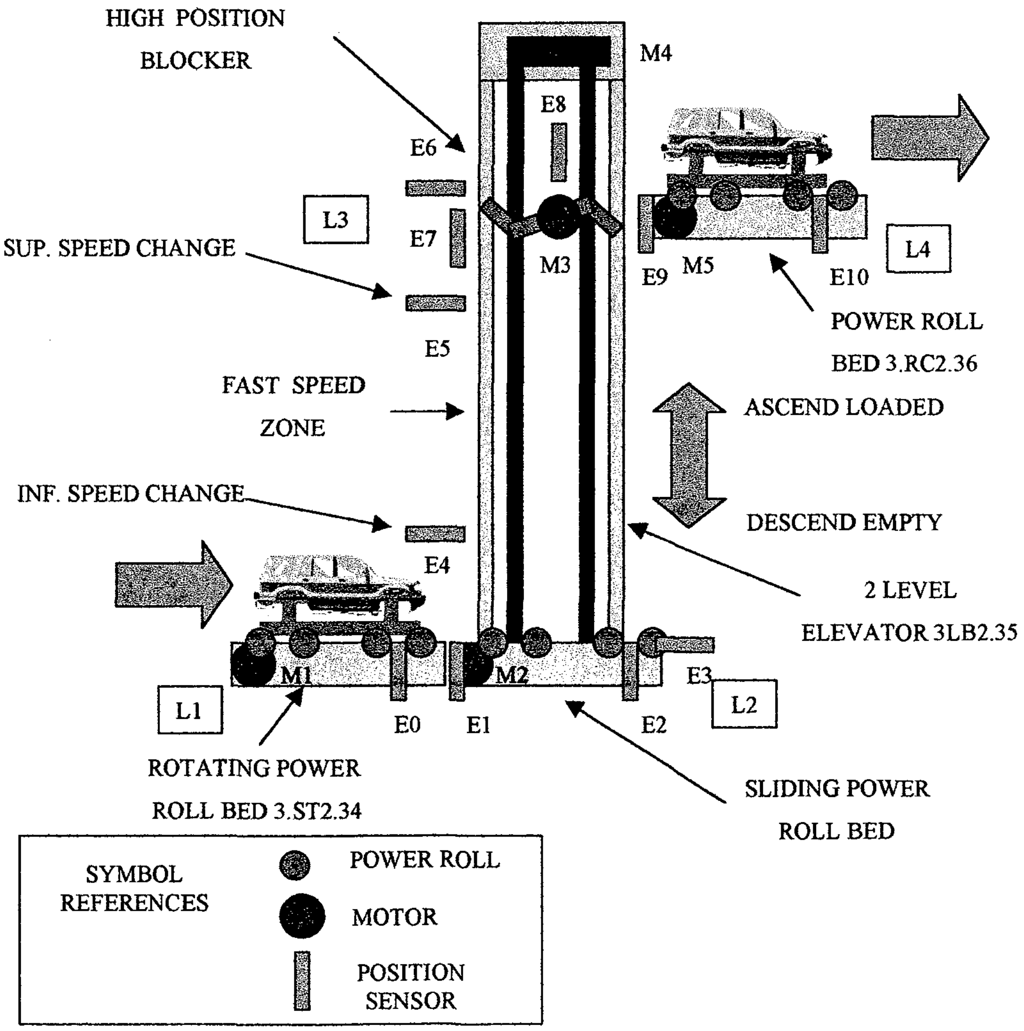


Figure 2.4. Two Level Elevator Layout

The function of the elevator 3.LB2.35 is to transfer the bodyshell on a skid (bodyshell for now) from a Low Position (Level 2 or Skid Transference) to a High Position (Level 3, or Phosphate Process Level). The elevator consists of a Sliding Power Roll Bed that slides on two parallel vertical rails to perform the vertical movement. This movement is divided in 3 sub-periods. First, at slow speed (Starting). Second, at high speed (Translation). Third, at slow speed (Braking). The load and transfer steps are the same as power roll beds. The "Blocker" fixes and blocks the position of the Sliding Power Roll Bed on the High Position (Level 3) aligned with the Power Roll Bed 3.RC2. 36 in order to enable the transfer between both conveyors.

Several sensors (E0 to E9) detect the position of the bodyshell at defined process states. We define some initial conditions for the 3.LB2.35 conveyor cycle analysis:

a. Rotating Power Roll Bed 3ST2.43 Waiting Loaded, with a bodyshell, ready to transfer.
b. Double Level Elevator 3.LB2.35 Empty in inferior position
c. Power Roll Bed 3.RC2.36 Loaded and Transferring the bodyshell on skid to the next conveyor (not displayed in Figure 2.4.)

The components that exchange information with the control PLC (CPU 3) and determine the Elevator cycle states are listed in Table 2.1.

Note: There are additional sensors and devices associated to safety and auxiliary functions that are not listed, in order to simplify the description. This Elevator has two operating modes, Manual and Automatic. The Automatic Mode is used for the regular production shift in normal operation. The Manual Mode is used for maintenance tasks, set up and the fail recovery process (it will be described in 2.3.1).

The Automatic cycle of the Elevator 3.LB.2.35 is described in Table 2.2. Only the States and Transitions that the system reaches on regular cycles are showed in Table 2.2. The

Fail States and their associated transitions will be shown later. The manual states are also ignored.

According to the PLC program structure, no time is associated to the process transitions. Regarding the definitions given in section 2.1.of the process states, the duration of each step in the process (Table 2.2.) are defined as follows

Empty Time $t_1 = 0s$

Load Time $t_2 = 6.3\ s$

Process + Movement $t_3 = t_{31} + t_{32} + t_{33} + t_{34}$

$t_3 = 4.4\ s + 8.6\ s + 4.1\ s + 3.9\ s$

$t_3 = 21\ s$

Wait Loaded to Transfer $t_4 = 154\ s$

Transfer + back to Empty $t_5 = t_{51} + t_{52} + t_{53} + t_{54} + t_{55}$

$t_5 = 4.5\ s + 4.0\ s + 4.3\ s + 7.3\ s + 4.1s$

$t_5 = 24.2\ s$

The duration of the time associated to the total conveyor cycle is:

$$t_{cycle} = t_1 + t_2 + t_3 + t_4 + t_5$$

$$t_{cycle} = 0s + 6.3s + 21s + 154s + 24.2s$$

$$t_{cycle} = 205.5\ s$$

The duration of the time associated to the conveyor run cycle is:

$$t_{run} = t_2 + t_3 + t_5 = 0s + 6.3s + 21s + 24.2s$$

$$t_{run} = 51.5s$$

Table 2.1. Elevator 3.LB2.35 Main Components

Element	Function	Action
E0	3.ST2.34 Skid End Position Detected	Detection
E1	3.LB2.35 Sliding Power Roll Bed Skid Advance Position Detected	Detection
E2	3.LB2.35 Sliding Power Roll Bed Skid End Position Detected	Detection

Table 2.1. Elevator 3.LB2.35 Main Components (cont.)

Element	Function	Action
E3	3.LB2.35 Sliding Power Roll Bed Low Position Detected	Detection
E4	3.LB2.35 Sliding Power Roll Bed speed change Inferior Position detected	Detection
E5	3.LB2.35 Sliding Power Roll Bed speed change Superior Position detected	Detection
E6	3.LB2.35 Sliding Power Roll Bed High Position Detected	Detection
E7	3.LB2.35 Blocker Extended Position Detected	Detection
E8	3.LB2.35 Blocker Retracted Position Detected	Detection
E9	3.RC2.36 Power Roll Bed Skid Advance Position Detected	Detection
E10	3.RC2.36 Power Roll Bed Skid Advance Position Detected	Detection
M1	3.ST2.34 Power Rolls Drive Motor	Movement
M2	3.LB2.35 Power Rolls Motor	Movement
M3	3.LB2.35 Sliding Power Roll Bed Blocker Motor	Blocking
M4	3.LB2.35 Sliding Power Roll Bed Vertical Movement Motor	Movement
M5	3.RC2.36 Power Rolls Motor	Movement

Table 2.2 Sequential States for Conveyor 3.LB2.35 in a Regular Operating Cycle

State of Cycle	Name	Condition Definition detected by sensors	Position	Actions	Time Associated
1	Empty	E1 off - E2 off - E3 on	L1	Waits for Bodyshell to load	$t_1 = 0$ s
Tr 1-2.	Load Starts	E0 on - E1 off - E2 off – E3 on	L1	M1 Start – M2 Start	-

Table 2.2 Sequential States for Conveyor 3.LB2.35 in a Regular Operating Cycle (cont.)

State of Cycle	Name	Condition Definition detected by sensors	Position	Actions	Time Associated
2	Load	E1 on – E3 on	Between L1 and L2	M1 on - M2 on	$t_2 = 6.3$ s
Tr 2-3.1.	Elevation Starts	E1 on –E2 on – E3 on	L2	M1 Stops – M2 Stops M4 Slow Speed Starts	-
3.1.	Slow Speed Elevation	E1 on – E2 on – E3 off	Between L2 and L3	M4 on Slow Speed (Elevation)	$t_{31} = 4.4$ s
Tr3.1-3.2	Inferior Speed Change	E4 on	E4 Location (Between L2 and L3)	M4 Change Slow To Fast Speed	-
3.2	Fast Speed Elevation	E1 on – E2 on E4 off	Between E4 and E5	M4 on Fast Speed (Elevation)	$t_{32} = 8.6$ s
Tr3.2–3.3	Superior Speed Change	E5 on	Between L2 and L3)	M4 Change Fast to Slow Speed	-
3.3.	Braking Slow Speed Elevation	E1 on – E2 on E5 off	Between E5 and L3	M4 on Slow Speed (Elevation)	$t_{33} = 4.1$ s
Tr3.3-3.4	Elevation Stops	E1 on – E2 on E6 on	L3	M4 Stops	-
3.4.	Blocking	E1 on – E2 on E6 on – E8 on	L3	M3 On(Blocking)	$t_{34} = 3.9$ s
Tr 3.4–4	Blocking Stops	E1 on – E2 on E6 on –E7 on	L3	M3 Stops	-
4	Loaded (Waiting to Transfer)	E1 on– E2 on E6 on– E7 on E10 on	L3	No(Idle loaded)	$t_4 = 154$ s
Tr 4 – 5.1	Transfer Starts	E2 on– E6 on E7 on– E10 off	L3	M2 Starts M5 Starts	-

Table 2.2 Sequential States for Conveyor 3.LB2.35 in a Regular Operating Cycle (cont.)

State of Cycle	Name	Condition Definition detected by sensors	Position	Actions	Time Associated
5.1	Transfer	E2 on – E6 on E7 on	L3	M2 on M5 on	$t_{51} = 4.5$ s
Tr 5.1–5.2	Transfer Ends	E2 off – E6 on E7 on	L3	M2 Stops – M3 Starts (Unblocking)	-
5.2.	Unblocking	E2 off – E1 off E6 on – E7 off	L3	M3 on(Unblocking)	$t_{52} = 4$ s
Tr5.2–5.3	Unblocking Ends	E1 off – E2 off E8 on	L3	M3 Stops M4 Starts	-
5.3	Slow Speed Descend	E6 on – E7 off E8 on	Between L3 and E5	M4 on (Descend)	$t_{53} = 4.3$ s
Tr 5.3–5.4	Superior Speed Change	E1 off – E2 off E5 on	E5 Location	M4 Changes Slow to Fast Speed (Descend)	-
5.4	Fast Speed Descend	E1 off – E2 off	Between E5 and E4	M4 on Fast Speed (Descend)	$t_{54} = 7.3$ s
Tr 5.4–5.5	Inferior Speed Change	E1 off – E2 off E4 on	Between E4 and L2	M4 Changes Fast to Slow Speed (Descend)	-
5.5	Braking Slow Speed Descend	E1 off – E2 off E3 off	Between E4 and E3	M4 on Slow Speed (Descend)	$t_{55} = 4.1$ s
Tr 5.5-1	Descend Stops	E1 off – E2 off E3 on	L2	M4 Stops	-
1	Empty	E1 off - E2 off E3 on	L1	Waits for Bodyshell to load	$t_1 = 0$ s

The Sequential States Listed in Table 2.2, are shown in a State Diagram in Figure 2.5

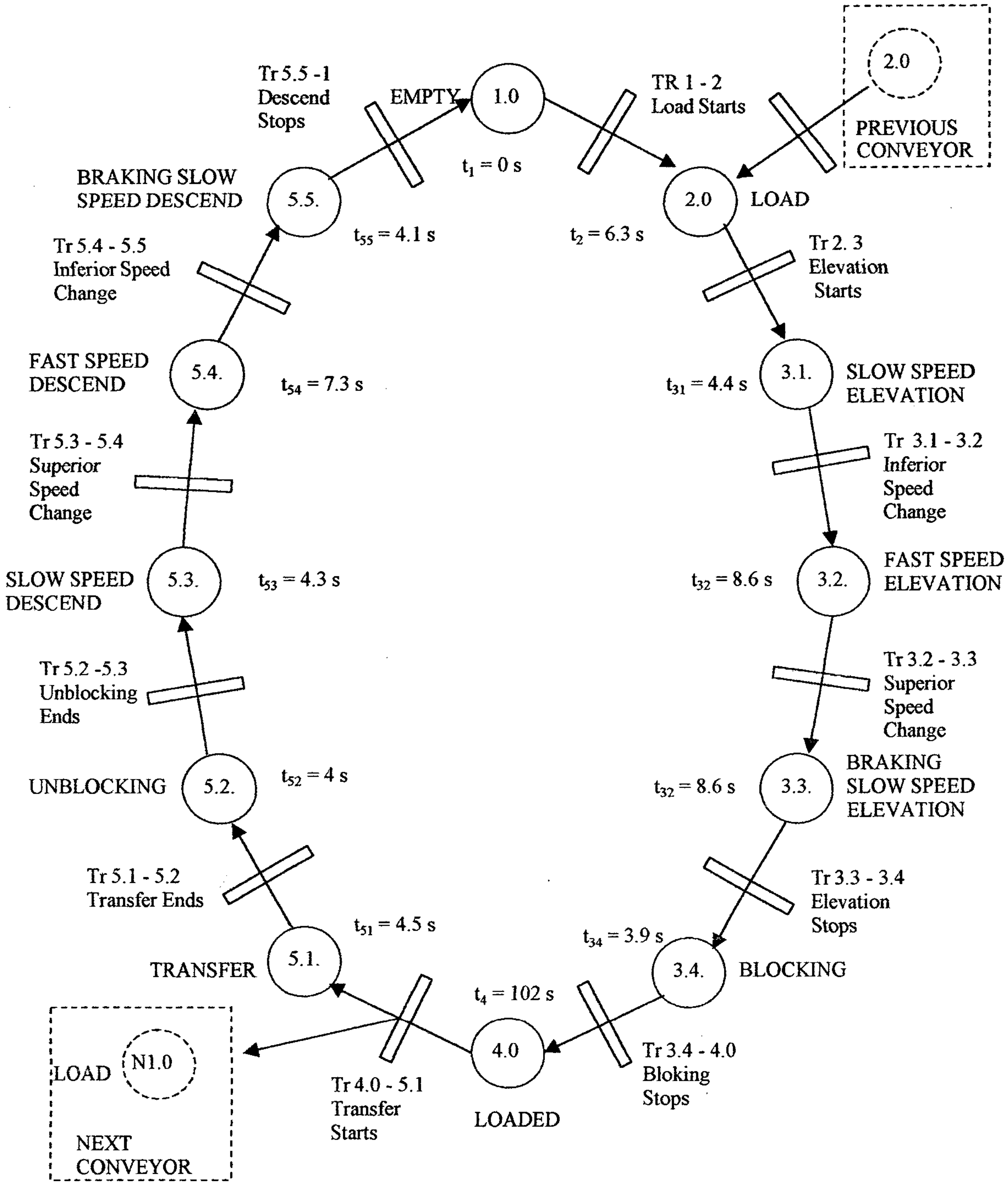


Figure 2.5Two level 3.LB2.35 Process State . Automatic Cycle .

The characteristics times t_{cycle} and t_{run} calculated are representative of the automatic cycle previously described.

2.3.1 Fault state

A description of what happens if a fault appears during one of the states of the elevator cycle. Although there are 26 different types of logic faults for this particular conveyor, a unique generic Fault State is considered by the PLC Program. The specific fault is shown in the Human Man Interface (HMI) associated to the PLC that controls the conveyor and in the Conveyor Supervisory Control And Data Acquisition System (Conveyor SCADA). The process that has to be followed in order to clear the fault and to restart the automatic cycle is the same for every fault type and it will be described as follows.

In the normal automatic cycle, the system is always in some of the states defined in Figure 2.5. When the associated transition condition is complete, it switches to the next state and so on throughout the entire automatic cycle. If, while a state is being executed, some fault occurs, a fault transition condition is met and the system switches to the Fault state. There are different types of faults. Some are associated to physical elements (sensors, motors, breakers, etc) and others are associated to logic conditions (process time, logic state sequence not matched). The PLC program has internally defined, by a Petri Net Logic, the sequence of states that have to be met to complete the process. Every excursion out of the defined logic sequence is recognized by the PLC program, that assign to the system a transition to the Fault State. For both types of faults (physical and logical) the element that is producing the problem or the logic state that was not met (system out of sequence) is recognized. A report of this fault is generated and sent to the HMI and Conveyor SCADA. The transitions to the fault state can be met at any of the automatic process states. For each automatic process state, there are different types of transitions that will lead to the fault state. The process represented by a state diagram including a generic fault state is shown in Figure 2.6.

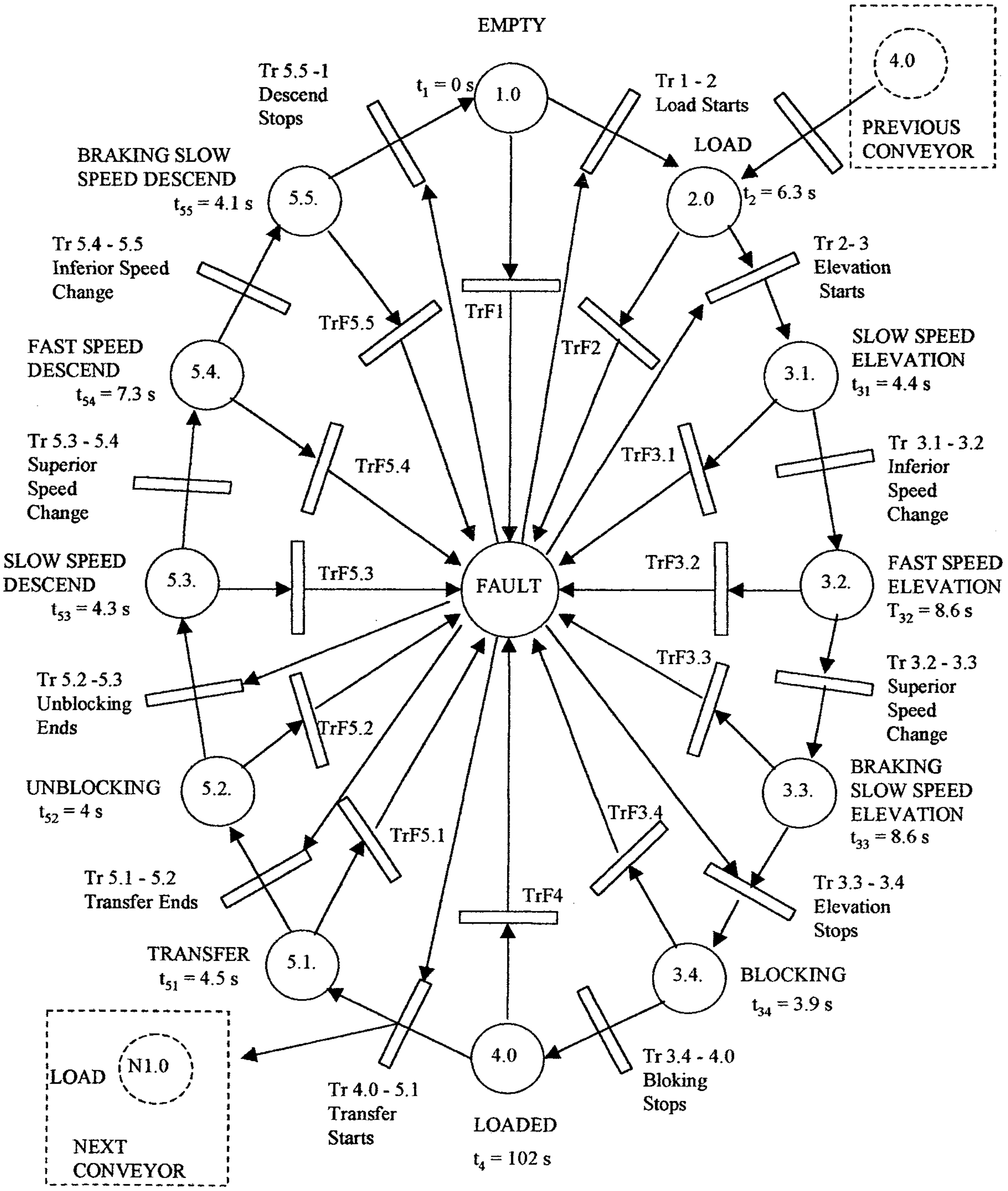


Figure 2.6. Two level elevator 3.LB2.35 - Process State Diagram.
Automatic Cycle including Fault State and associated transitions.

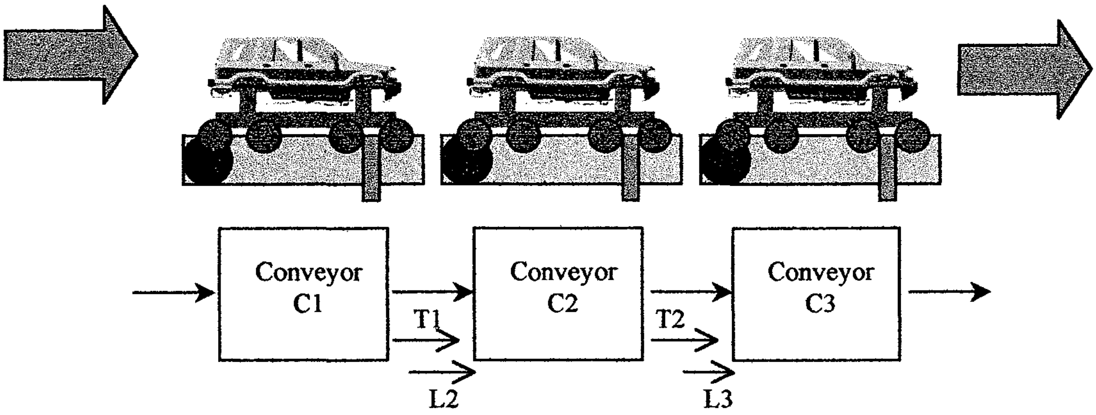
In Figure 2.6, a generic transition “TrFx” is shown for each ”x” state . This transition concentrates all the different transitions that can lead, departing from any of the automatic process states, to the Fault State. When the conveyor reaches a faulted state, all the elements that drive the movements (motors, pistons, brakes, valves) are stopped and the conveyor is held on a ”faulted state”. It is not possible to restart the cycle automatically, it has to be done in Manual Mode (i. e., it is a common safety requirement.).

Once the fault is recognized, and cleared by the maintenance crew, the Elevator has to be manually driven to one of the automatic process states in order to restart the cycle. It is possible to restart the automatic cycle only from certain enabled states shown in Figure 2.6 (e.g., the state 3.2: FAST SPEED ELEVATION). If a fault occurs when the car is driven to the upper elevator position in fast speed (State 3.2), the elevator will stop at that point. Then, after the fault is cleared, it has to be driven in Manual Mode through the transition Tr 3.3 - 3.4 (Elevation Stops) and then switched to Automatic Mode. At that point the automatic process continues its regular cycle. It could be also driven backwards through transition Tr2-3 and then switched to Automatic Mode. The elevation process will start again.

The period of time between when the transition to the Fault State is met until the System is returned to the Automatic Mode will be called “Restoration Time” and it will be used in the reliability calculations later.

2.4 Car transported by Consecutive Conveyors

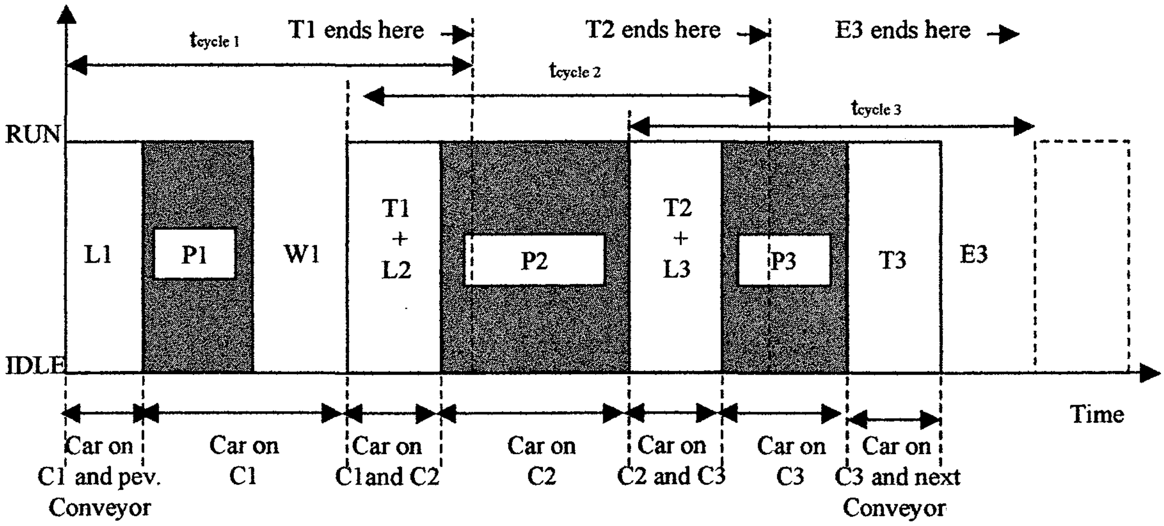
The conveyors operate sequentially, but not independently. The Load and Transfer stages are not independent for consecutive conveyors. It is represented in Figure 2.8 for the 3 consecutive conveyors shown in Figure 2.7. A State Time diagram shows the associated times for a car that is transported throughout the process. The time scale is drawn for an observer travelling in a car through the process.



T_i: Transfer and Return to Ready to load position State for conveyor "i"

L_i: Car Load State for conveyor "i"

Figure 2.7. Three conveyor system



E_i: Conveyor empty State for conveyor "i"
L_i: Car Load State for conveyor "i"
P_i: Car process and internal movement State for conveyor "i"
W_i: Wait for the next conveyor ready to load State for conveyor "i"
T_i: Transfer and reatum to ready to load position State for conveyor "i"

Figure 2.8. Time-state diagram for a car going through a Sequential Conveyor System

Figure 2.8 reveals the cycle times for each conveyor ($t_{cycle\ 1}$, $t_{cycle\ 2}$ and $t_{cycle\ 3}$). Along the production shift, each conveyor will process the same number of cars. Then, the cycle time for every conveyor will be assumed to be identical (i.e. $t_{cycle\ 1} = t_{cycle\ 2} = t_{cycle\ 3}$). The time that a car is on each conveyor is also shown in Figure 2.8. These times obviously are different between conveyors, and they are also independent. The total process time for a car will be the sum of the periods of time that a car spends on each of the conveyors involved on the process.

2.5. Multiple Consecutive Conveyors

In order to study the behavior of the multiple conveyor system, a prototype system that includes 5 sequential conveyors is shown in Figure 2.9

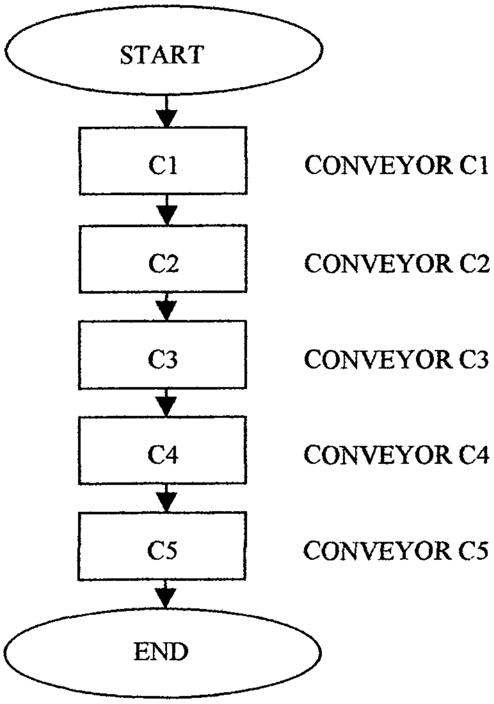


Figure 2.9. Conveyor Sequential System Diagram

At first sight, it appears that the system represented in Figure 2.9 is a serial system where all components of the system must be operating for system success. After the description and examples shown in the previous sections, it can be anticipated that this conveyor system can not be characterized by a series system model. It can be represented in a "Petri Nets" diagram shown in Figure 2.10.

In the Petri net logic shown in Figure 2.10, the car goes through the following state4.4 – 5.2 – 5.3 – 5.4 – END

It can be noted that there are some states that involve actions (Load, Process movement, Transfer) and other states that do not involve any action. In these states, the conveyor is stopped but it is not faulted. It is called an "Idle State". Meanwhile, other conveyors in the system could be active (i.e. Run State). Not necessarily all of the states have to be in an Idle or Run State simultaneously. Moreover, due to the differences between the characteristic times of different conveyors, there will be at the same time in the system, some conveyors in Run State (load, Process –Movement or Transfer), and others in Idle State (Ready to transfer or Empty). This behavior is different in a simple series system (e.g. radial distribution power system). For a series system, it is necessary to have all components in Active State when the system is in Active State. For a conveyor system there are some components in Active State and other in Idle State when the System is Active. It can be concluded that the conveyor system cannot be analyzed strictly as a series system and define the conveyor system as "Sequential".

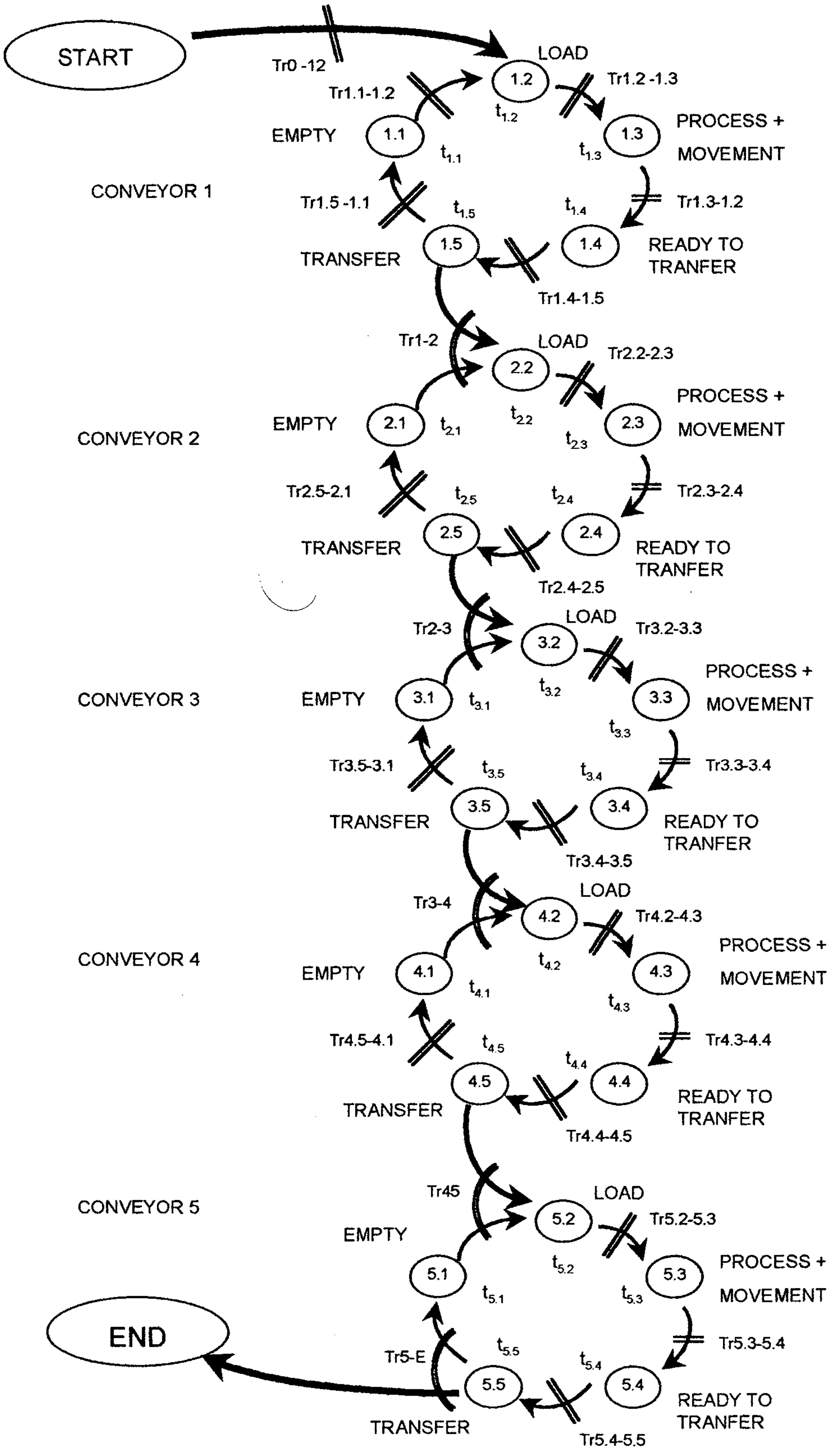


Figure 2.10. Multiple Conveyor Sequential System

The sequence that a car follows in Figure 2.10 is represented in a Multi Process Time – State diagram in Figure2.11.

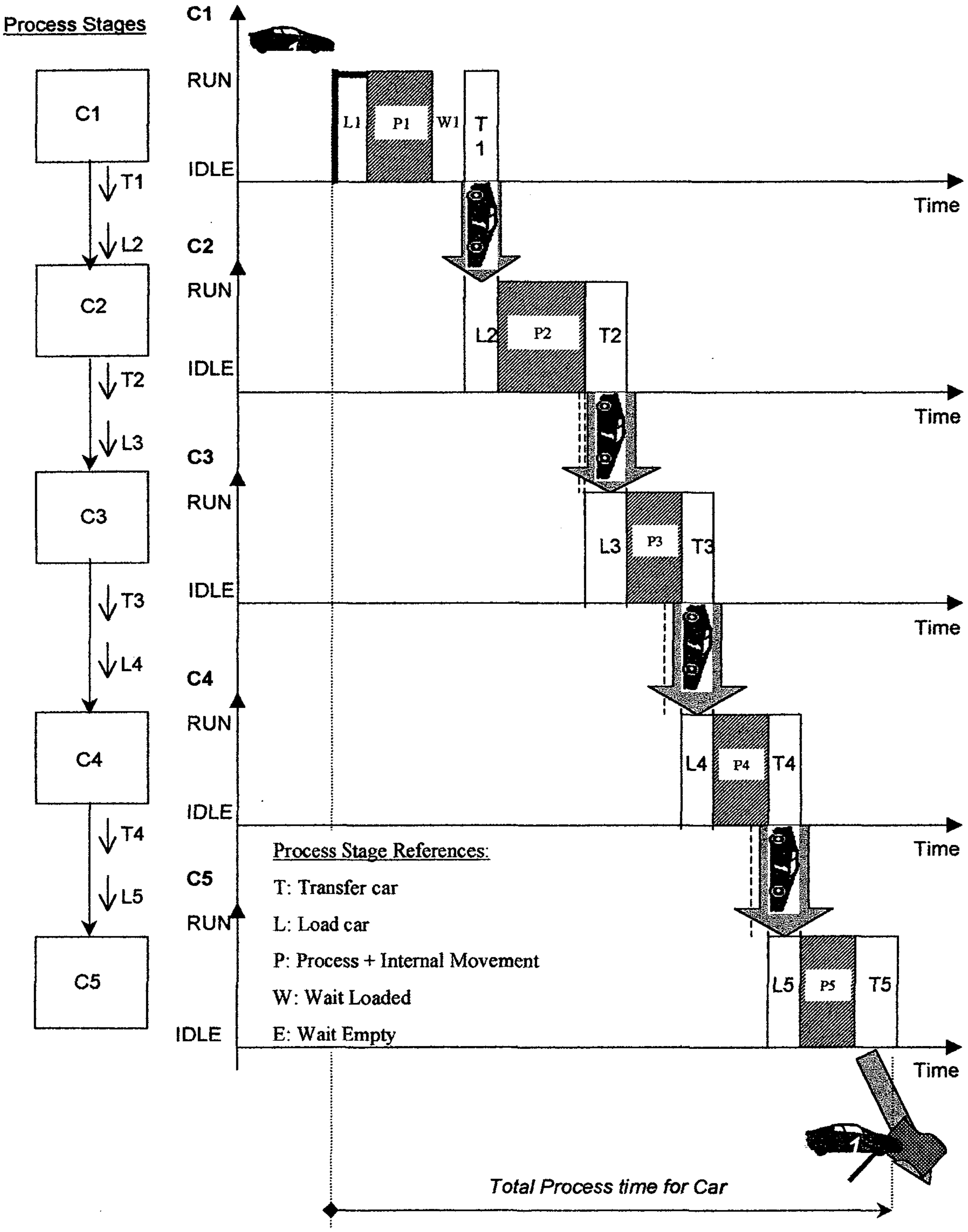


Figure 2.11. Time-state diagram for the system processing one car

A time-state diagram for the system processing more than one car is shown in Figure 2.12.

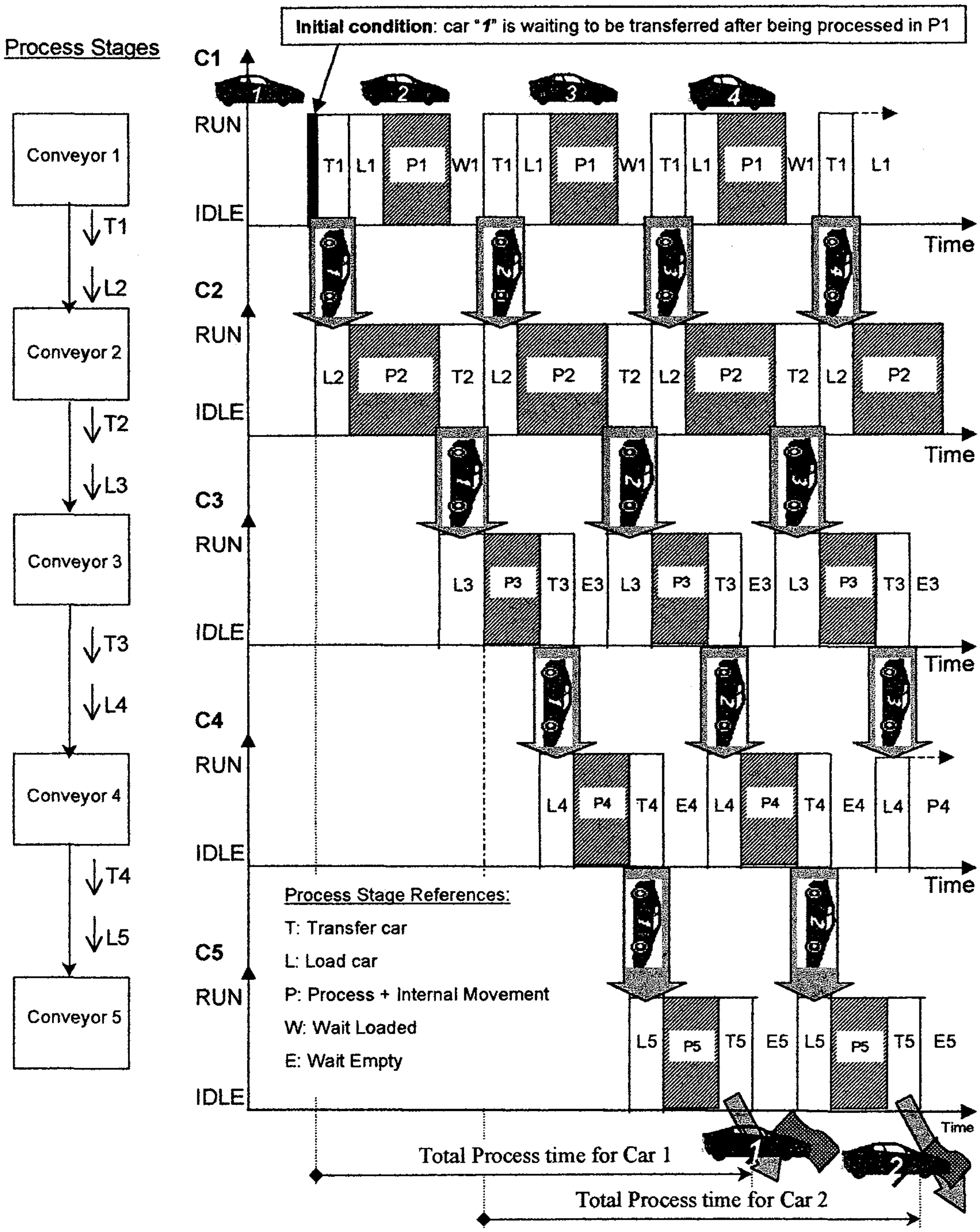


Figure 2.12. Time-state diagram for the multiple conveyor system

In Figure 2.12 it is assumed that the line is supplied with cars in a continuous mode at conveyor C1. This means that there is no time delay between cars at the beginning of the process. It will be assumed for this example, that the conveyor C2 has the largest cycle time. Based on this assumption, it can be observed how conveyor C2 is conditioning the previous and the next conveyors. In this case conveyor C1 will be forced in each cycle to wait for conveyor C2 to be in a "ready to load" state. On the other hand, conveyor C3 will be forced in each cycle to wait in "empty" state (e.g. waiting for the "ready to transfer" state of conveyor C2).

Due to the waiting and emptying times set by conveyor C2, it can be realized that the cycle time will be the same for all conveyors in the line. It will be independent from the load (t_2), process and internal movement (t_3), and transfer and return to ready to load position (t_5) times, resulting in:

$$t_{1.1}+t_{2.1}+t_{3.1}+t_{4.1}+t_{5.1}=t_{cycle}$$

$$t_{1.2}+t_{2.2}+t_{3.2}+t_{4.2}+t_{5.2}=t_{cycle}$$

....

$$t_{1.5}+t_{2.5}+t_{3.5}+t_{4.5}+t_{5.5}=t_{cycle}$$

Note: As previously stated, the assumption was made that there is no time delay between cars. Because of the production schedule, in general, a space is observed between cars. A time delay is introduced at the beginning of line in order to satisfy the schedule for the daily production. In this practical case, all conveyors will have the same cycle time, as assumed in the case being analyzed. But, the conveyor with the largest cycle time (e.g. the cycle time without delays) will also have either an empty time t_1 or a loaded time (waiting ready to transfer) t_4 non-zero.

2.6. Fault Analysis and Representation

This section presents analysis on how a failure in one of the conveyors in the manufacturing line affects the rest of the conveyors. A time state diagram is shown in Figure 2.13 for the multiple conveyor system with a fault in conveyor C3, state P3.

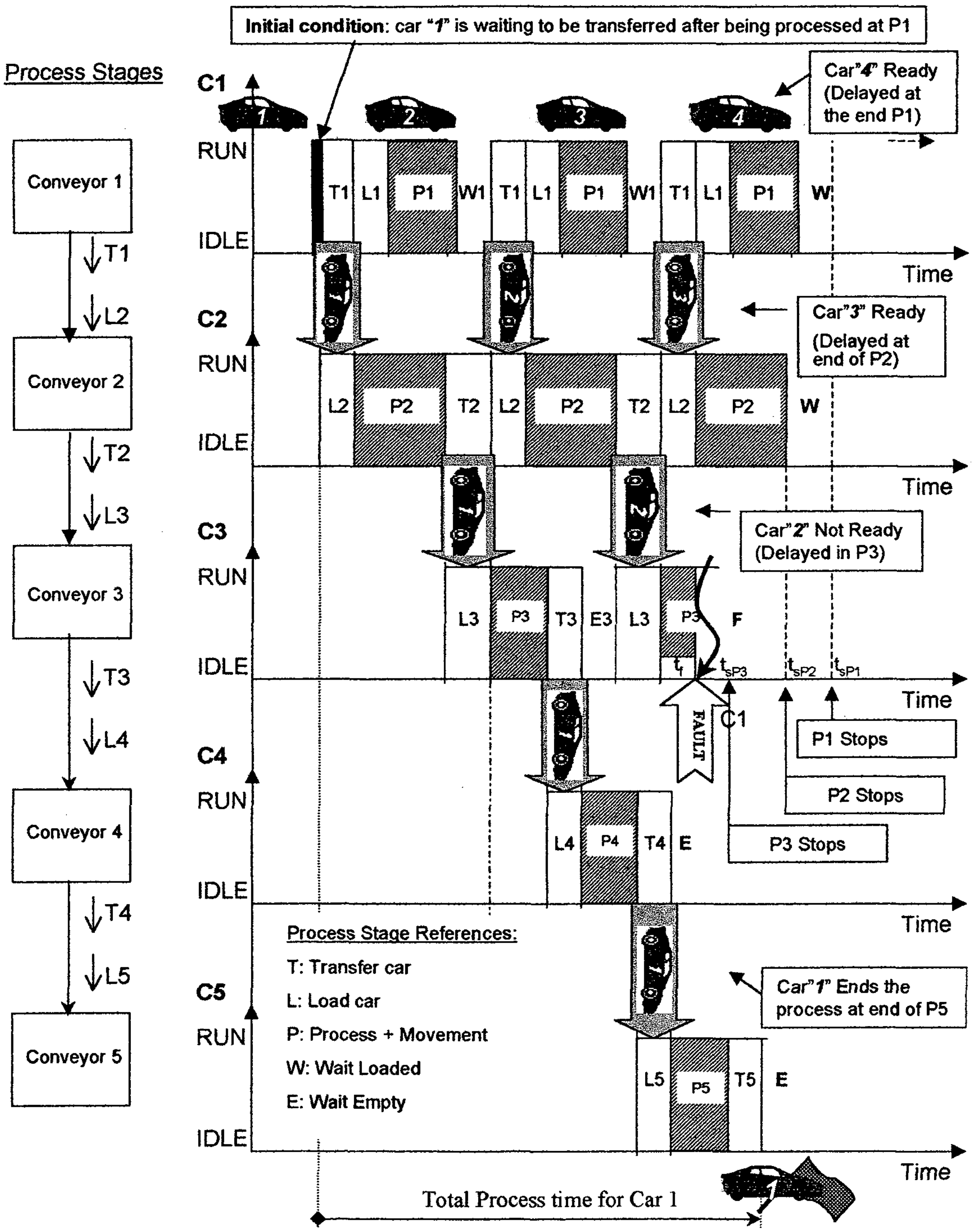


Figure 2.13. Time-state diagram for the multiple conveyor system with a fault in P3

It is assumed in Figure 2.13 that the same operating conditions used to analyze the system described in Figure 2.10, Figure 2.11 and Figure 2.12. The analysis focuses on the system behavior if a fault is present in conveyor C3 shown in Figure 2.13 once it was loaded and when it is in the process stage. To study the effect of this failure on other conveyors, it is assumed that the failure starts at t_f and lasts for several cycles. It can be seen in Figure 2.13 that the conveyors placed downstream of conveyor C3 (in this case conveyor C4 and conveyor C5) are not affected directly by the failure in conveyor C3. Conveyor C4 ends the cycle in progress and stays in a waiting "empty" state.

Upstream of conveyor C4 so-called "temporized cascade effect" can be seen. With conveyor C3 stopped, conveyor C2 and conveyor C1 continue its own cycles. Now, conveyor C2 will eventually stop in 2.3 state which is "waiting next conveyor ready to load". If the failure at conveyor C3 is not eliminated before the regular $t_{3.2}$ expires (associated with t_{sP2} in Figure 2.13), conveyor C2 will continue waiting beyond its regular cycle time. This state will be called "abnormally delayed". At this point conveyor C4 and conveyor C5 are empty, conveyor C3 failed, and conveyor C2 stopped. Following the same logic, if conveyor C3 is still down, after conveyor C2, conveyor C1 reaches the "abnormally delayed" state after stopping at t_{sP1}.

In conclusion, any delay time will affect the previous conveyors. The effect on these conveyors depends on the repair time of the failure in conveyor C3, the cycle time and the presence of "holes" (the time space between two consecutive cars) in the manufacturing line process. If the failure at conveyor C3 is repaired before t_{sP2}, the previous conveyors (e.g. C2 and C1) are not affected by the failure present in conveyor C3. If the repair time is longer, then the influence depends on its length according to t_{sP2}, and t_{sP1}. Finally, if the repair time is greater than t_{sP1} then the manufacture line will be completely stopped. The conveyors that stay in the "up" state have no failure and so they are delayed in an "empty" state (e.g. conveyors C4 and C5) or in a "waiting ready to transfer" state (e.g. conveyors C3 and C2).

This detailed example illustrates that the system cannot be modeled as a series system, since in a series system a failure of one of its components immediately stops the entire system.

Based on the analysis and description completed for the above conveyor system, this thesis develops a system and a method that can model and describe the behavior of the GM plant (paint-shop). Based on this model, the reliability parameters of the system can be calculated (failures per year or "λ" and repair duration per failure in minutes per year or "r") from the parameters calculated for each component individually.

2.7 Queueing Theory Approach for the Fault State Behavior Modelling

A multi conveyor sequential system can be modelled as a queueing system as shown in Figure 2.14.

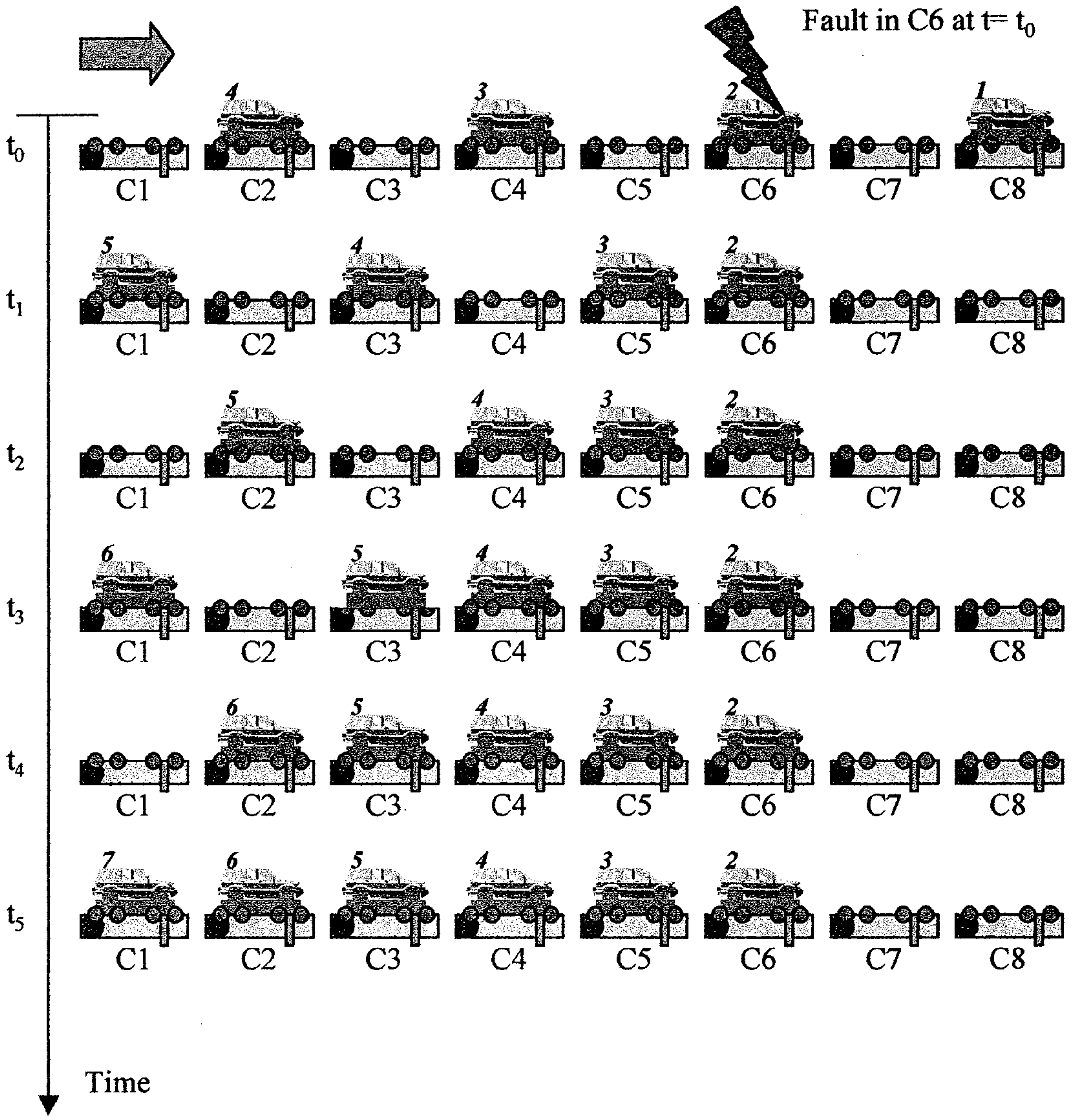


Figure 2.14. Queue Formation in the Conveyor System

($t_0 < t_1 < t_2 < t_3 < t_4 < t_5$)

The sector of the manufacturing shown in Figure 2.14 system consists of 8 consecutive conveyors. It is assumed that the system is operating under normal conditions. As stated in Chapter 1, the cars are sequenced at the beginning of the process, then the cars are assumed to advance throughout the conveyors uniformly.

In Figure 2.14, the conveyor system is shown at different time instants in its process.

Just before $t = t_0$ (-) the system is running under normal conditions. Due to the sequencing some conveyors are busy, or in Run State (conveyors C2, C4, C6, C8), and other conveyors are empty or Idle State in this case (conveyors C1, C3, C5, C7).

At $t = t_0$ a fault is declared in conveyor C6. Conveyor C6 stops its cycle.

At $t = t_{0+}$ the conveyor C6 is now in Fault State, and it will remain in this condition until it is repaired by the maintenance crew. Let's assume that conveyor C6 is not repaired for some time. By choosing this approach, an analysis of what happens to other conveyors in the system will be described.

The status of the system in steps of time Δt, where $\Delta t = t_{cycle}$ are analyzed. Then, in Figure 2.14, $t_1= t_0 + t_{cycle}$, $t_2= t_0 + 2\ t_{cycle}$, $t_3= t_0 + 3\ t_{cycle}$, $t_4= t_0 + 4\ t_{cycle}$ and $t_5= t_0 + 5\ t_{cycle}$

At $t = t_{0+}$, although conveyor C6 is in Fault State, the PLC that controls the conveyor system, will keep in operation the remain non faulted conveyors. For this sector conveyors C1, C2, C3, C4, C5, C7 and C8 will continue their normal cycles.

At $t = t_1$ conveyors C2 and C4 end their cycles and transfer the cars to conveyors C3 and C5, respectively. The same happens for conveyor C8 that, after transferring the car identified "*1*", now remains empty in Idle State, waiting for a new car to be loaded. As conveyor C6 was not repaired, conveyor C7 will also continue in Idle state waiting for a car to be loaded. A new car was loaded in conveyor C1 and it is being processed(car identified in Figure 2.14 with number"*6*").

At $t = t_2$ conveyors C1, C3 and C5 end their processes. Conveyors C1 and C2 transfer the cars to conveyors C2 and C4, respectively. For conveyor C5 it was not possible to transfer the car processed (car numbered "*3*") because conveyor C6 is in Fault State. Then, at this moment, a queue starts to be built. Meanwhile, conveyors C7 and C8 remain in Idle State empty waiting for a car to be loaded.

At $t = t_3$ conveyors C2 and C4 end their respective processes conveyor C2 transferred the car numbered "*5*" to conveyor C3, but conveyor C4 is not able to transfer the car numbered "*4*"to conveyor C5 because it was already loaded. At this moment, we have conveyors C5 and C4 ready to transfer but waiting in Idle State for the next conveyor to be ready to load.

If conveyor C6 is not repaired, the queue continues to grow, at the rate of a car each $\Delta t = t_{cycle}$. In this way, it can be observed that at $t = t_5$ we have a queue of 5 cars processed and waiting to be transferred.

As the fault remained uncleared at conveyor C6, the queue continues to grow until it reaches the beginning of the production line. For some systems this situation is extremely dangerous because of the processes involved.

Those processes that require some limited time under a determined temperature or under the action of chemical agents, will be, because of this situation, out of quality and process specification. The cars involved have to be checked and in some cases they are scrapped. For some processes like the Phosphate treatment, a stop greater than 3 minutes can result in some scrap units. The longer the time the greater the number of bodyshells that are damaged.

After describing the queue build up the elements in this process with a basic queueing system according to reference [5] can be identified. Generally, the arrival process is described in terms of the probability distribution of the interarrival times of elements (cars) and is denoted as A(t), where

$A(t)=P[\text{time between arrivals} \leq t]$
A(t) denotes the "probability of the event A"

The assumption in most queuing theories is that these inter-arrival times are independent, identically distributed random variables and, therefore, the stream of arrivals forms a stationary renewal process. Thus, only the distribution of A(t), which describes the time between arrivals, is usually of significance.

In our case A(t) is perfectly predictable, following a time linear law with arrivals separated by the cycle time t_{cycle} .

Defining for $t = t_0$ the first arrival,

$A(t)= 1$ for $t = t_0 + k^* t_{cycle}$, k integer

$A(t)= 0$ for $t \neq t_0 + k^* t_{cycle}$, k integer

These results are characterized by a discrete function, which significantly simplifies the problem.

The second statistical quantity, that must be described, is the amount of demand these arrivals take place upon the channel; this is usually referred to as the *service time* whose probability distribution is denoted by B(x), that is,

$B(x) = P[\text{service time} \leq x]$

Here, the service time refers to the length of time that a customer or product spends in the service facility.

In our case, because the t_{run} is always smaller than t_{cycle} , once the fault is cleared, the system will progressively recover to its regular distribution, and the queue will be "melted" and will disappear. Then, while a conveyor is faulted, as conveyor C6 shown in Figure 14, the service time can be considered as infinite. For this case,

$B(x) = 0, \ \forall x$ (conveyor in Fault)

With both variables defined in this manner, according to reference [5], our case is a trivial system to analyze if the arrival time is predictable. However, although the arrival time is predictable, it is not always constant. It will change with the production schedule changes and will change the speed of the queue built up and its effect on the reliability of the sequential manufacturing system.

The challenge in this thesis is to develop a practical method to calculate the availability of this productive system and account for changes in the production schedule.

CHAPTER 3 . RELIABILITY MODELLING OF A MANUFACTURING SYSTEM

3.1. Introduction

In order to begin the reliability analysis of the car manufacturing system, some basic definitions have to be made using the same terminology existing in current literature and standards. The following definitions are taken from the IEEE Std 493-1997 "Gold Book"[1]

3.1.1. Availability: As applied either to the performance of individual components or to that of a system, it is the long-term average fraction of time that a component or system is in service and satisfactorily performing its intended function. An alternative and equivalent definition for availability is the steady-state probability that a component or system is in service and operating.

3.1.2. Component: A piece of electrical or mechanical equipment, a line or circuit, or a section of a line or circuit, or a group of items that is viewed as an entity for the purposes of reliability evaluation.

3.1.3. Preventive maintenance: A system of planned inspection, testing, cleaning, drying, monitoring, adjusting, corrective modification, and minor repair of electrical and mechanical equipment to minimize or forestall future equipment operating problems or failures, which, depending upon equipment type, may require exercising or proof testing.

3.1.4. Expected failure duration: The expected or long-term average duration of a single failure event usually expressed as hours per failure.

3.1.5. Failure: Any trouble with a ystem component that causes any of the following to occur:

- Partial or complete plant shutdown, or below-standard plant operation
- Unacceptable performance of electrical and/or mechanical equipment
- Operation of the electrical protective relaying or emergency operation of the plant electrical system
- De-energization of any electric circuit of equipment.

A failure on a public utility supply system may cause the plant to experience either or both of the following events:

- A power interruption or loss of service
- A deviation from normal voltage or frequency outside the normal utility profile.

A failure on an in-plant component causes a forced outage of the component; that is, the component is unable to perform its intended function until it is repaired or replaced. The terms "failure" and "forced outage" are often used synonymously.

3.1.6. Failure rate: The mean number of failures of a component per unit exposure time. Usually exposure time is expressed in years and failure rate is given in failures per year.

3.1.7. Mean time to repair (MTTR): The mean time to repair or replace a failed component.

3.1.8. Repair time: The repair time of a failed component or the duration of a failure is the clock time from the occurrence of the failure of a component to the time when the component is restored to service, either by repair of the failed component or by substitution of a spare component for the failed component. It includes time for diagnosing the trouble, locating the failed component, waiting for parts, repairing or replacing, testing, and restoring the component to service. It is not the time required to restore service to load by putting alternate circuits into operation. The terms "repair time" and "forced outage duration" are often used synonymously.

3.1.9. Switching time: The period from the time a switching operation is required due to a component failure until that switching operation is completed. Switching operations include such operations as throw over to an alternate circuit, opening or closing a sectionalizing switch or circuit breaker, reclosing a circuit breaker following a trip-out due to a temporary fault, etc.

3.1.10. System: A group of components connected or associated in a fixed configuration to perform a specified function of distributing power.

3.1.11. Unavailability: The long-term average fraction of time that a component or system is out of service due to failures or scheduled outages. An alternative definition is the steady-state probability that a component or system is out of service due to failures or scheduled outages. Mathematically, unavailability = (1 - availability).

3.2. Differences between Power Systems and Manufacturing Systems

There are fundamental differences between the operation of power systems and manufacturing systems. While a power system's duty cycle is almost continuous, being interrupted because of faults or scheduled maintenance jobs, manufacturing systems have in most of the cases "working shifts" and "resting or idle shifts". A manufacturing system, will operate, for example in one day, one or two shifts of 9 hours each, and the remaining time will not be in service. In total 9 h over 24 h or 18 h over 24 h. It means that its daily service factor is defined as:

$$f_{s1} = \frac{9h}{24h} = 0.375 \text{ for one shift operation or } f_{s2} = \frac{18h}{24h} = 0.75 \text{ for two shift operation}$$

For the same period, a power system will operate 24 h over 24 h. It means its service factor is:

$$f_s = \frac{24h}{24h} = 1$$

Moreover, on weekends, normally the manufacturing system will not be in service, while the power system continues its regular service.

Due to the movement and processes involved, the need of preventive maintenance will be larger for a manufacturing system, which normally performs over 200 cycles per shift for a car manufacturing facility. On the other hand, except for the generating units, the power system is mostly stationary. It can be concluded that, for manufacturing systems, some of the reliability parameters will depend more on the cycles performed by the system than on the time of operation.

The fundamental problem is to develop a methodology to obtain the reliability indices of the whole system at any time, according to the production schedule and the accumulated production. The structure of the power systems can be analyzed[1] on the basis of Series and Parallel circuits.

Although the car manufacturing systems appears to be a series – parallel system, similar to a power system, it is not and based on the fact that a fault in one component affects the behavior of others is totally different. Then, the methods developed for reliability calculations in power systems in references [1], [2], [9], [10], [11] and [13] are not directly applicable to a manufacturing system and therefore a different methodology is used in this thesis that represents the behavior observed in Chapter 2.

Presently, some maintenance and reliability software programs [13] are able to calculate the reliability of a system if the logic of the system (with electrical and mechanical components) is based on series and parallel configurations, and their combinations. Those software packages include a database with only the main components or whole sub-systems. But they do not include components such as sensors, valves and control systems, that are present in each machine and that are responsible for an important number of failures or machines malfunction. These additional components are also included in the proposed reliability study methodology presented in this thesis.

A method is developed to account for the effects of aging and work cycles. A method is proposed that accounts for the mentioned effects on the reliability indices.

3.3. Failure of a component in a Machine

Every machine or system is integrated by several components that are responsible for such tasks as position detection, signal transmission, power distribution, torque production, fluid flux control, safety, etc.. Failure of some of these integrated components leads to a machine outage. From a reliability point of view, the logical behavior of these components, is serial. We note at this point that the representation of reliability model does not necessarily coincide with the electrical or mechanical circuit or layout representation. For the cases previously explained, the model presented in the IEEE Std 493-1997[1] is valid.(average restoration times are used).

3.4. Failure of a Machine or System in a Manufacturing Sequential System

The manufacturing sequential system is composed of several subsystems that interact with the product to be produced which is carried out throughout the process by a conveyor system. The conveyors are interconnected in a sequential way as explained in Chapters 1 and 2. When one of the subsystems fails or its cycle is stopped because of a failure in one of the associated processes, the rest of the conveyors normally keep running. After some time, the other conveyors are also affected (see section 2.6.). The proposed reliability methodology presents a mechanism to account for this particular behavior.

3.5. Existing Methods for Reliability Model Representation

Some reliability methods and programs for reliability calculations have been presented in references [1], [2], [9],[10]. Some of these methods are based on hand or spread sheet calculations and although they are suitable for systems with a small number of elements, it would be very complicated and tedious and perhaps almost impossible to perform a reliability analysis for a system integrated by a large number of components (e.g. 1000 or more).

The methodology presented in this chapter for reliability systems modeling is oriented to be suitable for reliability studies of systems composed of a large number of components, but the method is designed to be easy to implement, through a graphical block diagram interface.

3.6. Proposed Reliability Model Representation

For performing a reliability study of systems like power systems or a sequential manufacturing system, two parameters for every component is defined as follows:

λ_i = failure rate of component i
r_i = expected repair or replacement time of component i

Each component will be represented by a two element vector c

$$c_i = [\lambda_i , r_i] \tag{3.0.}$$

The system is modelled by reliability block diagrams. A reliability block diagram is defined as[15]: “the reliability block diagram is a circuitless diagram with an input and an output node whose vertices (called blocks) represent the components of a system and whose arcs describe the relationships between the various components. The system operates if there is a successful path between the input and the output nodes of the reliability block diagram”.

3.6.1. Data Management: Power System vs. Manufacturing Sequential System

For power system reliability analysis, it is a normal practice to work with the average down time, and all the studies performed are acceptable because what is most important, for these cases, is to determine the total downtime per year, which affects the utility and customer contracts, penalties and regulatory issues.

For a manufacturing sequential system, although it is important to determine the expected total downtime per year, it is in many cases, more important to discriminate between downtime for different failures because the effect on the product is not directly proportional to the total downtime. It is also interesting to determine how each element affects the total downtime in order to implement corrective actions on the Preventive Maintenance Plans.

In a series system the average downtime for each conveyor is independent of conveyor failures. However in sequential manufacturing line the downtime for each conveyor is dependent upon other conveyor failures and the cycle time. The use of average downtime values in the reliability analysis of a sequential system is inaccurate. In this thesis it is proposed to work with two vectors, one for the number of failure per year(Δ) and other for the downtime per failure(Γ). For a particular element in a system, the information is the same for both methods, but when we link them in a serial way, the information output will be totally different.

This chapter develops a Simulink Blockset with reliability blocks capable of dealing with the vector of information containing the reliability parameters for each system component and with other blocks designed to perform the desired reliability calculations.

3.7. Simulink Reliability Blockset

The reliability blocks for the traditional reliability analysis method is presented (Refer to Simulink Review in Appendix A). The Simulink software runs in the Matlab platform, which is specifically designed to work with matrices and it simplifies the manipulation of data. (Refer to Appendix A). The Reliability block set developed is shown in Figure 3.1.

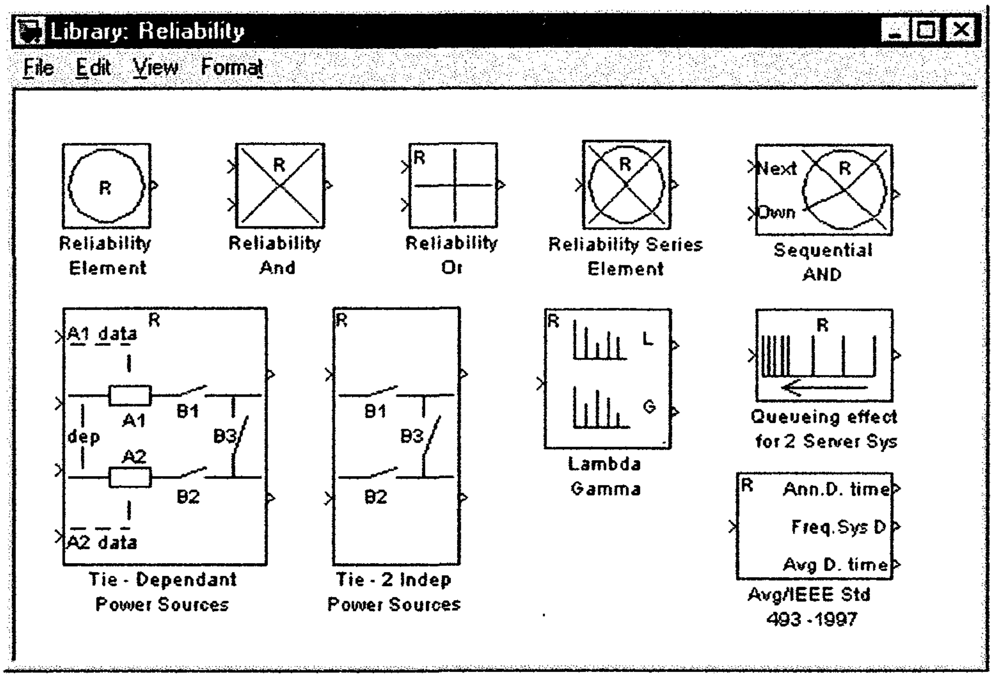


Figure 3.1. Reliability Block Set

3.7.1. Single Element

To represent a single element of a system, by its reliability indices, a block is defined that contains both reliability parameters and produces the output vector c_i. The reliability block designed to represent a single element is shown in Figure 3.2 where F represents the failure rate and H represents the repair time of a single element.

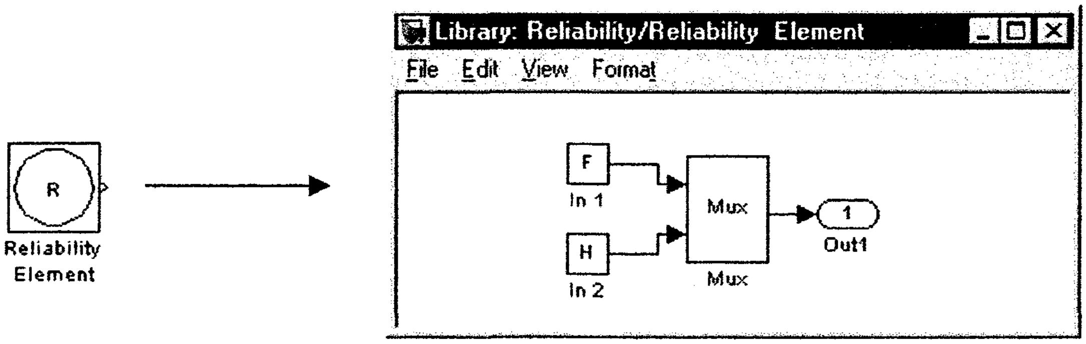
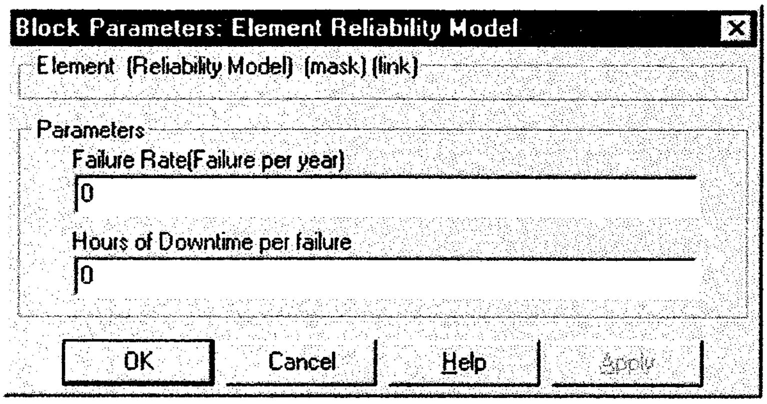


Figure 3.2.Reliability Block for Single Element

When "looking under the mask" it can be seen that the block reads both inputs and generates a unique output . This output is the vector c_i that represents the element i.

The reliability parameters are loaded in a user interface screen that is reached by double clicking on the block of Figure 3.3.


Block Parameters: Element Reliability Model

Element (Reliability Model) (mask) (link)

Parameters

Failure Rate(Failure per year)

0

Hours of Downtime per failure

0

Figure 3.3. User Interface Screen for Element Reliability Model

3.7.2. Series Diagram

According to Reference [15], "when a simple system consists of two or more blocks and the characteristics of the system are such that if any individual block fails, the system fails, then all the blocks are connected or placed in series". In a series diagram, the individual blocks are connected in series. The criteria for the system success is that all the blocks of the series string must work for the system success. If one or more blocks fail, the system fails. It does not always mean that the components are connected physically in series. The individual components can be physically connected in parallel but their block diagrams are connected in series, if their logical operation is serial.

A series diagram for 2 elements is represented in Figure 3.4., where λ_1 and λ_2 are the failure rates for element 1 and 2, respectively. In the same diagram, r_1 and r_2 are the average downtime per failure for each element.

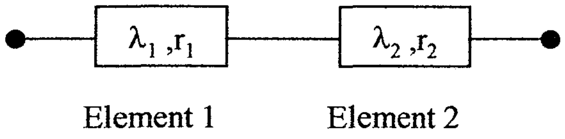


Figure 3.4. Two element series reliability diagram

For this series system, the total failure rate will be:

$$\lambda_s = \lambda_1 + \lambda_2 \quad \text{failures/year} \tag{3.1.}$$

The equation for the average downtime per failure for a series system is:

$$r_S = \frac{\lambda_1 r_1 + \lambda_2 r_2}{\lambda_1 + \lambda_2} \quad \text{hours/failure} \tag{3.2.}$$

The annual downtime for the series system is

$$U_s = \lambda_1 r_1 + \lambda_2 r_2 \quad \text{hours/year} \tag{3.3.}$$

The equation 3.2. is the classical representation for the downtime per failure for a series system, and in fact is an average value.

3.7.2.1 Series Element representation

To calculate the reliability indices of the system according to the causal logic of the Simulink blocks, it is necessary to establish a beginning and end for the serial system. Two blocks combinations will be developed to represent the series circuit.

The series block is represented in Figure 3.5.

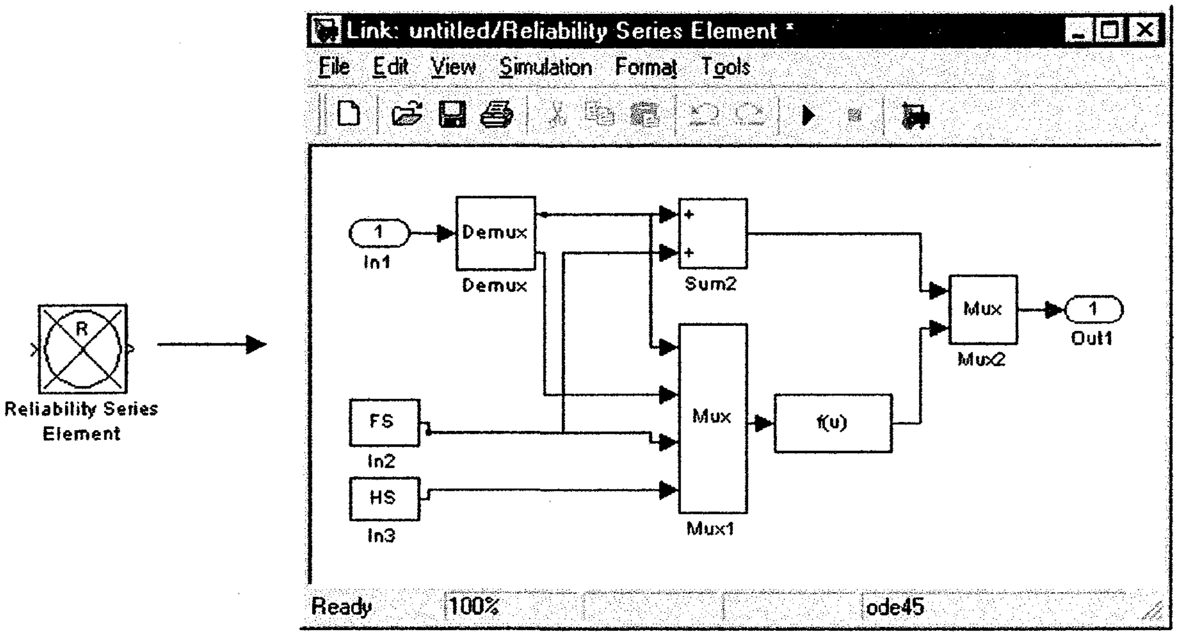
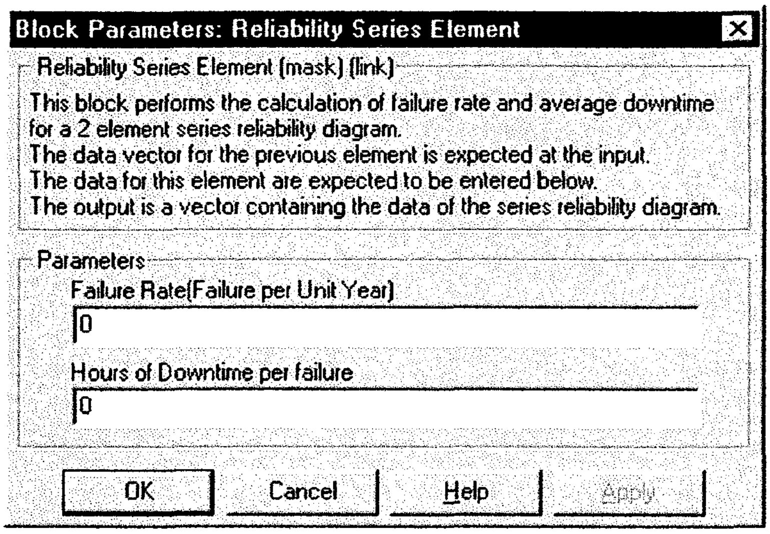


Figure 3.5. Reliability Series Element, block and internal block diagram.

It can be seen from Figure 3.5 the block diagram represents the calculation of equations (3.1.) and (3.2.). In Figure 3.5 FS is the failure rate and HS is the repair of the series element. These parameters are accessed by double clicking on the block of Figure 3.5. and loading the numerical values on the dialog screen shown in Figure 3.6.



Block Parameters: Reliability Series Element

Reliability Series Element (mask) (link)

This block performs the calculation of failure rate and average downtime for a 2 element series reliability diagram.
The data vector for the previous element is expected at the input.
The data for this element are expected to be entered below.
The output is a vector containing the data of the series reliability diagram.

Parameters

Failure Rate(Failure per Unit Year): 0

Hours of Downtime per failure: 0

Figure 3.6. Reliability Series Element user interface screen.

By using the two blocks presented, we can now represent, with the Simulink Reliability Blockset, the system represented in Figure 3.4. The resulting "Simulink Reliability Block Diagram" is shown in Figure 3.7.

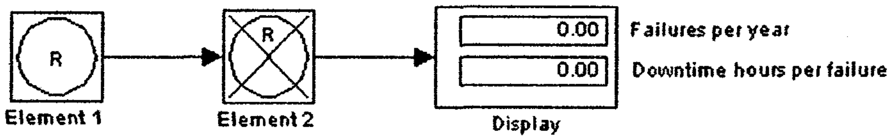


Figure 3.7. Simulink Reliability Block Diagram for two elements series diagram

The Simulink display block is added to close the serial system in order to display the numerical results. Instead of the display block, other blocks could be used to save the information in a matrix or send it to the Matlab Workspace ("To File" or "To Workspace" blocks.).

This methodology is appropriate for power distribution systems with a large number of components in serial connection, and we just have to add one "Simulink Reliability Series element" for representing each element in the power series circuit. When the

Simulink Reliability series diagram is complete, by clicking the "Start simulation" key in the Simulink Model Screen, the result will be shown in the Display block after calculation.

3.7.2.2. Series Systems representation

In the previous section, how to built a series elements reliability model that was appropriate for representing serial system composed by single elements was described. In that case, we had the reliability indices for each element, but, if we have a serial system composed for 2 sub-systems, such data will be the result of the calculation of the reliability indices for each sub-system. It would not be practical to load it in a individual block, because we should in that case, first calculate the subsystem and then, introduce its results in the single block. For those cases a Simulink block was developed for performing the series system calculation. The block is named "Reliability And" according to its logical function and is represented in Figure 3.8.

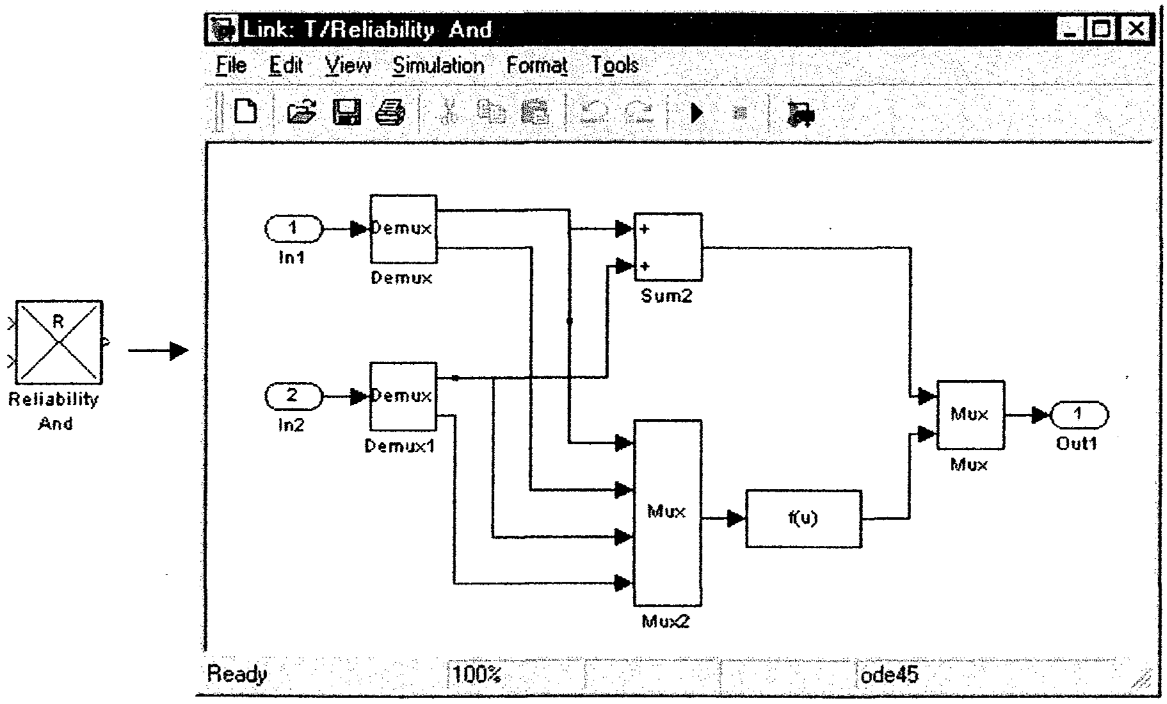


Fig 3. 8. Reliability And Block and internal block diagram

The same system represented in Figure 3.4 can be represented by a Reliability And Block. For this case, the Simulink model is shown in Figure 3.9.

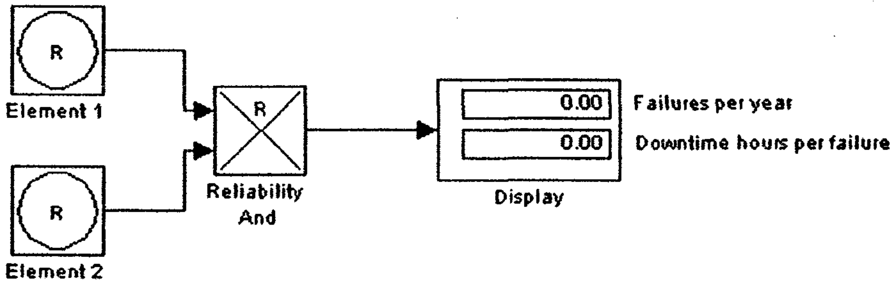


Figure 3.9. Series System Simulink Reliability Model using "Reliability And" block.

The results obtained with the block diagrams of Figure 3.7 and Figure 3. 9 are the same, but in Figure 3.9 one more block is used. The space used to build up the block diagram with "Reliability Series Element" will be considerably smaller than building up the block diagram with "Reliability and" blocks.

3.7.3. Parallel Systems

According to Reference [15], "if a simple system, consists of two or more blocks whose failure does not result in a direct system failure excepts in conjunction with other blocks, then the blocks are arranged or connected in parallel". The criteria for the system failure is that all the blocks of the parallel string must fail for the system failure. A diagram for two elements in parallel is shown in Figure 3.10.

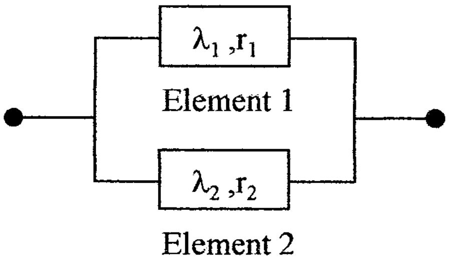


Figure 3.10. Two elements parallel reliability diagram

For the parallel system, the equivalent system failure rate is:

$$\lambda_p = \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{8760} \quad \text{failure/year} \qquad (3.4)$$

where λ_i: failures per year for element "i"

r_i: hours per failure for element "i"

The average downtime will be:

$$r_p = \frac{r_1 r_2}{r_1 + r_2} \quad \text{hours/failure} \qquad (3.5)$$

Note: Equations (3.4) and (3.5) are approximated and can be used when both $\frac{\lambda_1 r_1}{8760}$ and $\frac{\lambda_2 r_2}{8760}$ are smaller than 0.01.[1]

3.7.3.1. Parallel System Representation

The block designed for the parallel system representation is named "Reliability Or" and is shown in Figure 3.11.

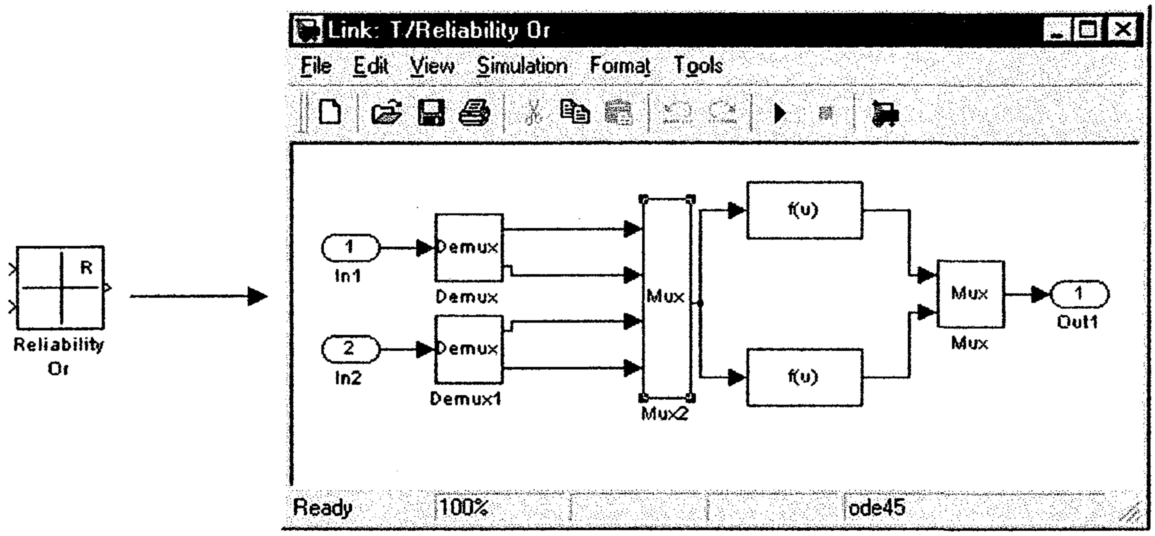


Figure 3.11. Reliability Or block and internal block diagram

The parallel element diagram of Figure 3.10 can be represented by the Simulink block diagram is shown in Figure 3.12.

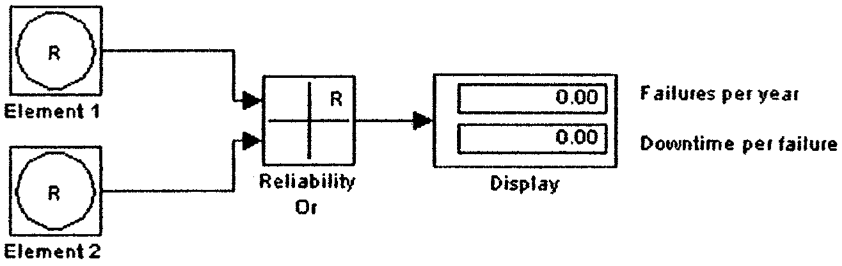


Figure 3.12. Parallel System Simulink Reliability Model

The Simulink display block is added to close the parallel system model and display the numerical results. Instead of the display block, other blocks could be used to save the information in a matrix or send it to the Matlab Workspace ("To File" or "To Workspace" blocks.).

This methodology is appropriate for power distribution systems and any other systems with elements working in parallel, performing the same function at the same time, for example, a double feeder cable for a single load. When the Simulink Reliability parallel diagram is complete, by following the same procedure shown for the series diagram, we obtain the reliability parameters indices shown in the Display block.

3.7.4. Combined parallel - series systems

With the Simulink Reliability blocks provided it is now possible to represent any combination of series and parallel systems. Some particular blocks for typical power system diagrams are developed as follows:

3.7.5 Selective Systems

In an industrial power distribution system, in order to improve its reliability, it is a common design practice to include "Tie breakers". These Tie Breakers have the function of switching between different power sources or power distribution configurations in order to reduce the downtime that is a result of equipment outages.

3.7.5.1. Selective System with Dependent Power Sources

A typical one line diagram of an industrial distribution system with two dependent power sources is shown in Figure 3.13.

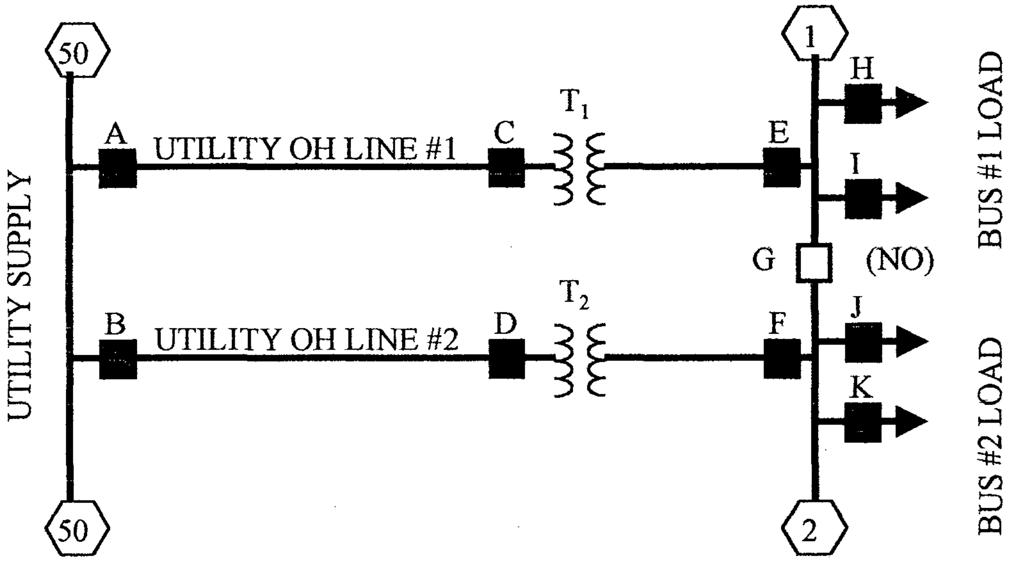


Figure 3.13. Selective Industrial Power Distribution System

In Figure 3.13, it is necessary to calculate the failure rate and downtime per year of the load on BUS #2, breaker K. The breaker G under normal operation is normally opened (NO). When some of the elements in one or both feeder lines (i. e. Utility Overhead or OH line, transformer or breakers) fails and interrupts power to the load, it is possible to transfer the load from the faulted line to the other operational feeder line, which is not faulted. Then, the downtime for one of these failures would be the switching time for breaker G in this example.

In order to simplify the analysis, the system is represented by the Zone Branch Methodology[11]. By this method, the system can be reduced to a simple "branch elements" and the system of Figure 3.13. is transformed to the one shown in Figure 3.14.

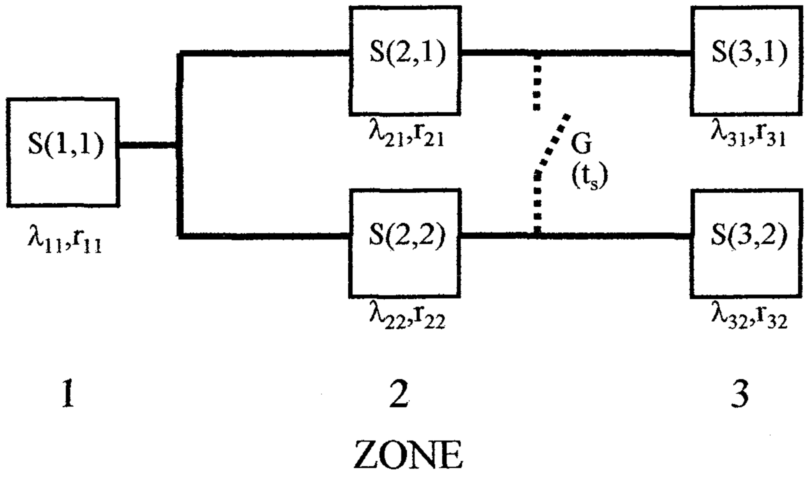


Figure 3.14. Zone Branch Diagram for the Industrial Distribution Selective System

Table 3.1 shows the zone branch list of the zone branch diagram of Figure 3.14 and the components of each zone branch.

Table 3.1. Zone Branch elements

Zone Branch	**Components**
S(1, 1)	Utility Supply(bus 50)
	Breakers A and B
S(2, 1)	Utility OH Line 1
	Breaker C
	Transformer T1
S(2, 2)	Utility OH Line 2
	Breaker D
	Transformer T2
S(3, 1)	Breakers E , H and I
	Bus 1
S(3, 2)	Breakers F, J and K
	Bus 2

It will be assumed that the simultaneous failures of both feeder lines is negligible. The effect of the breaker G switching in the Reliability Diagram is to switch both r_{21} and r_{22} to t_s. For representing the switching activities a block was developed which is shown in Figure 3.15.

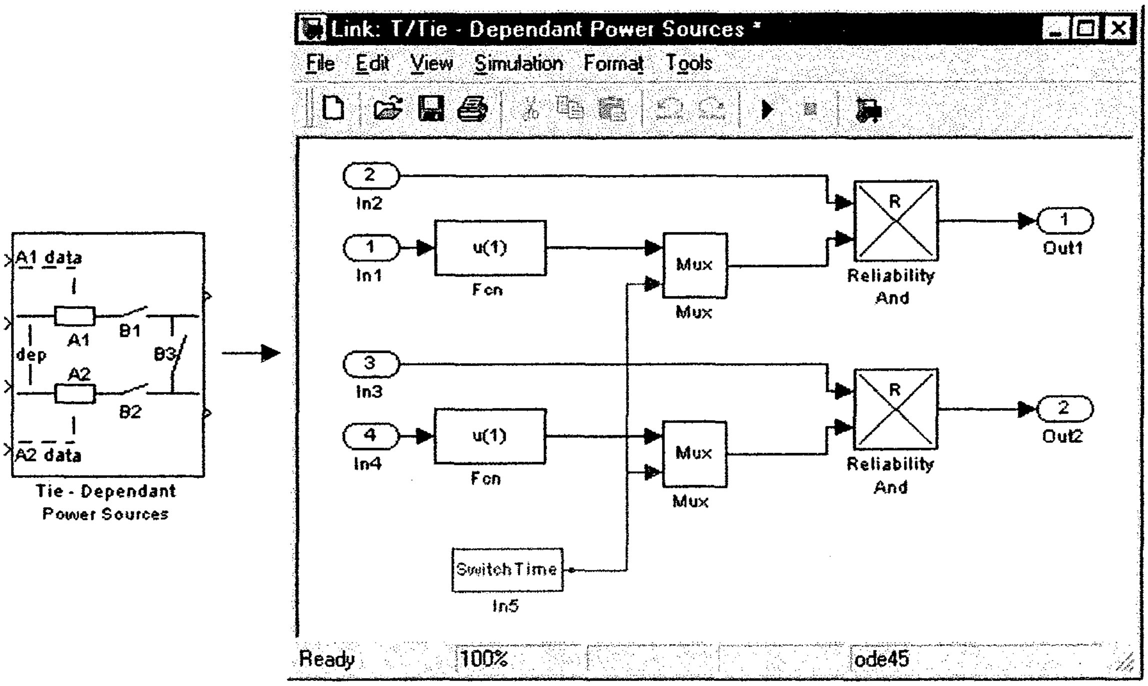
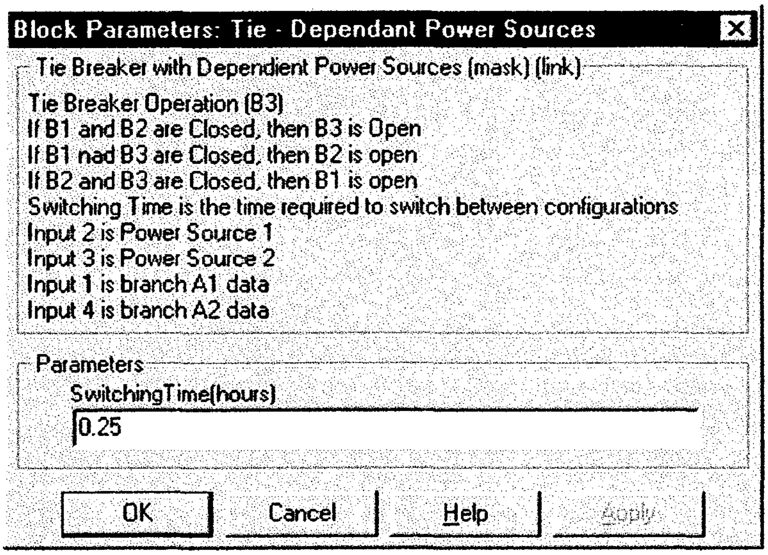


Figure 3.15 Reliability Tie - Dependant Power Sources and internal block diagram

It is clear that only the repair time associated with the branches that can be switched are affected (replaced by t_s). There is no change in the reliability indices of the branches that can not be switched by another when it is faulted. The tie – dependant power sources block is also suitable for other systems with two dependant power sources. To introduce the switching time into the block presented in Figure 3.15. it is necessary to double click on block to access the dialog box shown in Figure 3.16.



Block Parameters: Tie - Dependant Power Sources

Tie Breaker with Dependient Power Sources (mask) (link)

Tie Breaker Operation (B3)
If B1 and B2 are Closed, then B3 is Open
If B1 nad B3 are Closed, then B2 is open
If B2 and B3 are Closed, then B1 is open
Switching Time is the time required to switch between configurations
Input 2 is Power Source 1
Input 3 is Power Source 2
Input 1 is branch A1 data
Input 4 is branch A2 data

Parameters

SwitchingTime(hours)

0.25

Figure 3.16. Switching Time Dialog Box

The resulting Simulink block diagram for the system shown in Figure 3.13 and Figure 3.14 is shown in Figure 3.17. The elements of the zone branch diagram shown in Figure 3.14 are identified in Figure 3.17 with dotted lines.

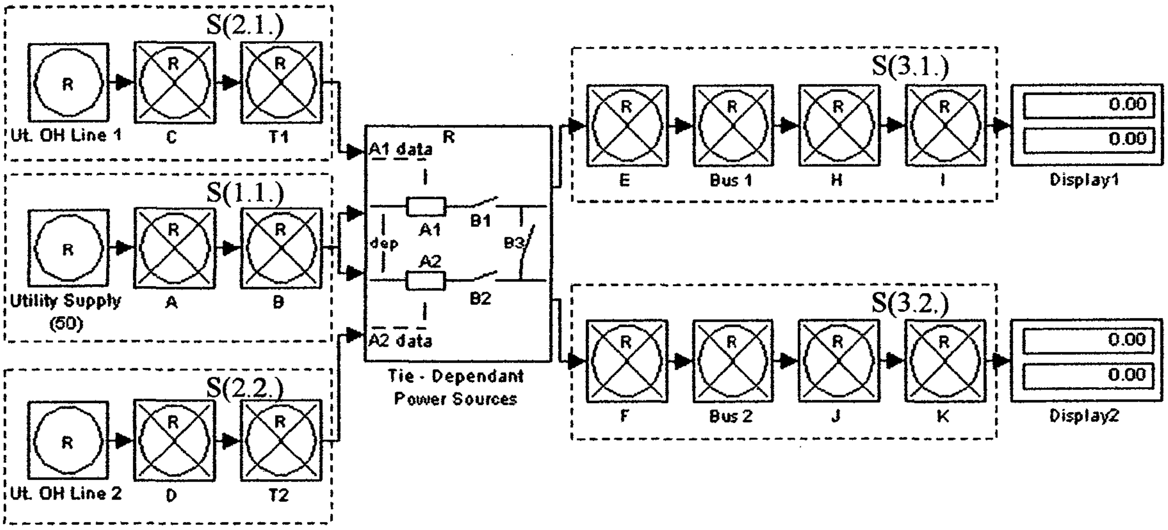


Figure 3.17. Simulink Reliability Block Diagram

In Figure 3.17, the Display 1 will show, after running the simulation the number of failures per year and downtime per failure for the Bus #1 Load. The same results for the Bus #2 Load will be shown in Display 2.

3.7.5.2. Selective System with Independent Power Sources

A system similar to that one of Figure 3.13., but fed with independent power sources is shown in Figure 3.18.

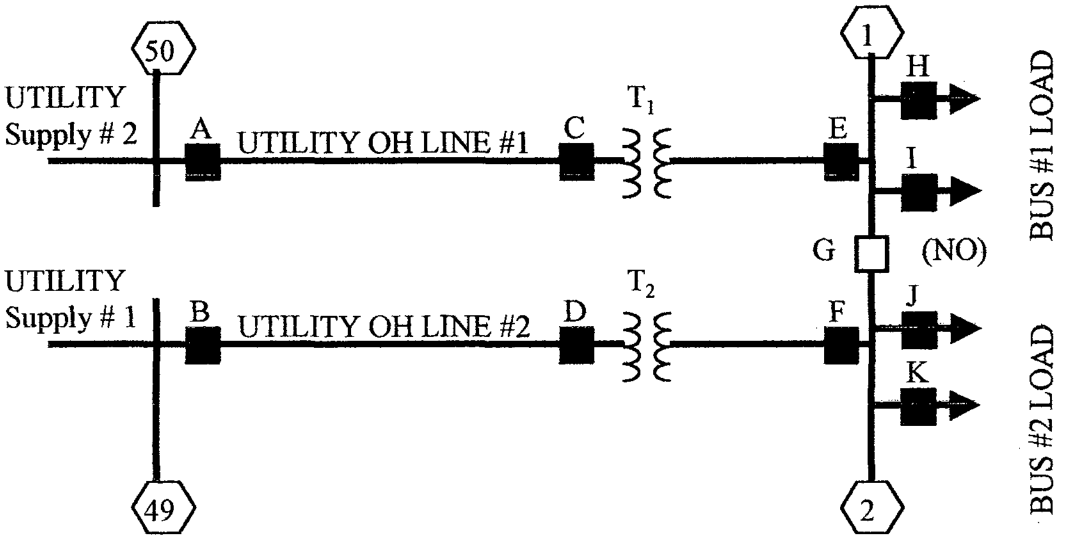


Figure 3.18. Selective Industrial Power Distribution System- 2 Independent Power Sources

The block developed to represent the effect on the downtime of tie breaker G is shown in Figure 3.19.

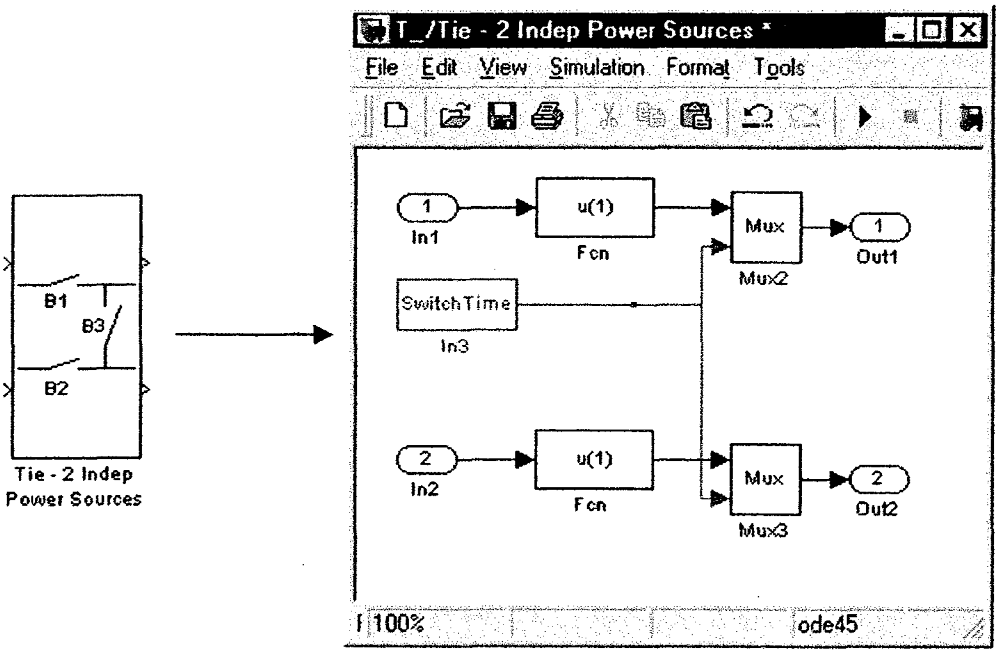


Figure 3.19. Simulink Tie -2 Independent Power Sources Block and internal block diagram

The Simulink block diagram that represents the system presented in Figure 3.18 is shown in Figure 3.20.

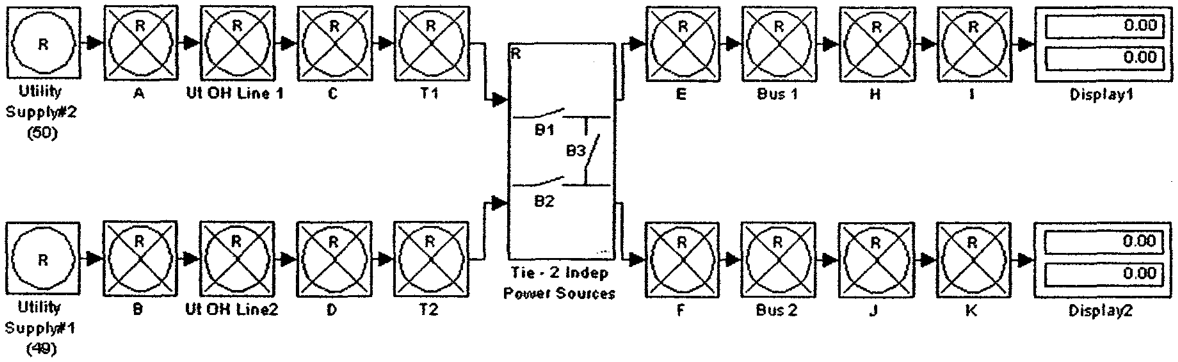


Figure 3.20. Simulink Reliability Block Diagram

By linking the Simulink Reliability blocks developed, it is possible to perform power system reliability studies and if any additional block are needed, they could be built up in a similar manner.

3.7.6. Failure Condition Analysis of a Manufacturing System

Most of the manufacturing subsystems (a conveyor or a machine for example) behave in a serial way. It means that, if an element of the system fails (a motor, a valve or a sensor, for example), the whole system will be down. Generally, there are no elements running in parallel, in such a way that if one fails the other can keep the subsystem in operation. In some cases there are sub-systems working in parallel and when one of them fails, the other can continue operating but with a lower production rate. Some of these cases are analyzed further in Chapter 4.

To develop the Simulink Reliability Model of a manufacturing subsystem the elements that produce a "failure stop" of a subsystem is identified by the following steps:

(1) Analysis of the logic of the controller, the layout of the subsystem and the elements associated with the operating cycle of the sub-system.

(2) Each element that was previously identified will be represented by a Simulink Reliability block.

(3) All the Simulink Reliability blocks are multiplexed into a single vector with a Simulink "Mux" block. The Mux block combines several input lines into one vector line where each input line can carry a scalar or vector signal and its output is a vector.

(4) To calculate the reliability indices the output of the Mux block will be linked to a block designed to sort the information and generate two output vectors. One of those vectors is built by the failure rates (Λ), and other built by the

down times (Γ). This block is called "Lambda-Gamma" and is shown in Figure 3.21.

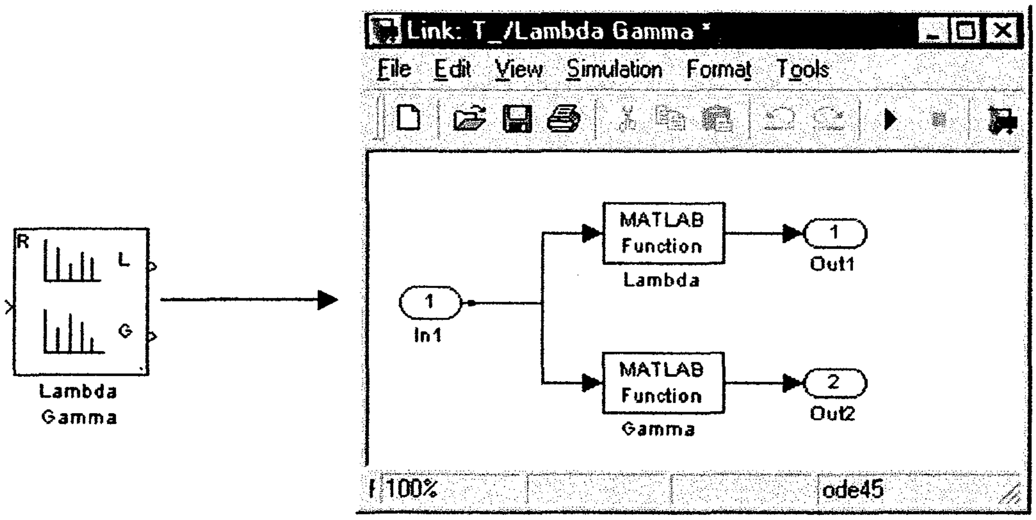


Figure 3.21. Lambda-Gamma Simulink Reliability block and internal block diagram

In the internal block diagram two Matlab functions perform the sorting of the input data vector and calculate the Lambda(Δ) and Gamma(Γ) vectors containing the failure rate and downtime per failure, respectively.

In order to reduce the large of the vectors Lambda and Gamma, the block shown in Figure 3.21 performs an average (serial logic calculation according equations 3.1 and 3.2) of the data for intervals of one minute.

The units of the output vectors are failure per year for Lambda and minutes per failure for Gamma where the adoption of minutes instead of hours is more appropriate for manufacturing systems. The blocks containing the data of single elements are designed for hours per failure for the downtime to keep the unit used in power system reliability analysis and to keep this proposed method suitable for both systems.

The Matlab Functions developed to calculate both vectors are transcribed in Appendix B.

The data organized in this way can be sent to the Matlab Workspace with a "To workspace" block or can be stored in a Matrix for further analysis. The Lambda-Gamma block can also be easily connected to any subsystem embedded in a major system in order to analyze its individual performance.

3.7.6.1 Example of a manufacturing subsystem or equipment.

In order to show how to apply the proposed methodology to an actual system, an example of a part of the manufacturing system is presented. The example is a simplified Power Roll Bed conveyor as the Conveyor C2 shown in Figure 3.22.

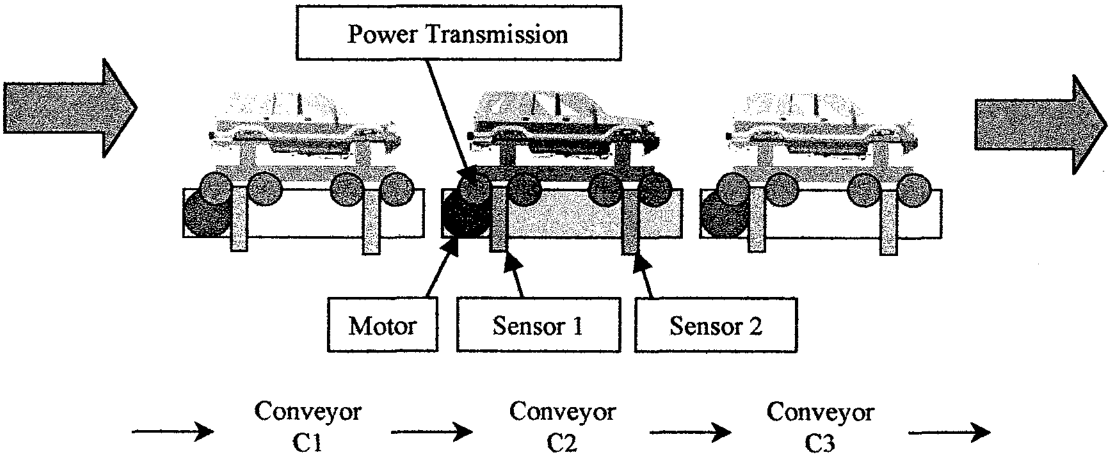


Figure 3.22. Power Roll Bed conveyor in a manufacturing line

After studying its automation, it can be concluded that the elements that can lead to a stop failure with its reliability parameters are shown in Table 3.2

Table 3.2 Elements identified for the conveyor C2 and associated reliability indices

Element	Failure Rate [Failures/year]	Downtime [Hours/failure]
Gearmotor and switchgear	0.1886	0.25
Sensors(2)	0.3166	0.30
Power Transmission(Belts and Rolls)	0.1450	0.45
Control Circuitry(PLC, Input/Output modules, communications and wiring)	0.3420	0.67
Power Failure	1.2300	0.68

The reliability data of the elements identified for the conveyor C2 and shown in Table 3.2.are represented by Simulink Reliability blocks and linked according to the proposed methodology. A Lambda-Gamma Simulink Reliability block is also included to perform the analysis of the results in the Matlab workspace and the resulting Simulink block diagram for the conveyor C2 of this example is shown in Figure 3.23.

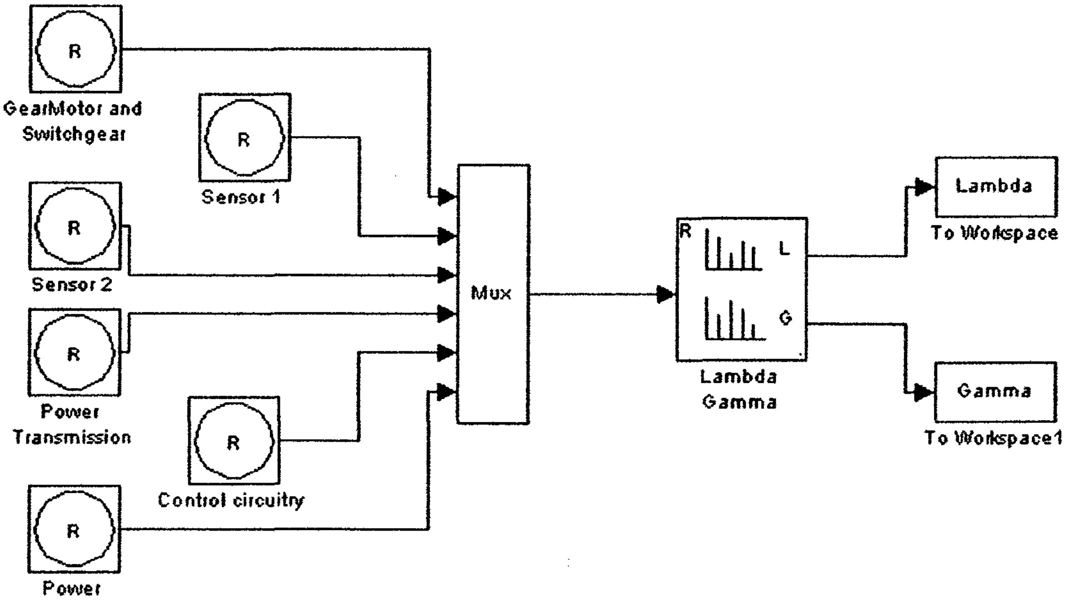


Figure 3.23. Simulink Reliability block diagram for the Conveyor C2

After building the model, it is necessary to run the Simulation. Because the parameters for the model are fixed, it is not necessary to set up the parameters of the simulation for more than one iteration. The calculation is direct because the model is not dynamic (e.g. the reliability parameters are constant) and one time interval is sufficient. For example, we can set up 0.004 seconds of total simulation time for a simulation step of 0.005 seconds. Only one vector is obtained for each "to workspace" block. Once the simulation ended, the Gamma and Lambda vectors are available at the Matlab Workspace.

The results obtained are:

Lambda =[0.1875 0.6332 0.1450 1.5720]

Gamma =[15.0000 18.0000 27.0000 40.6695]

It can be noted that the reliability indices for some elements with similar downtimes, have been reduced to one element. This is very important if we consider that a large industrial system will be integrated by thousands of elements. A Matlab bar plot is shown in Figure 3.24.

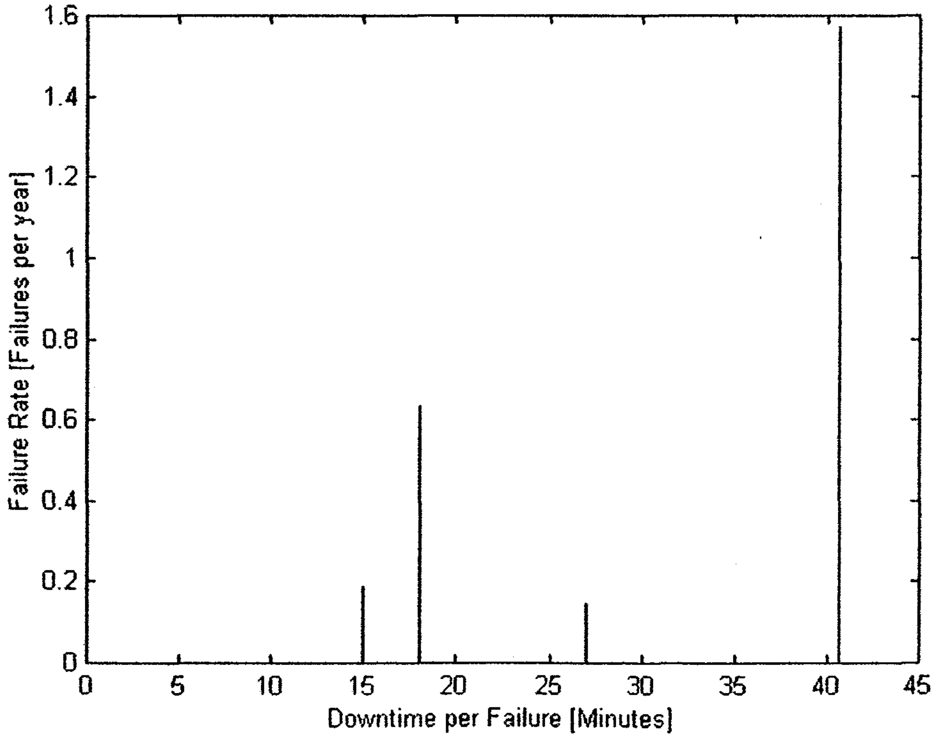


Figure 3.24. Failure rate vs Downtime per failure for the Conveyor C2

Discussion

Although this particular case is perhaps trivial, the reliability indices managed in this way are very useful to analyze a Manufacturing Industrial System and the power of the proposed method will be illustrated when the study of a larger actual manufacturing system will be conducted in Chapter 4.

3.7.7 Sequential Manufacturing Systems Reliability Modelling

The manufacturing sequential system is explained and analyzed in detail in Chapter 2. It was explained (Chapter 2, sections 2.3. to 2.7) how a fault in a conveyor will affect the rest of the conveyors in the production line.

It was shown in section 2.7 that, for consecutive conveyors, when one of them is down at $t = t_0$, after $t = t_{cycle}$, the previous conveyor will stop the cycle. It means:

$$t_{stop} = t_0 + t_{cycle}. \tag{3.6}$$

A particular conveyor C_i, characterized by a failure rate λ_i and a downtime per failure r_i, will affect the previous conveyor C_{i-1} in the following way:

$$t_{Ci-1} = r_i - t_{cycle}(\text{downtime at } C_{i-1} \text{ due to a fault of } r_i \text{ at } C_i) \tag{3.7}$$

but, if $r_i < t_{cycle}$, the previous conveyor will not be affected.

A conveyor C_i can be characterized by the vectors $\Lambda\mathbf{i}$ and $\Gamma\mathbf{i}$ that are defined as follows:

$$\Lambda\mathbf{i} = [\lambda i_1, \lambda i_2, \ldots. \lambda i_{m-1}, \lambda i_m, \lambda i_{m+1}, \ldots., \lambda i_{n-1}, \lambda i_n] \tag{3.8}$$

$$\Gamma\mathbf{i} = [ri_1, ri_2, \ldots, ri_{m-1}, ri_m, ri_{m+1}, \ldots.., ri_{n-1}, ri_n] \tag{3.9}$$

The elements of Λi and Γ_i are sorted monotonically increasing. Then, for a given t_{cycle} where:

$$ri_{m-1} < t_{cycle} < ri_m \tag{3.10}$$

the elements of Λ_i and Γ_i that will affect the previous conveyor will be those for which

$$t_{cycle} > ri_j \text{ , where } j = n \text{ to } m \tag{3.11}$$

It is proposed now to build up two new reliability parameter vectors Λi^C and Γi^C with n-(m-1) elements keeping the failure rate and downtime per failure format and representing the effect of a failure at conveyor C_i on the previous conveyor C_{i-1}.
The new vectors will be called Λi^C and Γi^C are:

$$\Lambda i^C = [\, \lambda i_m \,,\, \lambda i_{m+1} \,,\, \ldots\ldots,\, \lambda i_{n-1} \,,\, \lambda i_n \,] \tag{3.12}$$

$$\Gamma i^C = [(ri_m - t_{cycle}),(ri_{m+1}-t_{cycle}), \ldots\ldots,(ri_{n-1}-t_{cycle}),(ri_n-t_{cycle})] \tag{3.13}$$

Then, the conveyor C_{i-1} can be represented by both the total failure rate (Λi^*) and total downtime per failure (Γi^*) data vectors that will be the result of its own parameters, Λi_{-1} and Γi_{-1}, and the effect of the previous conveyor C_i, Λ_i^* and Γ_i^* are defined as:

$$\Lambda_i^* = \Lambda i_{-1} \,\hat{}{*}\, \Lambda i^C \tag{3.14}$$

$$\Gamma_i^* = \Gamma i_{-1} \,\hat{}{*}\, \Gamma i^C \tag{3.15}$$

The symbol ^* means that both vectors represent sub-systems logically related in a serial manner. The number of elements involved in the calculation of equations (3.14) and (3.15) can be very large and because of this a Matlab Subroutine was developed to calculate it. The Matlab function is then included in a new Simulink Reliability block that will perform the desired calculations just by linking it to the system. The Simulink block and internal block diagram is shown in Figure 3.25. The Matlab function that was developed to perform the calculations called “transffa” and is transcribed in Appendix B.

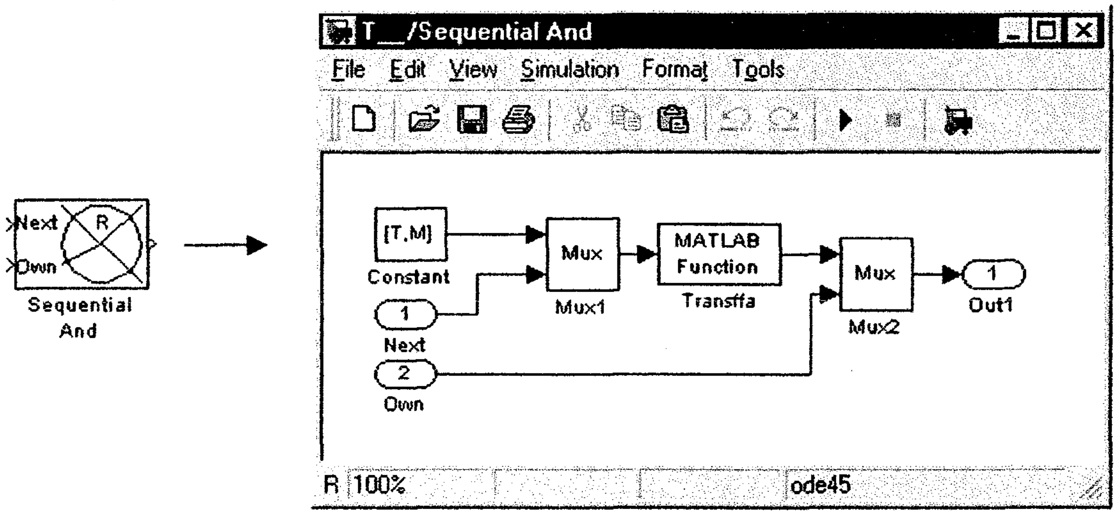
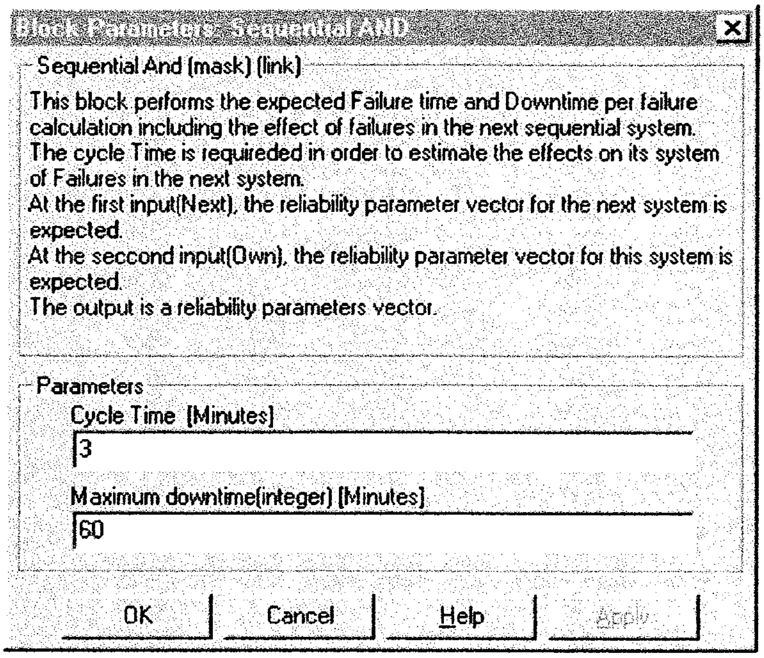


Figure 3.25. “Sequential And” Reliability Block and Internal block diagram

By double clicking on the “ Sequential And” block access to the dialog box is gained as shown in Figure 3.26.



Sequential And (mask) (link)

This block performs the expected Failure time and Downtime per failure calculation including the effect of failures in the next sequential system.
The cycle Time is requireded in order to estimate the effects on its system of Failures in the next system.
At the first input(Next), the reliability parameter vector for the next system is expected.
At the seccond input(Own), the reliability parameter vector for this system is expected.
The output is a reliability parameters vector.

Parameters

Cycle Time [Minutes]
3

Maximum downtime(integer) [Minutes]
60

Figure 3.26. "Sequential And" Reliability block dialog screen

The parameters asked by the Reliability "Sequential And" block are the Cycle Time, which is necessary to perform the calculations, and the Maximum Downtime, which is necessary to limit the Matlab Function output. This last parameter is necessary for the Matlab student version which was used to develop the Simulink Reliability block set. After both parameters have been loaded in the Sequential And block, it is linked to the sub-systems of the sequential system.

The " Sequential And" Simulink block has two inputs. The first one is called "Next" and the reliability indices vectors (Λ_{i+1} and Γ_{i+1}) carrying the data of the Next sequential subsystem in the productive line is expected. The second input (Own) expects the reliability vector carrying the data for the subsystem which defines the expected modified failure per year (Λi) and downtime per failure (Γ_i) vectors, that will, after the simulation, includes the downtime due to failures in the next conveyor (Λi^* and Γi^*).

3.7.7.1.Example of Sequential Systems Reliability Modelling

An example of the "Sequential And" block assuming a sequential system of 3 conveyors shown in Figure 3.27 will be presented.

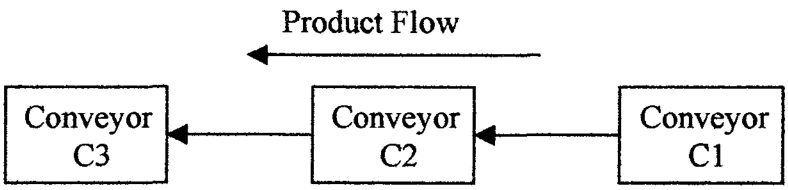


Figure 3.27. Three Conveyor sequential system

In order to simplify the example, the reliability block diagrams of each conveyor are grouped with a Simulink "Subsystem" block. The resulting Simulink Reliability block diagram for the system of Figure 3.27 is shown in Figure 3.28.

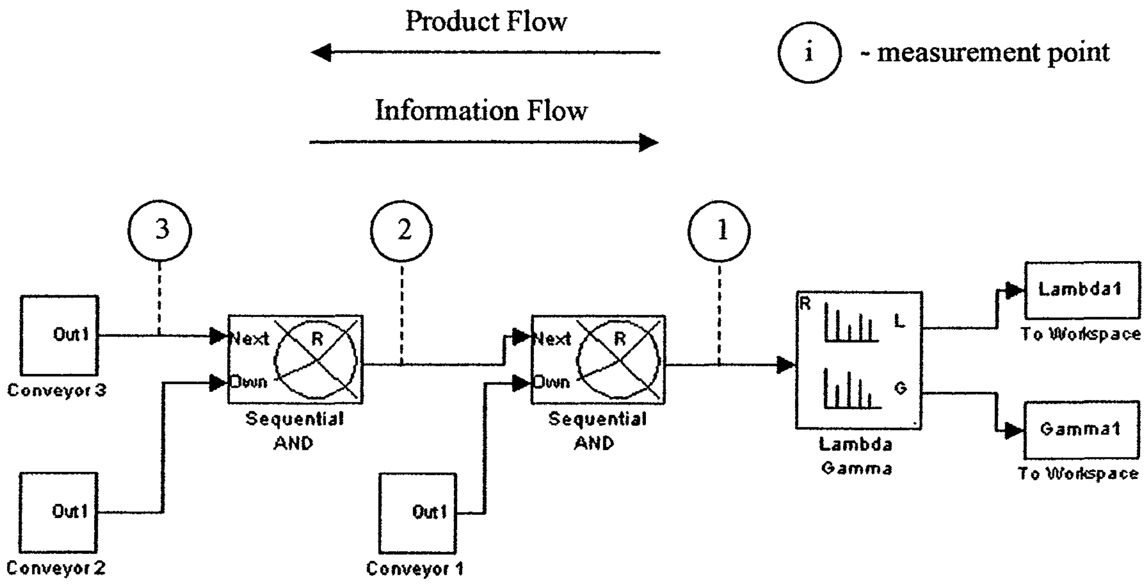


Figure 3.28 Simulink Reliability Model for Three Conveyor Sequential System

In Figure 3.28 it can be observed that, in the Simulink reliability block diagram the information flow is opposite to the product flow. This is due to the causality of the relationship between consecutive systems. As was previously explained, to predict the expected failure rate and downtime per failure of a sequential sub-system "i", it is necessary to define the same reliability data vectors Λ_{i+1} and Γ_{i+1} for the subsystem that is downstream in the productive line. Then, it must be realized at this point that the methodology starts to build up the whole system from the last sub-system.

To show the method that was explained, in Figure 3.28, three measurement points were linked with dotted lines. In measurement point "3" the Reliability data of conveyor 3 is accessed. This conveyor is the last in the productive line and has no other subsystems downstream, and its reliability parameter vectors Λ_3 and Γ_3 are the result of the data of its own elements. In measurement point "2" we will observe the data of Conveyor 2 including the effect of Conveyor 3 (Λ_2^* and Γ_2^*), and, in point "1", are the Reliability vectors for Conveyor 1 accounting the effects of Conveyor 2 and Conveyor 3 (Λ_1^* and Γ_1^*). In fact in point "1" we can observe the Reliability vectors for the whole system (Λ_{tot} and Γ_{tot}) are observed resulting in:

$$\Lambda_{tot} = \Lambda_1^*$$
$$\Gamma_{tot} = \Gamma_1^*$$

The elements of the 3 conveyors presented in this example are represented by their reliability indices shown in Table 3.2. This data is loaded in the Simulink reliability blocks of Figure 3.28.

Table 3.3. Conveyors reliability data

Subsystem	**Component Type**	**ID**	**Failure rate [Failures / year]**	**Downtime per Failure [Hour / failure]**
Conveyor 1	Motor	M1.1	0.8	0.25
	Sensor	S1.2	2	0.04
	Belt	B1.3	0.7	0.09
	Control	C1.4	0.5	0.14
Conveyor 2	Motor	M2.1	0.8	0.25
	Sensor	S2.2	2	0.04
	Belt	B2.3	0.7	0.09
	Control	C2.4	0.5	0.14
Conveyor 3	Motor	M3.1	0.8	0.25
	Sensor	S3.2	2	0.04
	Belt	B3.3	0.7	0.09
	Control	C3.4	0.5	0.14

For this particular example the reliability indices will be calculated for a production rate of 20 cars/hour with a Cycle time of 3 minutes. The results of the simulation, for the measurement points 1, 2, and 3 in Figure 3.27, are shown in Figure 3.29. a, b and c. On the same figure each element of the conveyor was identified by the ID shown in Table 3.3.

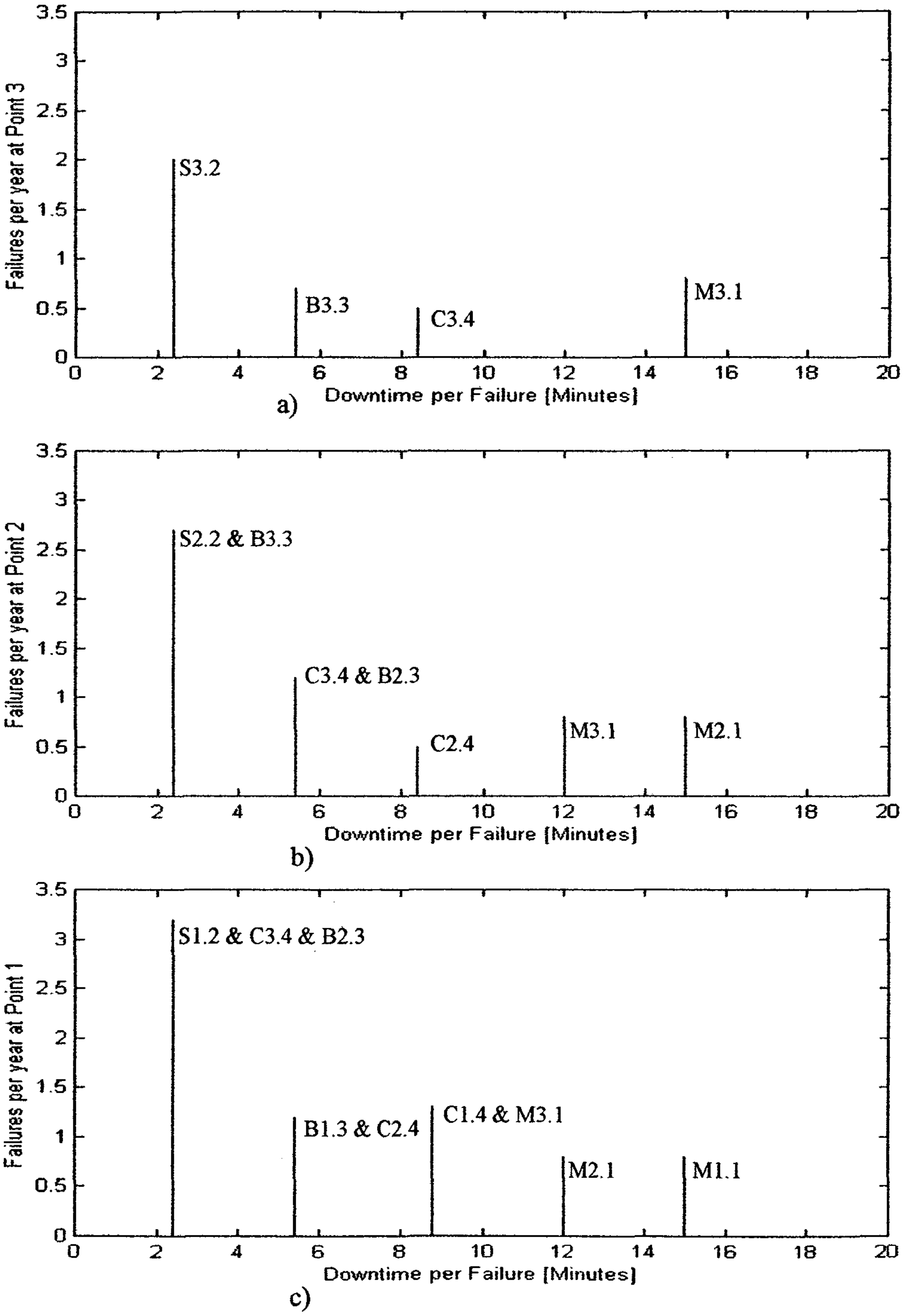


Figure 3.29. Failures per year vs Downtime per failure. a) Point 3, b) Point 2, c) Point 1

Discussion of the three conveyor sequential system example:

Considering that in the automatic manufacturing systems under the coverage range of this study, "the product unit that does not start on time at the first conveyor is unit not produced" because the feeding speed of the production line is constant. It will yield information of how many products will not be produced because of the production system downtime.

Calculation of the annual downtime of the example shown in Figure 3.28 analyzed for the different measurement points is shown below.

Measurement Point 3: Annual duration of interruptions (U_s)

$$U_{s3} = \sum_{i=1}^{4} \lambda_i * r_i$$

(where i is the order number of the elements of reliability 4-element vectors Δ_3 and Γ_3, which are in fact the reliability indices of Conveyor C3 .)

$$U_{s3} = 2.4*2.5+5.4*0.7+8.4*0.5+15*0.8$$

$$U_{s3} = 24.78\ minutes$$

Measurement Point 2: Annual duration of interruptions (U_{s2})

$$U_{s2} = \sum_{i=1}^{5} \lambda_i * r_i$$

(where i is the order number of the 5-element vectors Λ_2^* and Γ_2^*, which are the combination of the reliability index vectors of Conveyor C2 (Λ_2 and Γ_2), and Conveyor C3(Λ_3 and Γ_3) (affected by T_{cycle}.)

U_{s2}= 2.4*2.7+5.4*1.2+8.4*0.5+12*0.8+15*0.8

U_{s2} = 38.76 minutes/year

Measurement Point 1: Annual duration of interruptions (U_{s1})

$$U_{s1} = \sum_{i=1}^{5} \lambda_i * r_i$$

(where *i* is the order number of the elements of reliability 5-element vectors Λ_1^* and Γ_1^*, which are the combination of the reliability indexes of Conveyor C1(Λ_1 and Γ_1),, C2 affected by T_{cycle} and Conveyor C3 affected by 2* T_{cycle}(Δ_2^* and Γ_2^*,.)

U_{s1}= 3.2*2.4000+1.2*5.4000+1.3*8.7692+0.8*12.0000+0.8*15.0000

U_{s1} = 47.16 minutes/year

Comparing the results with a single conveyor which has a total downtime of 24.78 minutes for a single conveyor (Measurement point 3), for two consecutive conveyors results

$$\frac{U_{s2}}{U_{s3}} = \frac{38.76\ minutes}{24.78\ minutes}$$

$$\frac{U_{s2}}{U_{s3}} = 1.56$$

The annual downtime for two consecutive conveyors is 1.56 times greater than that of a single conveyor.

For the whole system the results are:

$$\frac{U_{s2}}{U_{s3}} = \frac{47.16\ minutes}{24.78\ minutes}$$

$$\frac{U_{s2}}{U_{s3}} = 1.903$$

The annual downtime for three consecutive conveyors is 1.903 times grater than that of a single conveyor. The total annual downtime is almost double that for a single conveyor, and this is only a very simple system consisting of only 3 conveyors. This effect will also increase when the cycle time is decreased because of an increment in the production level. These effects will be analyzed in the next chapter.

3.7.8. Sequential System with two alternative paths

A system with two alternative paths is shown in Figure 3.29 will be analyzed.

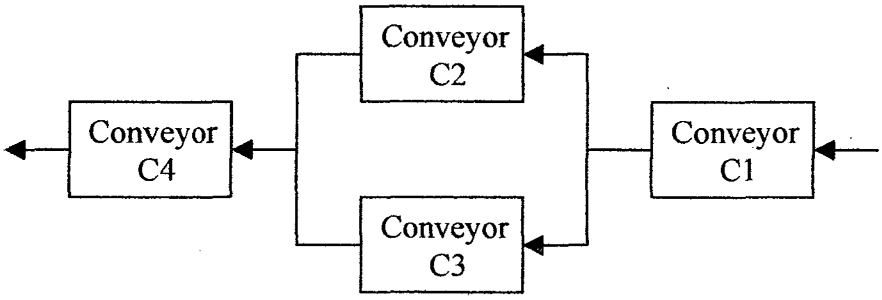


Figure 3.30. Conveyor sequential system with two alternative paths

The layout shown in Figure 3.30 is frequently adopted in industrial design to improve the reliability of the industrial system or to increase the production rate by parallel processing. It is necessary to determine in which way a fault of the parallel conveyors (C3 or C2) affects the productive line.

Because conveyors C2 and C3 are working in parallel, if the products are distributed alternatively between both lines, each one will process half of the production, and then, their cycle times will be half of the cycle time of the manufacturing line.

$$t_{cycle2} = t_{cycle3} = t_{cycle} * 2 \tag{3.16}$$

It was explained in Chapter 2 that a conveyor is characterized by the run time (t_{run}), which is smaller than the process cycle time t_{cycle} but, because of design restrictions, generally, one of the alternative paths is not capable of maintaining the production level by its own. Then, when a fault in one of the parallel lines (conveyors C2 or C3) is forced to send all the products through the remaining line, it will not be able to do it with the required speed and a queue at conveyor C1 will start to grow. The queue building means that the conveyors downstream of C1 will stop in the state " Waiting ready to transfer". If the fault is not repaired, the queue will continue growing and finally, the cycle time of the manufacturing process will result

$$t_{cycle*} = t_{cycle2} = t_{cycle3}.$$

Analyzing this effect by queueing theory[5], the system is characterized by an arrival time between samples of $t_{arr} = t_{cycle}$ and the service time of:

$$t_{serv} = t_{cycle2} = t_{cycle3} \text{ where } t_{arr} < t_{serv}$$

For the analysis of the case proposed and because of the characteristics of the manufacturing process t_{arr} and t_{serv} are assumed constant.

If the failure downtime at conveyor C2 is smaller than T_{cycle2} , it will not be seen by conveyor C1. Because of the assumption previously made where it was stated that t_{arr} and t_{serv} are constant, the relationship between the failure downtime for conveyor C2 and waiting downtime for conveyor C1 will be linear when the failure downtime will be greater than the $t_{cycle2} = 2^{*}\, t_{cycle}$. Once a fault is started at conveyor C2, after t_{cycle2}, for each t_{serv}, the waiting time will increase t_{serv} - t_{arr} . Then, the transfer function for $t_{wait} = f(t_{fault})$ is:

$$t_{wait} = 0 \qquad \text{for } t_{fault} \leq 2^{*} t_{arr}$$

$$t_{wait} = -2 * T_{arr} + \frac{t_{serv} + t_{arr}}{t_{rserv}} * t_{fault} \qquad \text{for } t_{fault} > 2^{*} t_{arr} \qquad (3.17)$$

and for this particular case is:

$$t_{wait} = 0 \qquad \text{for } t \leq 2^{*} t_{cycle}$$

$$t_{wait} = -2 * t_{cycle} + \frac{t_{run2} + t_{cycle}}{t_{run2}} * t_{fault} \qquad \text{for } t > 2^{*} t_{cycle} \qquad (3.18)$$

Then, a fault of $t = t_{fC2}$ at Conveyor C2 will affect Conveyor C1 in:

$$t_{1wait} = t_{1wait}(t_{fC2})$$

$$(3.19)$$

$$t_{1wait} = -2 * t_{cycle} + \frac{t_{run2} + t_{cycle}}{t_{run2}} * t_{fC2}$$

Equation 3.19 is implemented with a Matlab function named "2squeue" (See Appendix B) and it is masked in a new Simulink Reliability model that is shown in Figure 3.31.

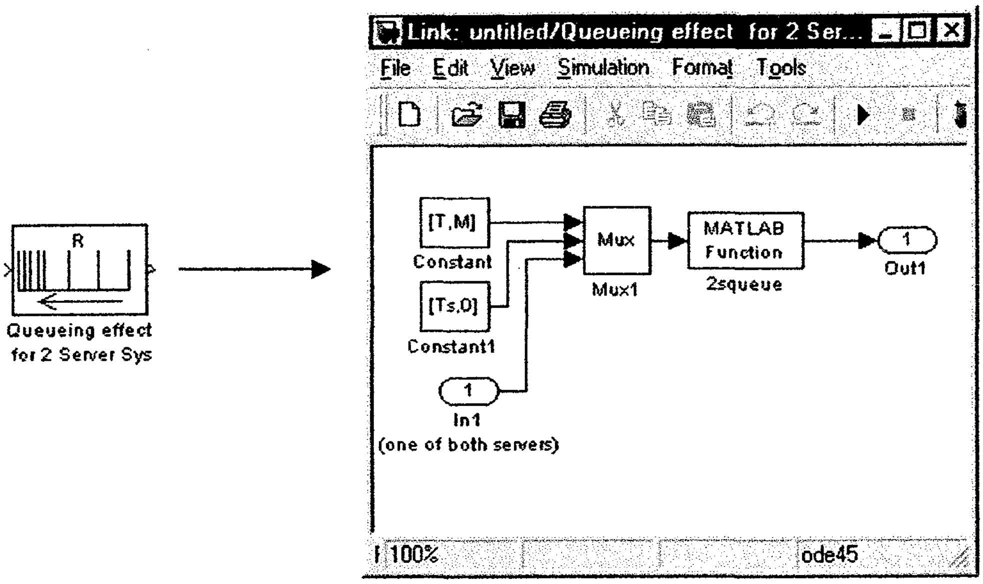
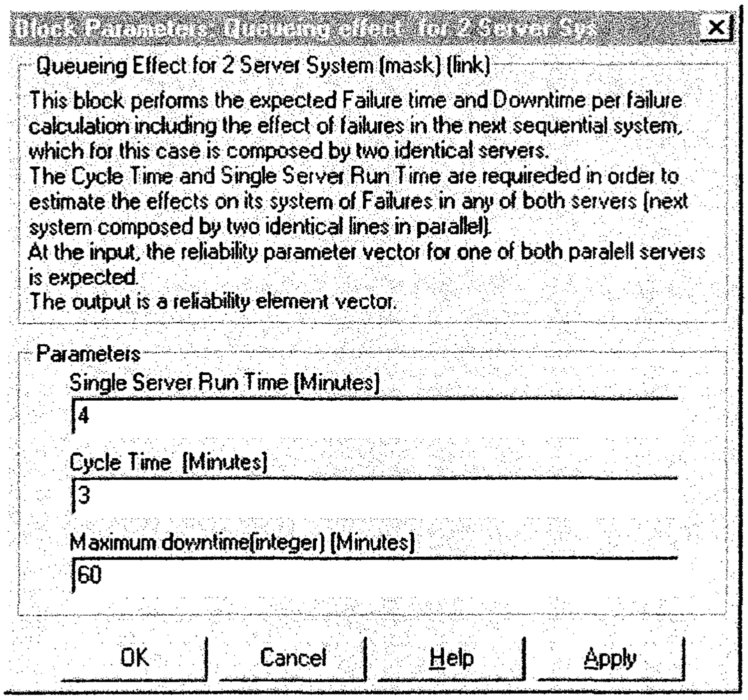


Figure 3.31. Queueing effect for 2 Server System Simulink Reliability block

By double clicking on the icon we access to the dialog block shown in Figure 3.32.



Queueing Effect for 2 Server System (mask) (link)

This block performs the expected Failure time and Downtime per failure calculation including the effect of failures in the next sequential system, which for this case is composed by two identical servers.
The Cycle Time and Single Server Run Time are requireded in order to estimate the effects on its system of Failures in any of both servers (next system composed by two identical lines in parallel).
At the input, the reliability parameter vector for one of both paralell servers is expected.
The output is a reliability element vector.

Parameters

Single Server Run Time [Minutes]
4

Cycle Time [Minutes]
3

Maximum downtime(integer) [Minutes]
60

Figure 3.32. Simulink dialog box(Queueing effect for 2 Server System)

The system presented in Figure 3.30 was modelled with the Simulink Reliability block shown in Figure 3.33.

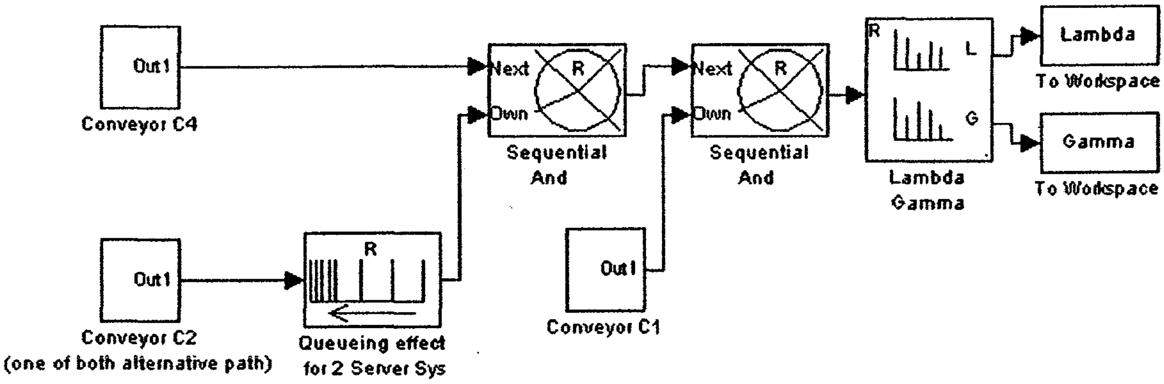


Figure 3.33. Simulink Reliability block diagram

3.7.9. Average Calculations according to IEEE Std. 493 – 1997

To simplify the calculation of the annual downtime a new Simulink Reliability block was designed as shown in Figure 3.34. The block calculates the annual failure rate and the average downtime per failure according to IEEE Std 493 – 1997 [1].

For a given system of n serial elements:

Total Annual Downtime

$$\lambda r_{tot} = \sum_{i=1}^{n} \lambda_i * r_i = U_{total} \tag{3.20}$$

Frequency of system outages

$$\lambda_{tot} = \sum_{i=1}^{n} \lambda_i \tag{3.21}$$

Average Downtime per outage

$$r_{avg} = \frac{\lambda r_{tot}}{\lambda_{tot}} \tag{3.22}$$

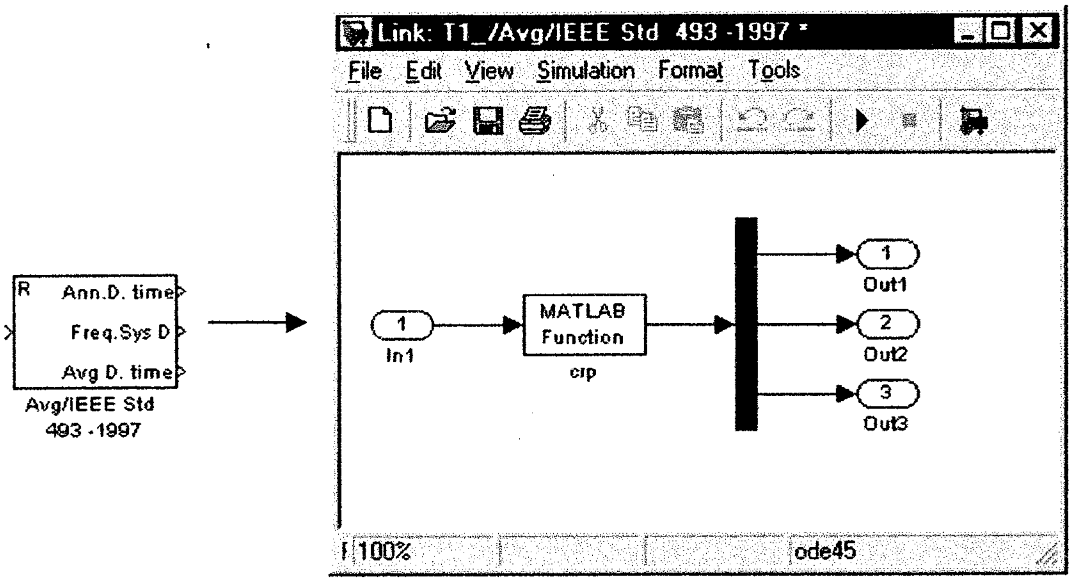


Figure 3.34. Avg/IEEE Std 493-1997 Simulink Block and internal block diagram

3.8. Discussion

The methodology presented in this chapter is practical. The examples presented worked effectively, both for power systems and sequential systems. Due to the simplicity in translating the Reliability block diagrams to the Simulink block diagrams, this method is very easy to use and it is not necessary to do any hand calculations.

The methodology presented in this chapter is applied to the Phosphate Elpo System of the General Motors Rosario Paint Shop Plant in Rosario, Argentina in Chapter 4.

CHAPTER 4. MANUFACTURING SEQUENTIAL SYSTEM MODELLING

The elements and components that integrate a manufacturing system are modelled in Chapter 3. A real complex manufacturing sequential system is presented in this chapter to demonstrate the usefulness of the proposed method.

4.1. The Phosphate-Elpo process

The industrial system to be analyzed is the Phosphate-Elpo process shown in Figure 4.1. The Paint Shop process starts at the point named P1 (entrance gate to the Paint Shop Plant) and ends at P9 (outlet of the Elpo cooler). The Components of the Phosphate- Elpo process can be divided in two main categories, Conveyors Systems and Process Systems. The Conveyors Systems are, according to the sequence in the process line:

a - CPU3 Conveyor System 3
b - Phosphate Pendulum
c - CPU4 Conveyor System
d - Elpo Pendulum
e - CPU5 Conveyor System

The Process Systems are, sorted according to the sequence in the process line:

a - Phosphate Process
b - AC/DC Elpo rectifier
c - Elpo Process
d - Elpo Oven

Each of these systems is controlled by a Programmable Logic Controller (PLC), which performs several functions like information data process, outputs management and alarming. Each PLC manages between 500 and 2000 external variables, among Analog / Digital Inputs and Analog / Digital Outputs. Some of them also exchange information. The PLC control systems with the data exchange links are shown in Figure 4.2.

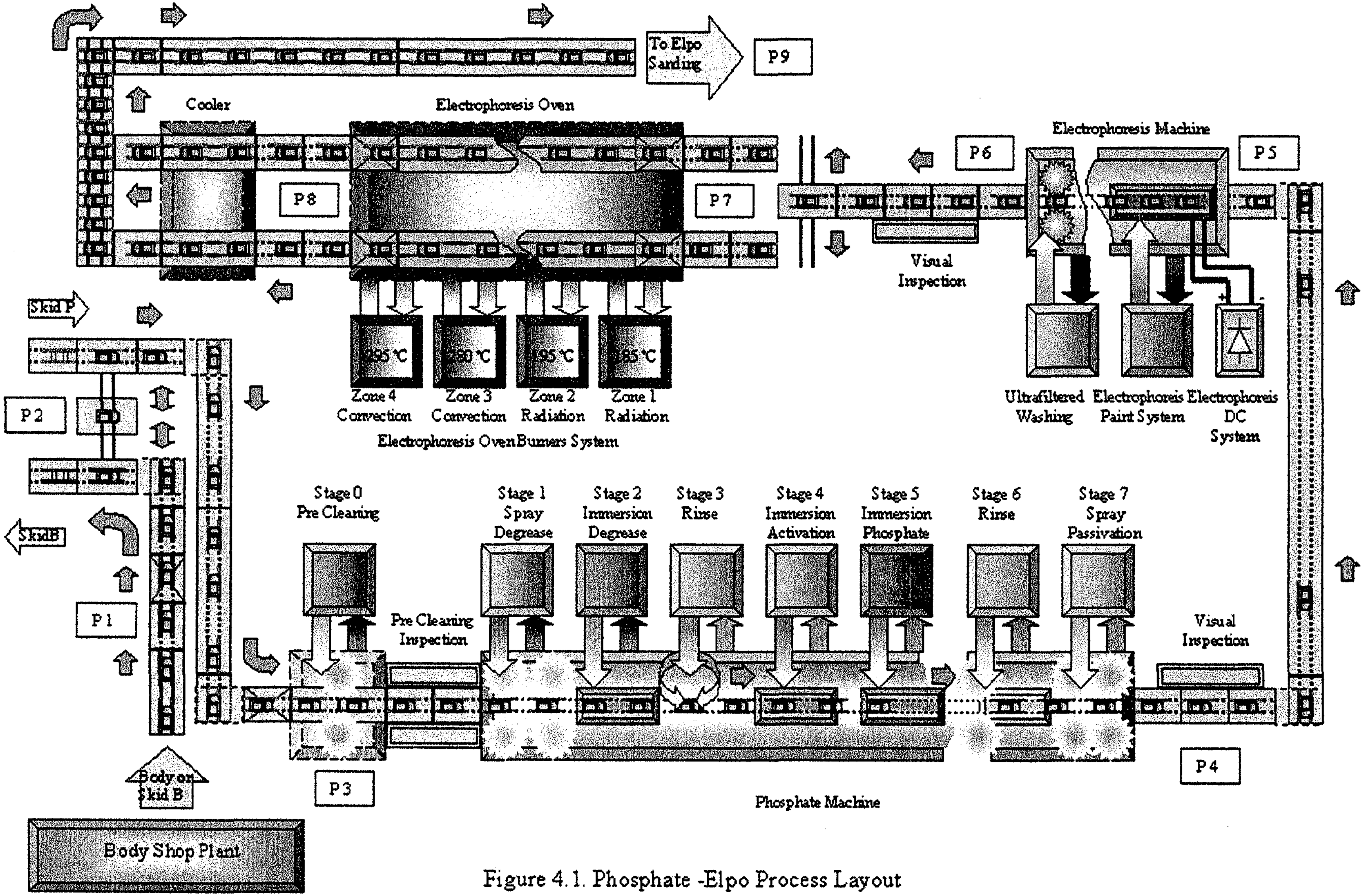


Figure 4.1. Phosphate -Elpo Process Layout

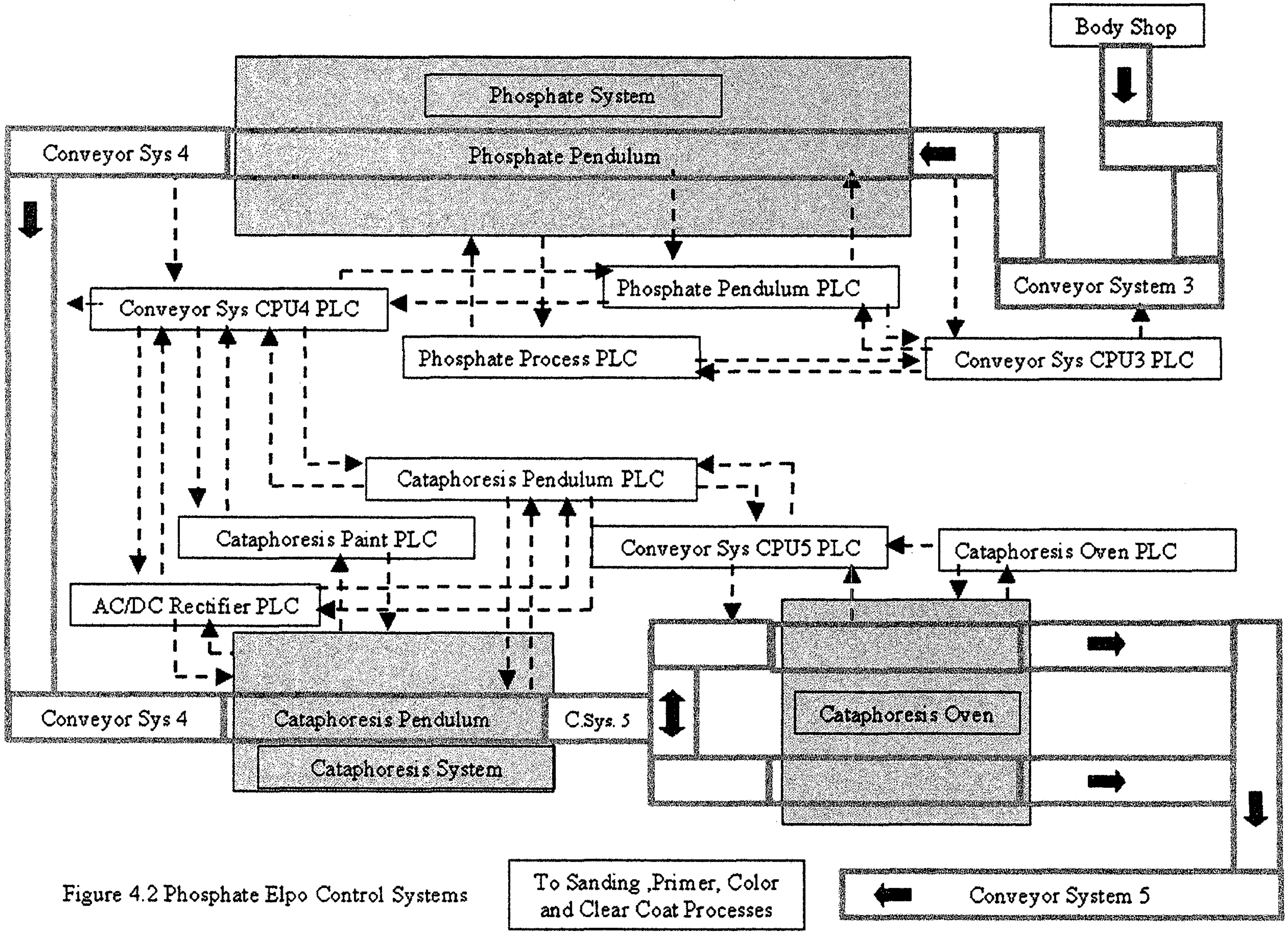


Figure 4.2 Phosphate Elpo Control Systems

4.2 Failures in an Automated Production System

The system is fully automated by the 9 PLCs shown in Figure 3.2.. The PLCs control the different processes and the cars flux throughout the productive line. When an abnormal situation or a component or sub-system fails, it is detected by the PLC that is controlling these failure elements. An alarm is tripped and the sector of the process that is failing is stopped. Depending on the fault type and its severity, the whole system controlled by the PLC can be stopped. When a system is stopped, it will lead to the detention of other systems. For example, if one of the 3 rectifiers of the AC/DC Elpo Rectifier System presents a severe fault, the PLC will stop the other two operating zones. After this, with the Rectifier System down, the Elpo Pendulum will stop the car loading process. The Elpo Pendulum will continue running but in the condition "Pendulum not ready to load".

The interconnection between PLCs is completed by "relay interlocks" or communications networks in such a way that when one CPU is down or the interlock signal is down, the rest of the PLCs in the system that are checking that interlock signal will stop their respective cycles.

To model this productive system, it is necessary to determine the logical relationships between the components and which component or subsystem failure will lead to a system outage. It is necessary to understand the PLC Control Logic Diagram for PLC that control the system and in which way they are linked. The PLC Control Logic Diagram is produced in the early stages of the design of the system and normally it is not updated despite the numerous modifications to them. There are a few codification methods commercially available to write a Logic Control Program for a PLC, but the most widespread is the "Ladder Logic", which are used for programming the PLCs that are commanding the plant under study.

Once the PLC Control Logic Diagram is rebuilt, attending to the logical relationship between components, the Reliability Block Diagram is built up. The elements of the switchgear equipment, wiring, power distribution system, power transmission and any other component that are not monitored by the PLC have to be added to the Reliability Block Diagram in the same way.

Equipment that can cause a stop in the productive system was added to the Reliability Block Diagram. In order to show the proposed procedure, a simple example will be presented prior to modelling of the whole system.

4.3. Example of PLC Automated System Modelling

Lets assume a sector of a sequential system of conveyors shown in Figure 4.3, where the reliability of the conveyor named C2 will be analyzed. It is a very simplified Power Roll Bed consisting of a single speed gearmotor MC22 that drives the power rolls and two inductive sensors E21 and E22 that detect the position of the skid that is loaded with a bodyshell.

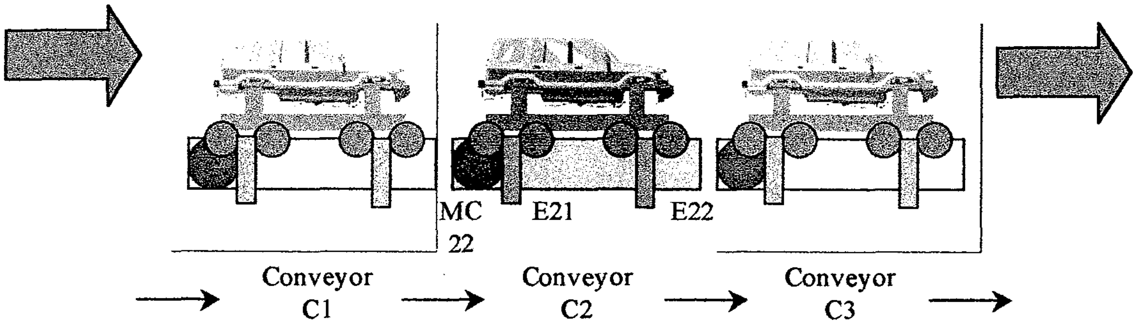


Figure 4.3. Three conveyor system

To construct the conveyor C2 reliability block diagram, the electrical circuits, both Power and Control, and the PLC Ladder Logic Program will be analyzed. Only the elements of conveyor 2 in automatic control are represented in Figure 4.4. (Power and Control Circuit) and Figure 4.5 (PLC Ladder Logic Program). Many other elements for the manual control, signaling panel, Human Man Interface and cycle control that are present in the PLC program are not represented in order to simplify the example.

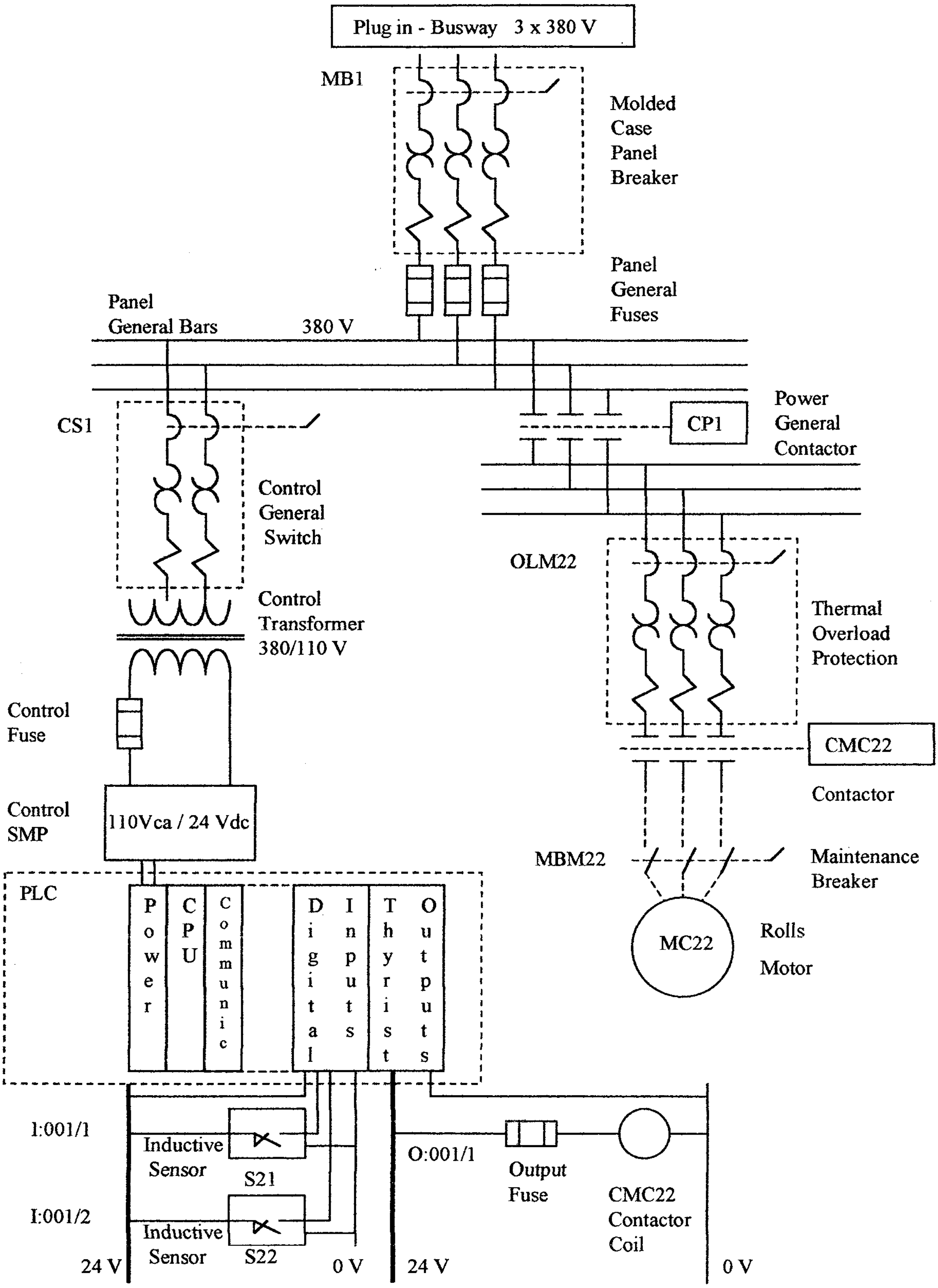


Figure 4.4. Power and Control Circuits

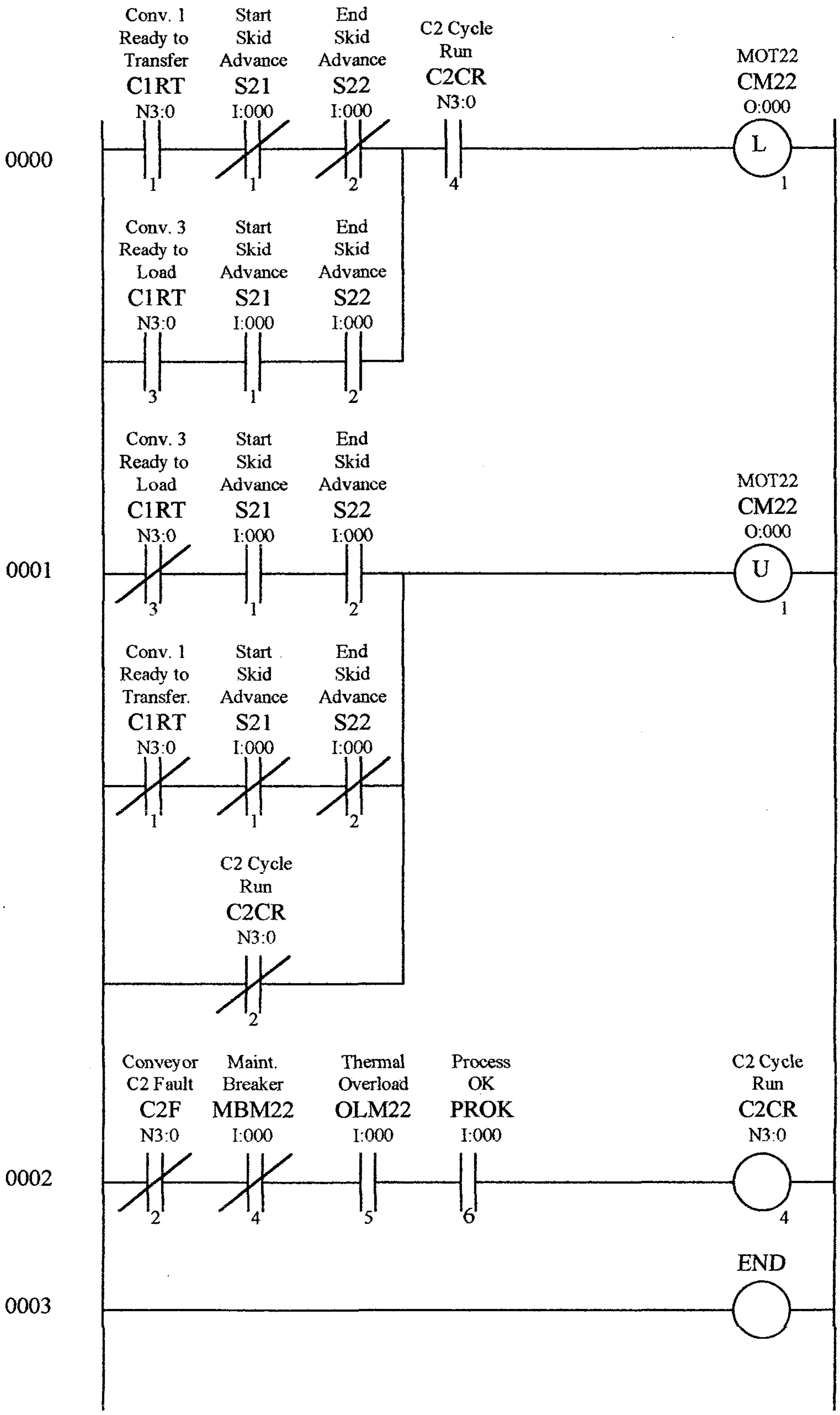


Figure 4.5. PLC Ladder Logic Program

For conveyor C2, its main component is the gearmotor MC22 responsible for forward movement. Now, it is necessary to determine which elements can lead it to an abnormal down condition and its logical relationship. The elements are defined in the following three steps:

(1) Analyze the PLC Ladder logic that commands the contactor that drives the motor, it is CM22.

(2) Analyze the Control Circuit that drives the CM22 contactor and elements that affect its behavior, sensors for example.

(3) Analyze the field elements and power circuit that feeds the motor M22.

(1) PLC Ladder Logic

Diagram 4.5 shows a typical PLC Ladder Logic representation, which is, for this particular case, developed for Allen Bradley PLC 5 Series. (The instructions used for the PLC Ladder presented in Figure 4.5 and the addressing or variables are described in Appendix C.)

The Ladder PLC Programming Language is derived from the classical "Relay Logic" that was used in the early years of the industrial automation. Each rung in the Ladder Logic represents what in the Relay Logic is the circuitry that energize / de-energize the coil of a relay. In the Ladder Logic the previous concept of "energize the coil of a relay" is replaced by "make a line true". The element placed at the right in a rung is associated to an internal memory in the PLC memory map, which can take binary values (one or zero). When the rung is true, the memory value is one and when the rung is not true, the memory value is set to zero. The memory element can be assigned to an external output or just to internal logical variables used for example to represent logical states.

In the example of Figure 4.5, the nomenclature used to represent each instruction is based on three elements:

-Address: Internal memory addressing

-Symbol: Short name or variable name (Optional)

-Description: Long name/ variable description (Optional)

Figure 4.6 shows an example with the described nomenclature identified.

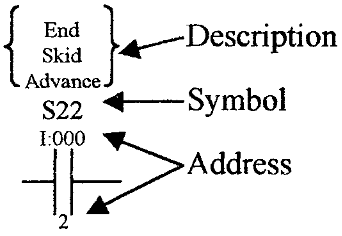


Figure 4.6 PLC Instruction Nomenclature

In Figure 4.5, rung 0000 of the PLC ladder represents the logical conditions that are necessary to meet in order to start the motor M22. Then, to start M22 we have two possible paths:

Path - p1 : Conveyor 1 ready to transfer, C21 not sensing, C22 not sensing and C2 Cycle Run (This leads to the Load State, see 2.1-2.4)

Path - p2 : Conveyor 3 ready to load, C21 sensing, C22 sensing and C2 Cycle Run (This leads to the Transfer State, see 2.1-2.4)

But C2 cycle run is a concentration of elements, which are (rung 0002):

e1 - Conveyor C2 Fault: it is a fault concentrator and summarize failures of logic, time out, fire, and others inherent to the Conveyor C2. (not shown in Figure 4.5 to simplify the example)

e2 - Overload protection

e3 - Maintenance Breaker (on position)

e4 - Process OK: it is an interlock Signal that is exchanged with the PLC that command the process. It means that if the process is down, the motor will not be enabled to start the cycle.

Hence, any failure or condition in one of the element of those described in p-1, p-2,e-1,e-2, e-3 or e-4 that not enable the rung 0000 when it should, will disable the motor C22 to start the cycle on time, and then it will be in down condition. These elements are:

f1 - Sensor E21

f2 - Sensor E22

f3 - Conveyor C2 Fault

f4 - Thermal Overload Protection

f5 - Maintenance Breaker

f6 - Process

These are the elements that we can identify from the PLC Ladder Logic that can lead to a conveyor C2 outage.

(2) Control Circuit

It should be realized at this point, that we are in the PLC Ladder Logic not working with physical elements but with the "PLC memory representation" of physical elements that are stored in the PLC Mapping Memory and then, not only a failure in the physical element will lead to conveyor stop by failure, but a failure in the memory/physical element interface could also lead to the same failure (see Figure 4.4.,Control circuit). The

Input and Output modules and their associated circuitry to the elements listed should be included in the analysis. The following failure causes will be considered:

f7 - PLC Input (x 5 times: Sensors S21 and S22, M22 Overload protection, maintenance breaker and process)

f8 - PLC Output(x 1 time: M22)

These elements concentrate the failures in the control circuitry, Input and Output modules respectively.

(3) Field Elements and power circuits

Now we will identify in the circuit diagram of Figure 4.4 the elements that can lead to a failure of Conveyor C2. They are:

**Thermal Overload Protection OLM22(already identified in PLC Ladder Logic)

**Maintenance Breaker MBM22(already identified in PLC Ladder Logic)

f9 - Contactor CMC22

f10 - Motor M22

f11 - Power Source

Note: When a failure in the power source or in one branch or sector happens, many elements will be affected. To determine which elements of the power source to include, it is necessary to analyze the system that is being studied and represent which element of the power system affects the system or components of the system under study. For this particular case, to determine the reliability of the conveyor C2, it is necessary to include contactor CP1 and then the reliability of the power source at "panel general busbar".

For more complex cases, it is proposed to consider a particular element or sub-system under study, just the elements of the power system which failure will affect this element or subsystem, and finally, consider the power system reliability at the point where the system under study has a common power source connection. Then, the resulting Simulink Reliability Block Diagram is shown in Figure 4.7.

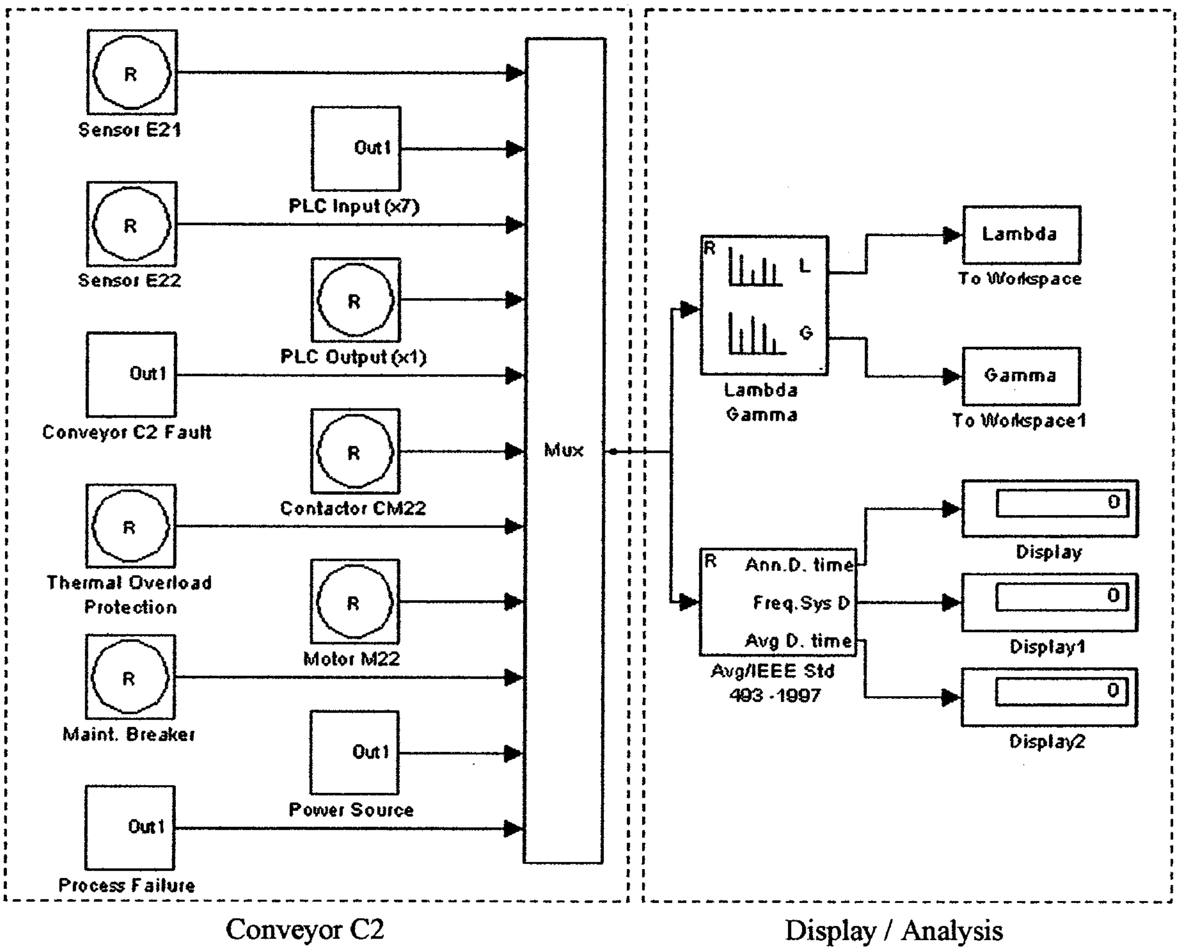


Figure 4.7. Simulink Reliability block diagram

Some of the blocks presented in Figure 4.7 are subsystems (Process Failure, Conveyor C2 Fault, PLC input and Power Source) which group many individual components. The additional blocks labeled “Display / Analysis” were linked just to calculate and display the results. This proposed procedure will be applied to model the industrial process in the next step.

4.4. GM Rosario Plant Phosphate-Elpo System Modelling

This system was described in Chapter 1 and its layout is shown in Figure 4.1. The system is 100% automatic and Figure 4.2 shows that it is controlled by nine PLCs.
To study the reliability of the whole system initially the system will be subdivided according to the PLC controllers that perform the automatic command and the reliability indices for each subsystem (vectors Γ and Λ) will be determined. Then the subsystems will be linked regarding to the interlocks that relate the PLC programs among subsystems.

4.4.1. Individual components representation and reliability indices survey.

Throughout the plant, there are many individual components that are identical and that operate under the same environment conditions. Their failure rate per year and downtime per failure parameters will be the same and it is proposed to represent them as elements of a matrix. That matrix will contain the elements of each component and before simulation is run, it will be loaded in the Matlab Workspace. This matrix will be named "R", and will be a two column matrix, in such way, that in a row will store the reliability indices of a particular element. It will be very useful if there is a need of changing any reliability indices because just changing the matrix element value will change every single element inside the reliability block diagram. Studying changes in reliability indices of components because of aging can easily be performed by affecting the original "R" matrix, with the appropriate aging formulas.

The reliability indices of the single elements that conform the Phosphate – Elpo System are normally not available from typical data standards, opposite to what happens for power systems components, for which it is possible to access to sampled data found in the appendixes of IEEE Std 493-1997.

Fortunately, the Maintenance Department of the Paint Shop Plant has implemented an efficient procedure to record the failures and its causes which occurred in the plant since its operation started. The information is recorded in "on board books" where the maintenance crew and supervisors write down the failure data, specifying:

(a) Faulted equipment

(b) Downtime

(c) Element that cause the failure and fault type

(d) Action taken to restore the faulted system

(e) Element damaged / replaced / repaired

The Predictive Maintenance work schedule is performed automatically by the Computerized Maintenance Management System (CMMS) which schedule and delivers monthly over five hundred predictive maintenance work orders that are manually loaded after completion. This data it is very useful for the Paint Shop Maintenance Department administration. However, a failure code has not been properly defined. Although the CMMS is able to do it, is impractical at this moment to implement the data in this manner. We can imagine what effort take to store every element damaged/replaced or repaired and that every and each of the thousands of components that are installed in the plant should be previously loaded in the CMMS database. On the other hand, the method of the "on board books" to save the failure data is very simple, reliable, not time consuming, and it works.

The failure data stored in the "on board books" was classified and sorted in a worksheet. The reliability data table is shown in Appendix D. Although many elements are the same, it has been observed through the years of plant operation, that the failure rate of equipment is different depending on the environment in which they are operating. The proposed classification developed by the Paint Shop Maintenance Department takes care of these differences and is shown in Appendix D.

4.4.2 Subsystems Modelling

Since the conveyors are the core of the reliability modelling for this particular system, the Conveyors Systems will be modelled in the first stages and then the rest of the subsystems that integrate the Phosphate- Elpo process will be included.

4.4.2.1. Conveyor System CPU3

The sector of the Conveyor System CPU3 that affects the Phosphate Elpo process is shown in Figure 4.8.

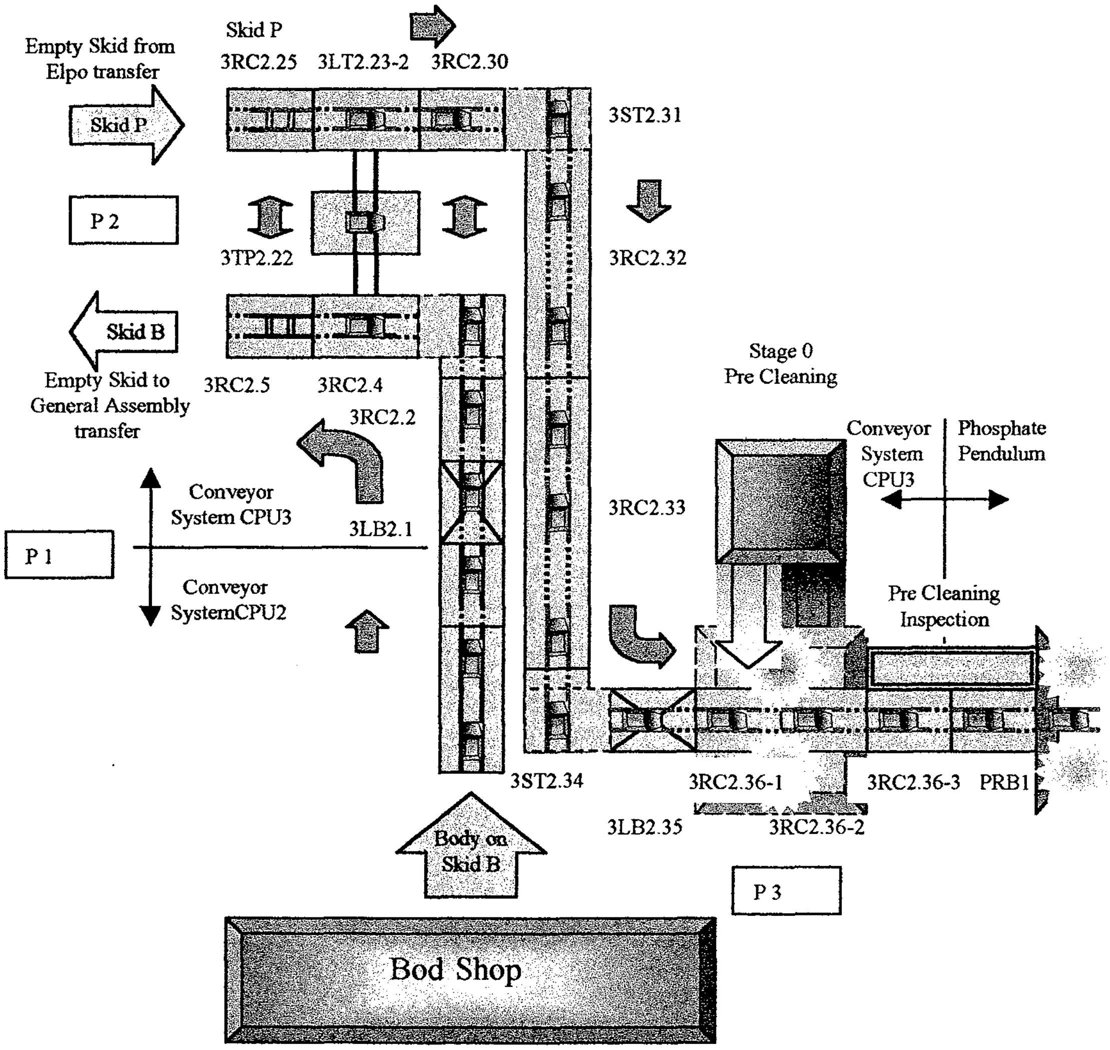


Figure 4.8. Conveyor System CPU3.

In this stage of the process the conveyor system is sequential, without buffers or back up lines and is integrated by 15 conveyors of different types. The nomenclature of the conveyor gives an idea of the conveyor system to which it belongs, the conveyor type, and the position in the conveyor system. For example, 3RC2-4 means:

3: Conveyor System CPU3

RC: Power Rolls Bed Conveyor

2-4: it is the 4th conveyor in the Conveyor System CPU3

The other types of conveyors present in this section are:
LB: Two level Elevator
ST: 90 ° Turn Power Rolls Bed
TP: Telescope- Scissors
LT: Lifter

The PLC program is implemented by applying the "Petri Nets" theory, which is extremely complex and time consuming to analyze. An independent ladder sub-routine was developed for each type of conveyor (for example, subroutine LAD 102- SBR_MR is associated to the Power Roll Bed conveyor type), and other for each particular conveyor (for example LAD 32-3RC2_2 which manage the conveyor 3RC2.2). Other sub-routines perform the linking of the system, communications, data exchange and alarming functions. A basic diagram that shows the elements of the PLC Ladder logic program for conveyors like Conveyor System CPU 3 is shown in Appendix E.

For each type of conveyor, a Simulink block diagram is developed, grouped and then copied to represent the identical conveyors to build up the Conveyor System CPU3. The reliability block diagram developed for one of the conveyors, which is the Turn Power Roll Bed is shown in Figure 4.9.

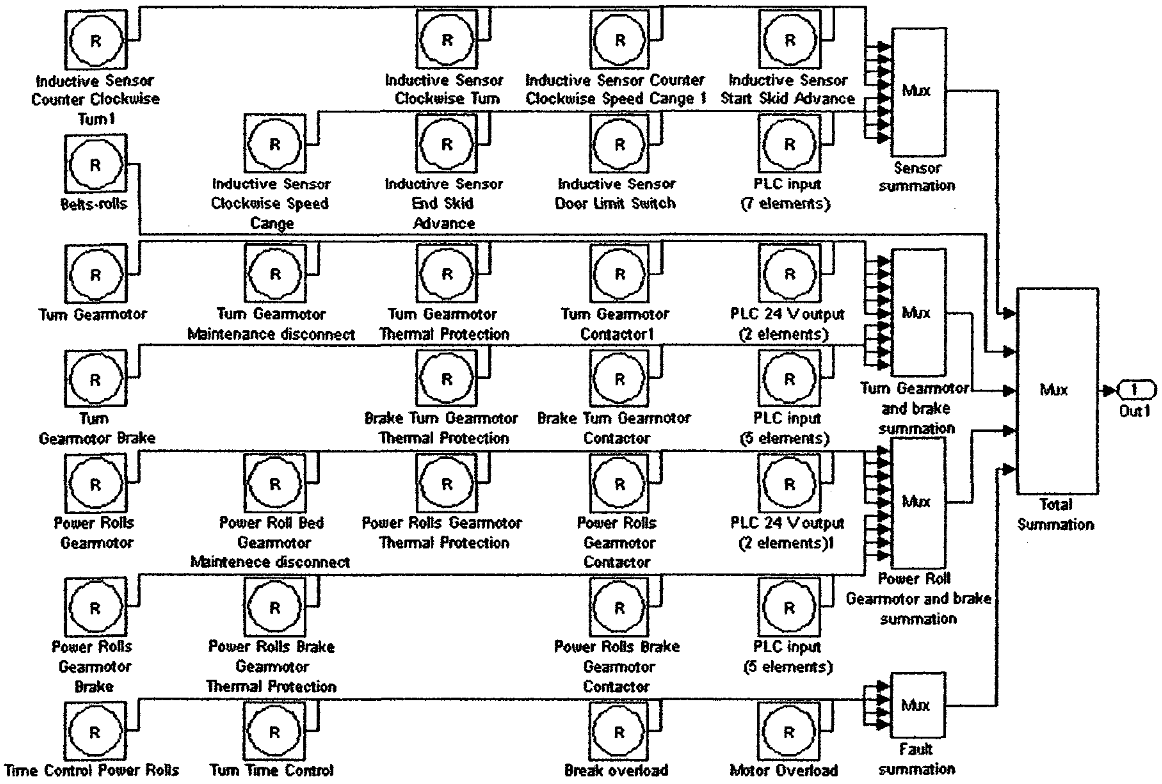


Figure 4.9. Turn Power Roll Bed Simulink Reliability block diagram

In Figure 4.9, the elements were grouped according to their functionality by using Simulink "Mux" blocks. The elements grouped under "Fault Summation" are logic and physical faults that are detected by the PLC. Once a block diagram for the conveyor is complete, the blocks are grouped in order to represent the conveyor with only a block.
For the others conveyors of the Conveyor System CPU3 the models are produced in the same way.

The Conveyor System CPU3 Simulink reliability model that results from linking its conveyors model blocks is shown in Figure 4.10. The power and control elements that are common to all the conveyors of the Conveyor System CPU3 are also included in the model.

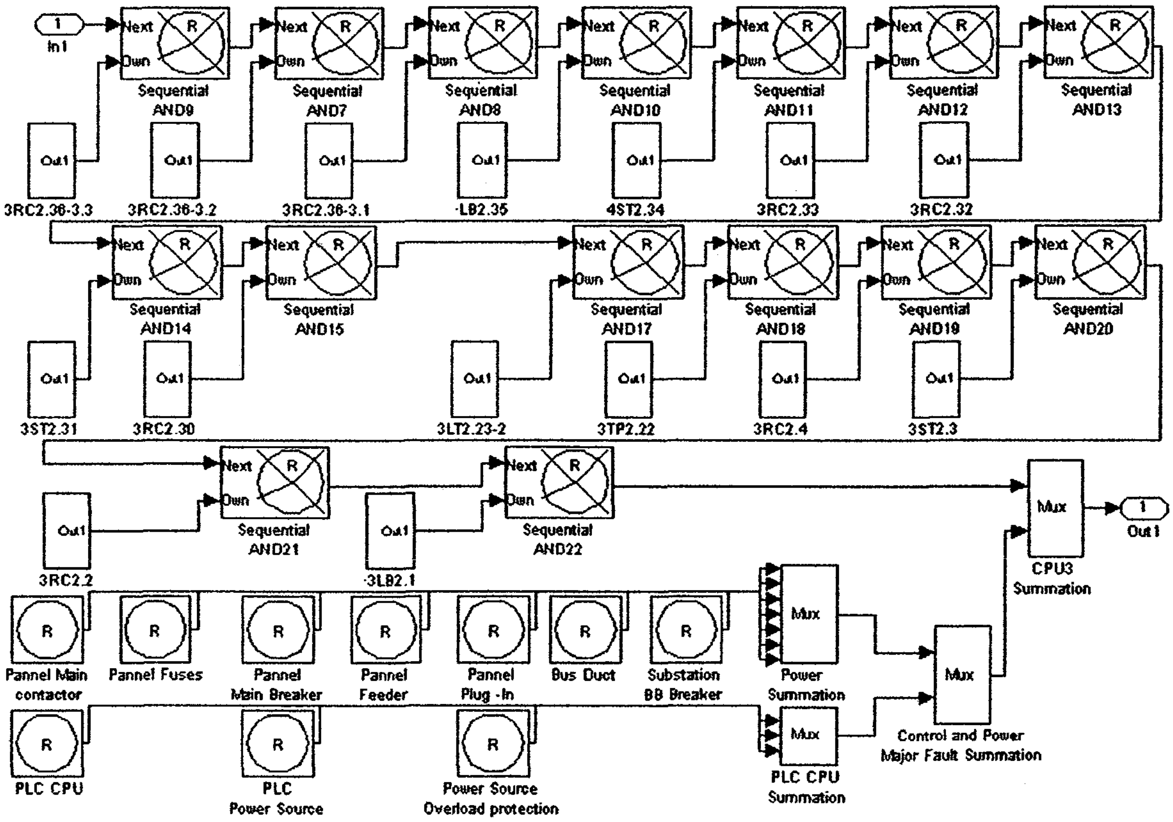


Figure 4.10. Conveyor System CPU3 Simulink Reliability block

4.4.2.2 Phosphate Pendulum Conveyor System

This conveyor system is composed by three main conveyors, the Phosphate Pendulum and two Power Roll Bed (PRB) that execute the loading and transferring duties. In the layout of Figure 4.11 both are represented as PRB2 and PRB3 respectively. The Phosphate Process is highly dependant from the Pendulum conveyor behavior because of the chemical process involved. The pendulum is then responsible for the timing of the process and when it is in the productive shift, it never stops except when it is in faulted state. The PRB2 and PRB3 perform its duties with the pendulum running and, if any fault happens during the loading or transferring process, the pendulum will be stopped.

The Phosphate pendulum conveyor system has room for 35 cars and, a failure leading to a pendulum stop can produce many "out of quality standard" scraped bodyshells due mainly to acid overexposure, depending on the downtime.

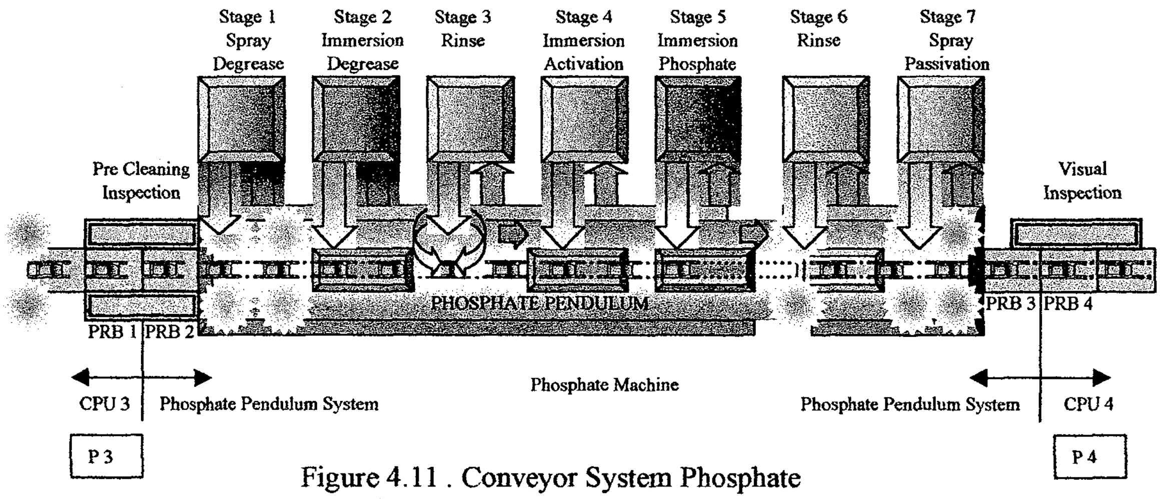


Figure 4.11 . Conveyor System Phosphate

The PLC program that controls this Conveyor System is totally different from that one which controls the Conveyor System CPU3. It is not based on Petri Net theory nor apparently any other structured programming method. Basically, the PLC output that controls the Variable Speed Drive responsible for the main motors driving is conditioned with a set of internal variables that represent operational conditions, failure recognition and logical interlocks. Every one of them was identified and included in the Simulink reliability block diagram.

Overall, more than 200 elements were identified in the pendulum PLC ladder logic, electric and mechanical diagrams, and fault modes. In order to simplify the representation, the elements are grouped according to their logic relationships with Simulink subsystem blocks, which are finally linked with Simulink mux blocks. The resulting Simulink Reliability block diagram for the Phosphate Pendulum is shown in Figure 4.12.

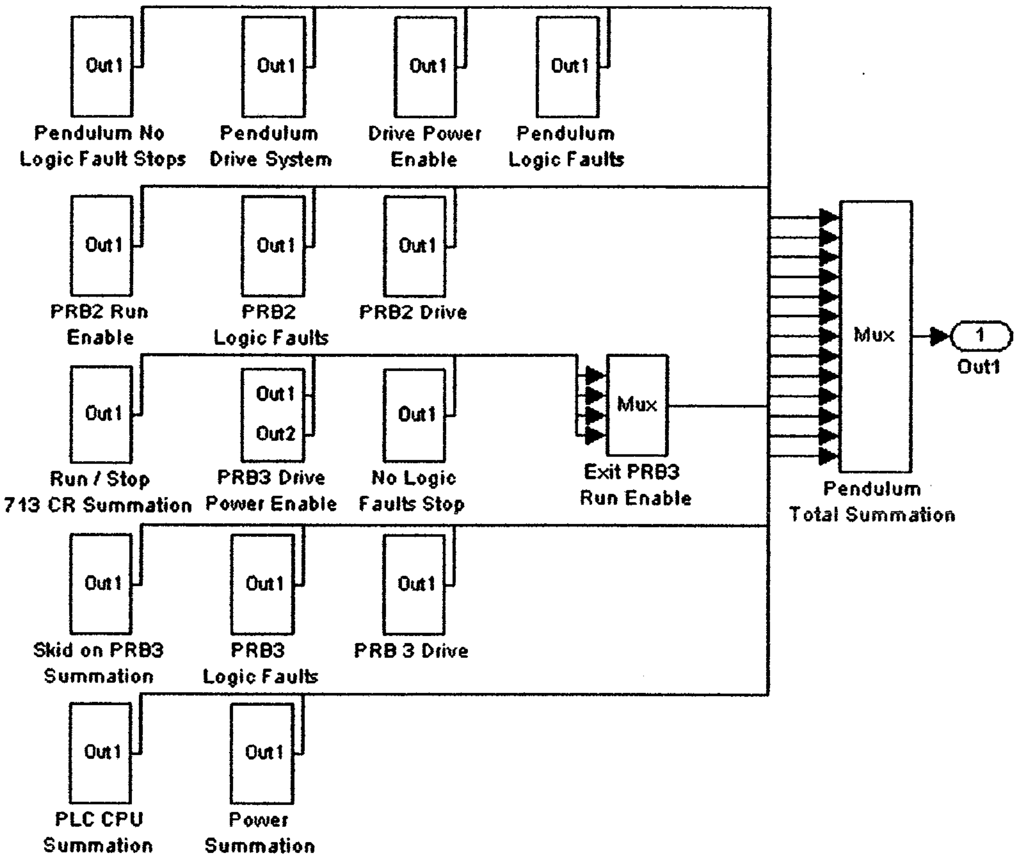


Figure 4.12 Phosphate Pendulum Simulink Reliability block diagram

4.4.2.3. Conveyor System CPU 4

There are two sectors of conveyors controlled by the CPU4 PLC that are affected to the Phosphate - Elpo process. The first one (CPU4 Remote 1 or CPU4-R1) is between the Phosphate pendulum exit gate and the Elpo pendulum entrance gate, and the second (CPU4 Remote 2 or CPU4-R2) , between the Elpo pendulum exit gate and the Elpo oven entrance gate. Both sectors are shown in Figure 4.13.

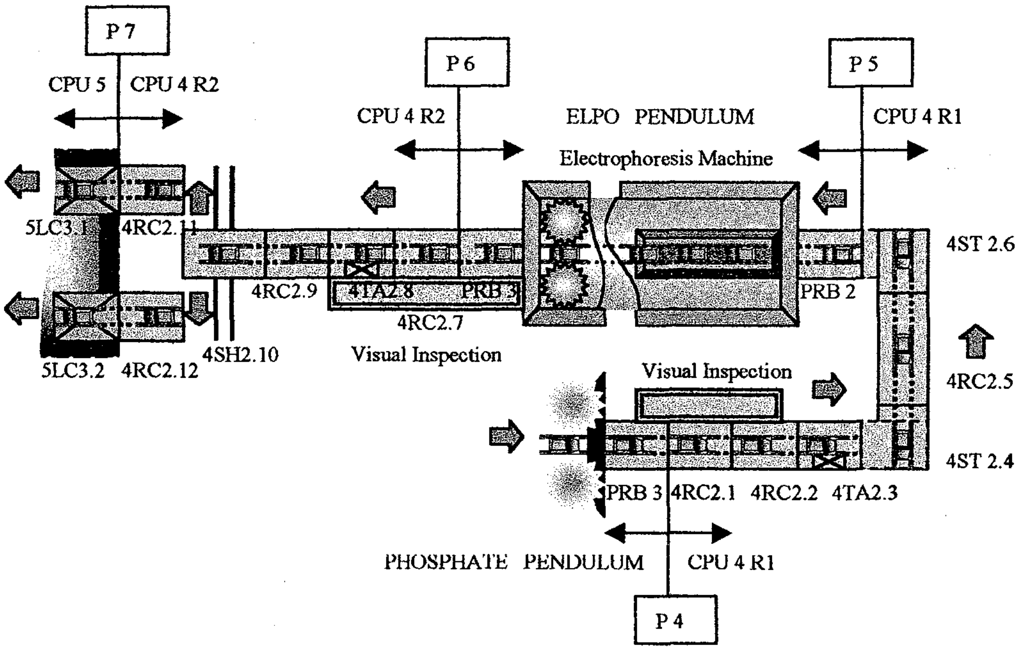


Figure 4.13. Conveyor System CPU 4

In the first sector, CPU4 R1 (P4 to P5) of the Elpo – Phosphate process, the Conveyor System CPU4 links the exit gate of the Phosphate Pendulum to the entrance gate of the Elpo Pendulum, without buffers or back up lines and is integrated by 7 conveyors of different types.

In the second sector, CPU4 R2 (P6 to P7), the Conveyor System CPU4 links the exit gate of the Elpo Pendulum to both entrance gates of the Elpo Oven. This sector is particularly different from the conveyors analyzed up to this point. The system can select, at the conveyor SH2.10, between 2 different paths. But the processing speed of each alternative path is limited due to process requirements (required exposure time to a tight temperature profile), resulting in the processing time being smaller than the production cycle time. Hence, if one of two lines fails, the remaining up line will not be able to take the entire production rate. For example, if the system is producing 20 cars/hour, one of the alternative lines will be able to process only 13 cars/hour.

When one of the alternative lines is down, a queue is built, characterized by a fix server time (Process time or $T_{process}$) and a fixed arrival time(Cycle time or T_{cycle}). This particular behavior is represented by the block developed in Chapter 3 named "Queueing Effect for 2 Server System".

The CPU 4 R2 Conveyor System presented here is represented in the Simulink Reliability block diagram of Figure 4.14.

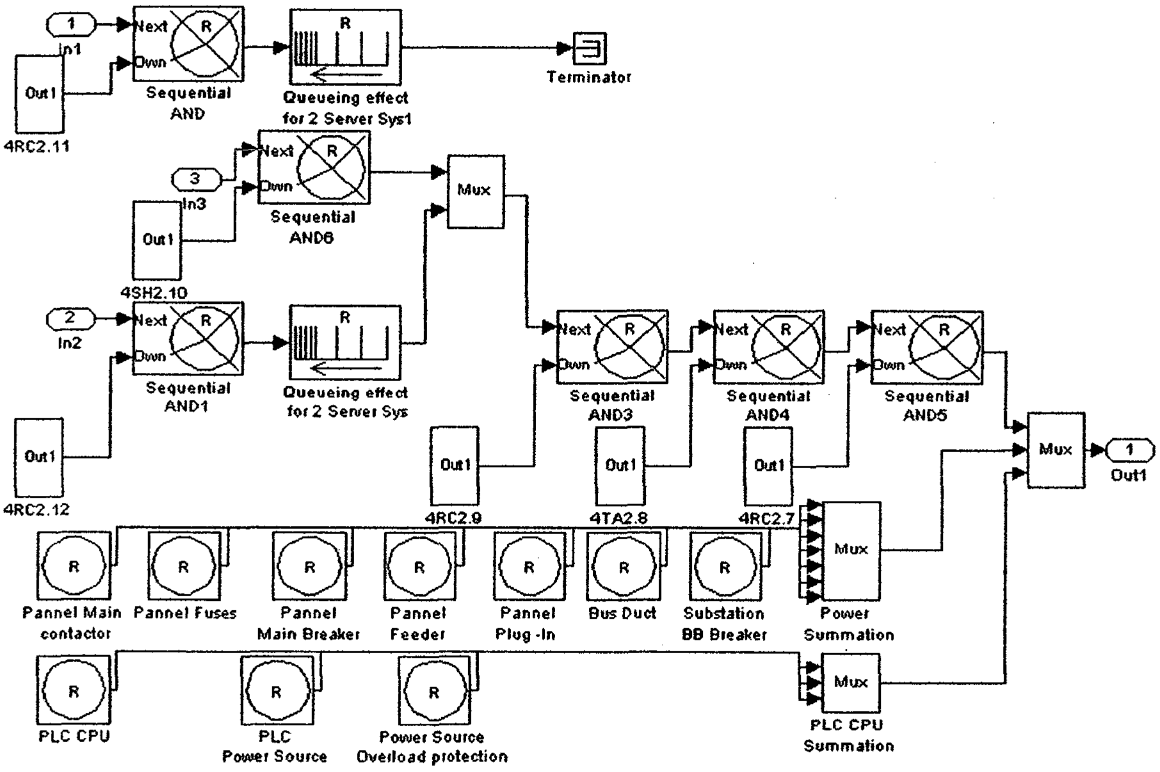


Figure 4.14 Conveyor System CPU4 (R2) Simulink Reliability block diagram

The nomenclature of the conveyor is the same explained for Conveyor System CPU 3 with some new conveyor types added:

TA: Tiltable PRB
SH: Shift PRB

The PLC program is implemented by applying the "Petri Nets" theory, in the same way as it was done for Conveyor System CPU 3.

4.4.2.4. Elpo Pendulum Conveyor System

This conveyor system is composed of three main conveyors, the Elpo Pendulum and two Power Roll Bed (PRB) that execute the loading and transferring duties. In the layout of Figure 4.15 both are represented as PRB2 and PRB3 respectively.

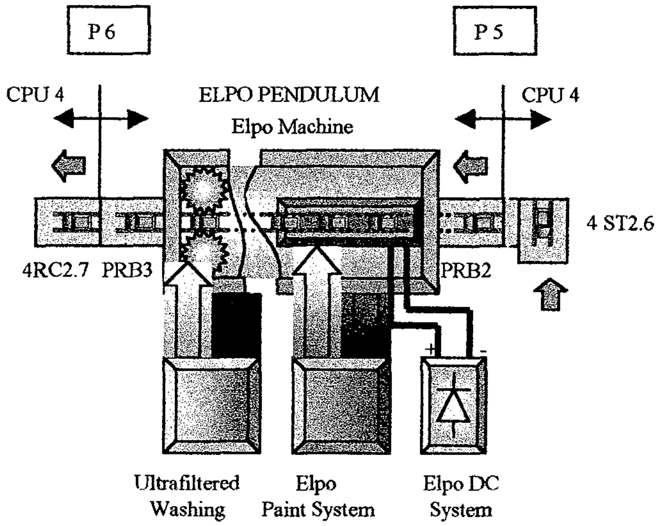


Figure 4.15 Elpo Pendulum Conveyor System

This conveyor system is almost the same as the Phosphate Pendulum Conveyor System. The main difference between both pendulums is that the Elpo pendulum is shorter, with room for only 12 cars, whereas the Phosphate pendulum has space for 35 cars. There are, for the Elpo pendulum, other systems that will determine if it is or is not enabled to load a car. They are the AC/ DC Rectifier System and the Elpo Process System.

Another important aspect that differentiates both pendulums is the fact that the chemicals in the phosphate machine are acids and alkalis that are highly corrosive while in the Elpo machine the paint and rinses are water based.

4.4.2.5. CPU5 Conveyor System

The sector of the Conveyor System CPU5 that is affected to the Phosphate Elpo process is shown in Figure 4.16.

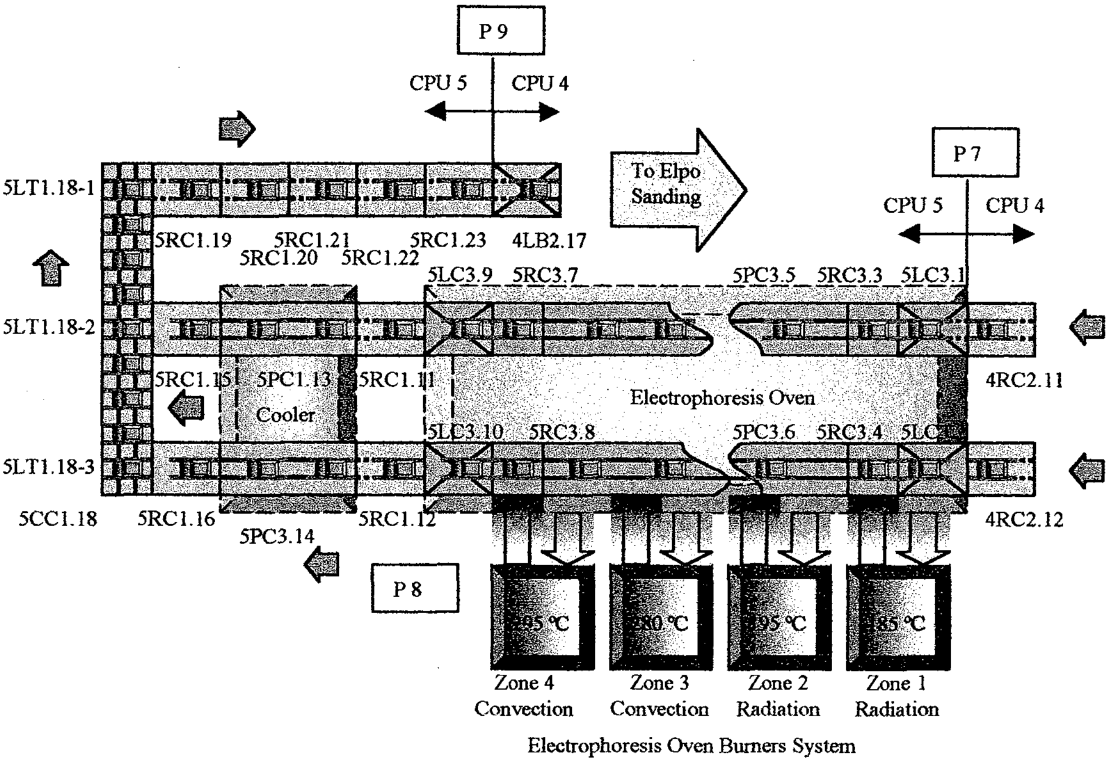


Figure 4.16. CPU5 Conveyor System

In this stage of the process the conveyor system is sequential, with the two parallel oven lines that are identical and merge after the Cooler. The system continues in a single line layout. The conveyors that carry the bodyshells throughout the oven present the singularity that they are located inside the oven and if one of the components that are inside the oven fail (sensors, chains, bearings, rolls, etc) it is not possible to repair them in the production shift and it is necessary to cool down the oven that is between 200° C and 300 ° C to 50° C in order to enable the maintenance crew to perform the repair job inside the oven. This cool down process takes about seven hours. Then, these particular elements will be modelled with downtime per failure indices that reflect the exposed situation. It was explained in Chapter 1 that this facilities works in shifts of production and non production. The downtime per failure will be limited up to the end of the shift, assuming that the system will be repaired in the non productive shift.

The PLC program of Conveyor System CPU5 is similar to that one explained for Conveyor System CPU3 but with some new types of conveyors that are present at this stage which and are:

LC: 2 Level Elevator, chain driven
PC: Chain Conveyor
CC: Transversal Conveyor
LT: Lifter

The Conveyor System CPU5 Simulink reliability model that results from linking its conveyors is shown in Figure 4.17.

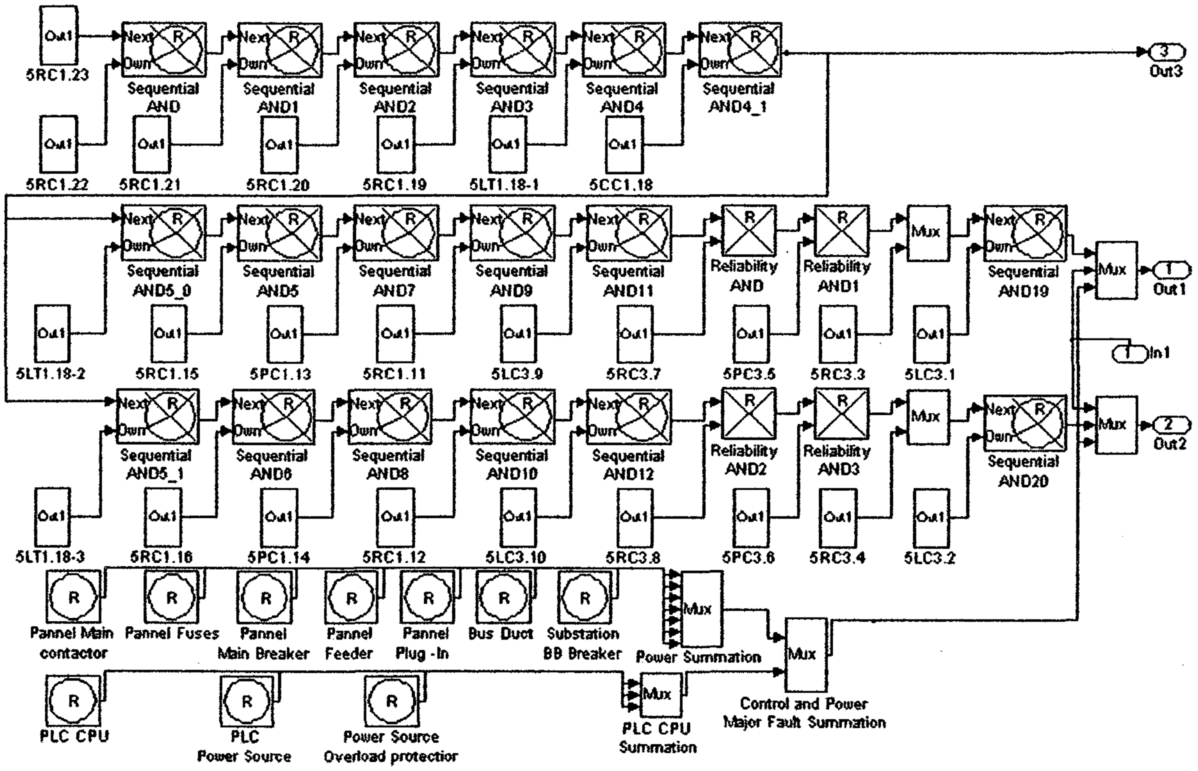


Figure 4.17 Conveyor System CPU 5 Simulink Reliability block diagram

4.4.2.6. Phosphate Process

In order to analyze which way a failure in one of the states of the Phosphate process will affect the production level, both PLC control logic programs, Conveyor System Phosphate pendulum and Phosphate process are analyzed.

The Phosphate process was described in Chapter 1 and basically, consists of several pumping systems, including controls of process variables such as temperature, conductivity, Ph and level. Most of the pumping systems operate with two or even three identical systems working in parallel (OR logic) in such way that if one of them is down, the system will continue operating.

It is assumed that the Phosphate system is "ready to load" when all the seven stages are operating and with the variables under control within their specified working bands. The

Phosphate process and Phosphate conveyor PLCs are linked through "interlock relays", which exchange "on / off" signals carrying information related to "ready to load / not ready to load" status.

When the Phosphate process is "ready to load", the Phosphate process PLC will activate a specific output. This signal is fed into an Input of the Phosphate pendulum PLC, which through its logic will enable the loading of cars in the pendulum conveyor through the PRB1 conveyor. This behavior, from a reliability point of view, is an "and " relationship, and can be modelled with a Simulink "mux" block. The Simulink block diagram for the Phosphate system including the 7 pumping stages described in Chapter 1 is shown in Figure 4.18.

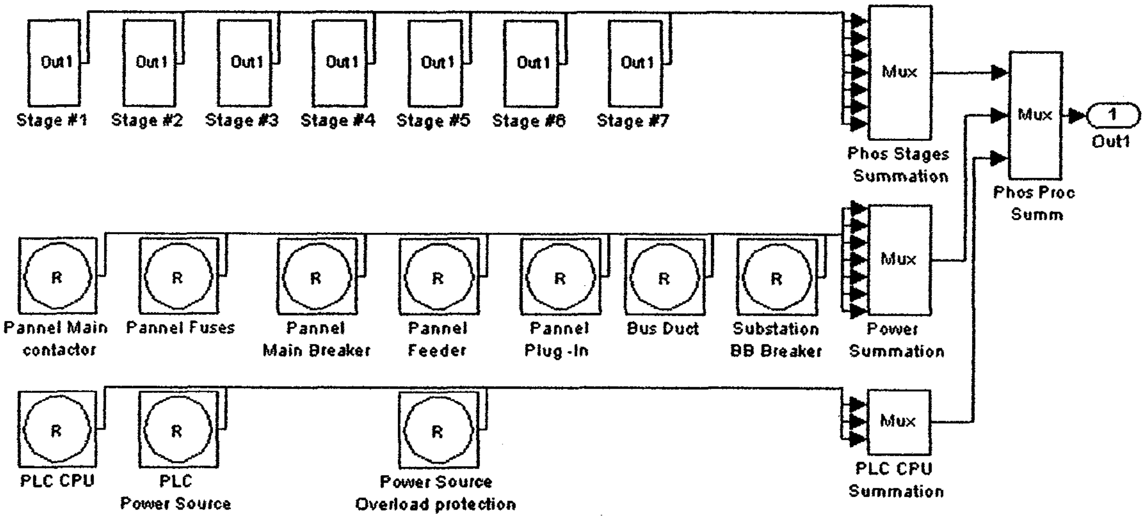


Figure 4.18. Phosphate System Simulink block diagram

It can be seen from Figure 4.18 that the only elements of the power system that can affect the Phosphate system are identified. The elements of the power system that are common to all the subsystems (upstream) will be considered further.

The stages of the Phosphate process are grouped in subsystems in order to simplify the scheme, and as an example , the Stage #3 is shown in Figure 4.19.

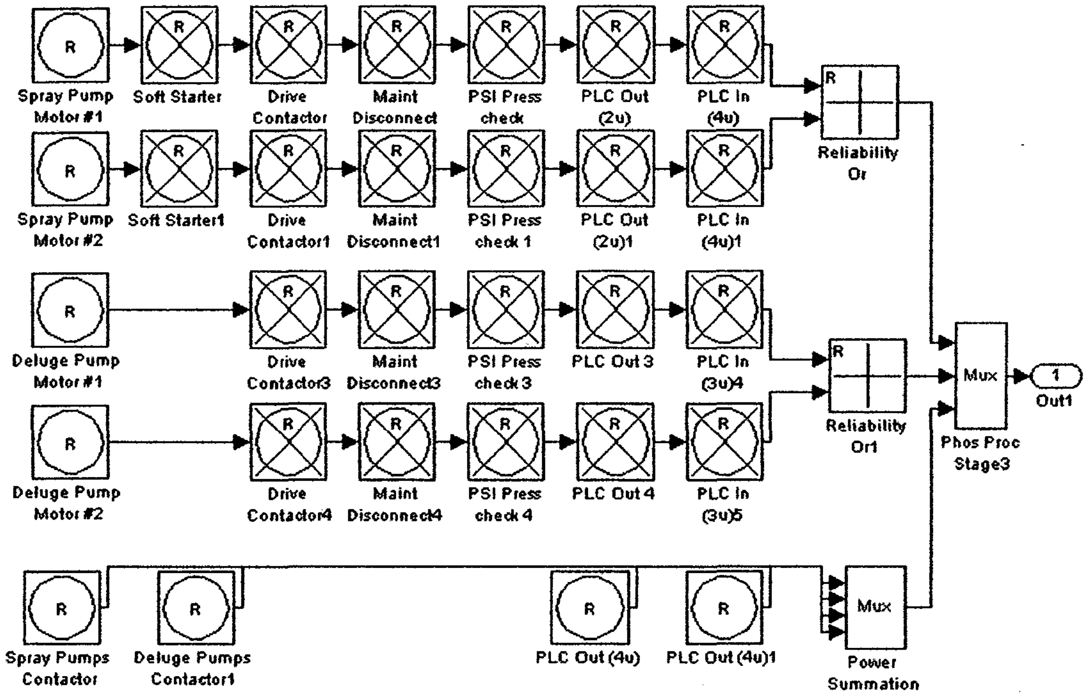


Figure 4.19. Phosphate Process Stage #3

4.4.2.7. Elpo Process

The Elpo Process control logic is similar to the Phosphate Process. The block diagram for the Elpo Process is shown in Figure 4.20.

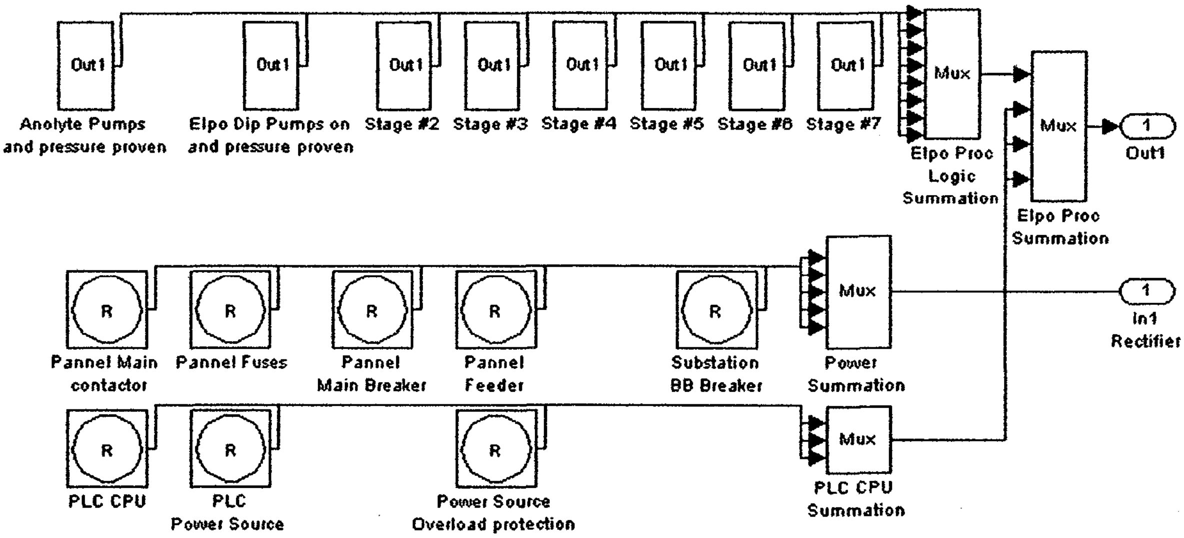


Figure 4.20. Elpo Process Simulink block diagram

4.4.2.8 Elpo rectifier

The Elpo rectifier consists of three - 3 phase AC/DC independent rectifiers that feeds every zone of the Elpo Dip as shown in Figure 4.21. This system is basically a power system which was modelled according to the IEEE Std 493-1997 recommendations.

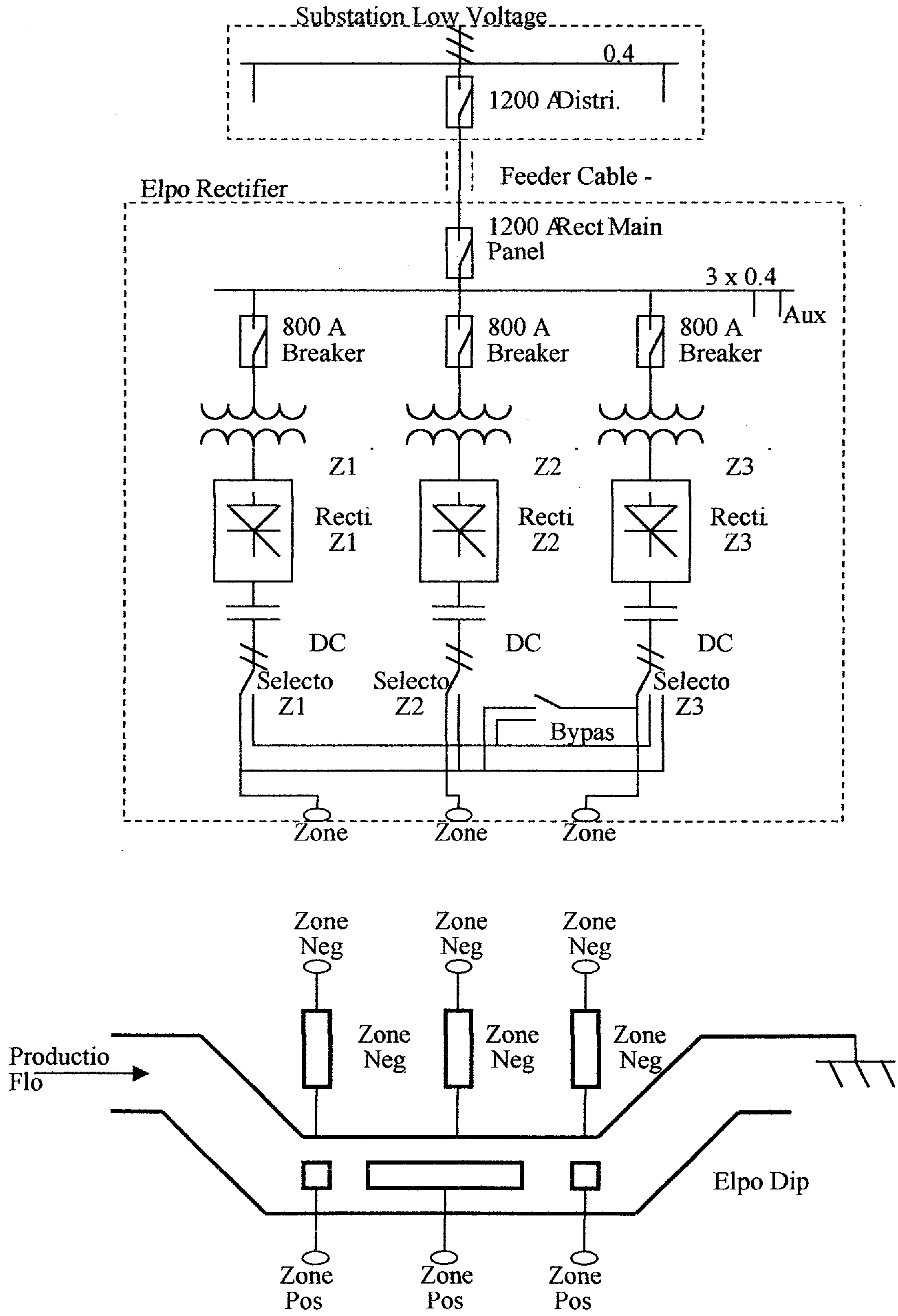


Figure 4.21. Elpo Rectifier One Line diagram

4.4.2.9. Elpo rectifier Failure Analysis and Modelling

Failure Case 1: Failure in one of the Rectifiers: in case of a failure in one of a rectifiers, it is possible by some manual switching maneuvers, under no load conditions, to feed the 3 Elpo dip zones with two rectifiers. This sub-system was modelled with the Simulink block "Tie Independent Power Sources" presented in Chapter 3 and the time for the switching obtained from data provided by the GM Rosario Paint Shop Plant Department recorded from field failures. It is shown in the block diagram of Figure 4.22.

Failure Case 2: Failure in the PLC Controller. The control of the voltage is done by independent Automatic Voltage Controllers (AVR) for each zone, and the PLC is responsible for the data management, security, measurement and exchange of set points, alarming and measurement information with the Human Man Interface (HMI). If the PLC fails, it is possible to operate the system manually, by setting the voltage references directly on the AVR boards with potentiometers. This fact is also considered in the model shown in Figure 4.22.

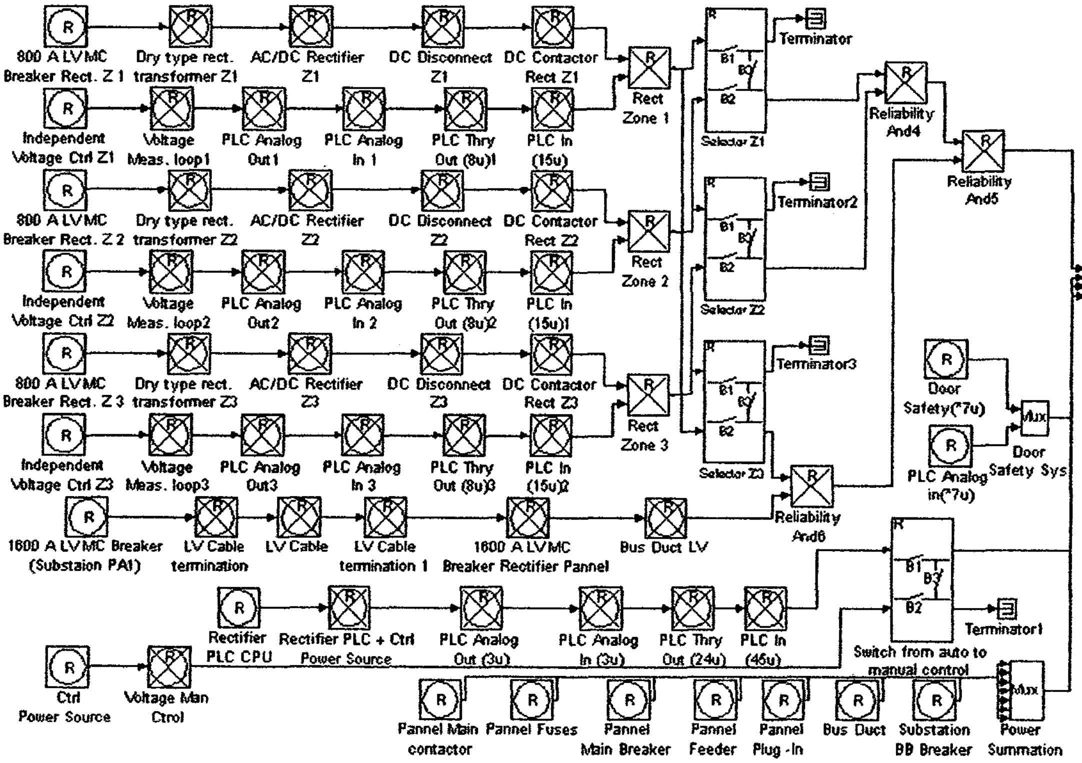


Figure 4.22. Elpo Rectifier Simulink block diagram

4.4.2.10. Elpo Oven

The Elpo oven was described in Chapter 1 and is composed by 4 independent zones based on a gas fired burner and a recirculating air heating system. If one of the zones fails, the Elpo oven can be operated with the remaining 3 zones and by changing the temperature setpoint according to requirements of the Process Engineering and Quality Departments, in order to maintain the GM Quality Standard requirements. The switching and adjustment process is modelled by the "Tie Breaker for Independent Power Sources" block presented in Chapter 3. The Simulink block diagram for the Elpo Oven is shown in Figure 4.23.

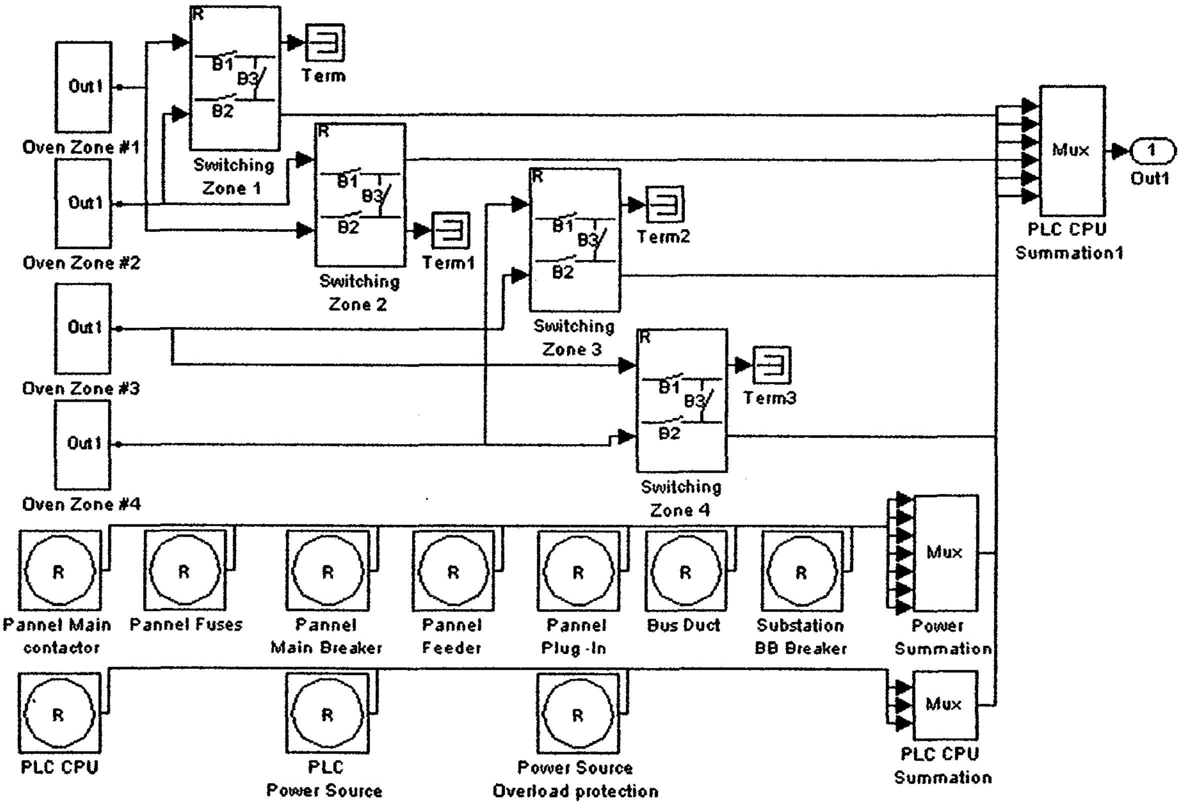


Figure 4.23. Elpo Oven Simulink block diagram

4.4.10 Power System

The one line diagram of the Power System that feeds the GM Rosario Plant, from the main substation to the Phosphate –Elpo System busway is shown in Figure 4.24.

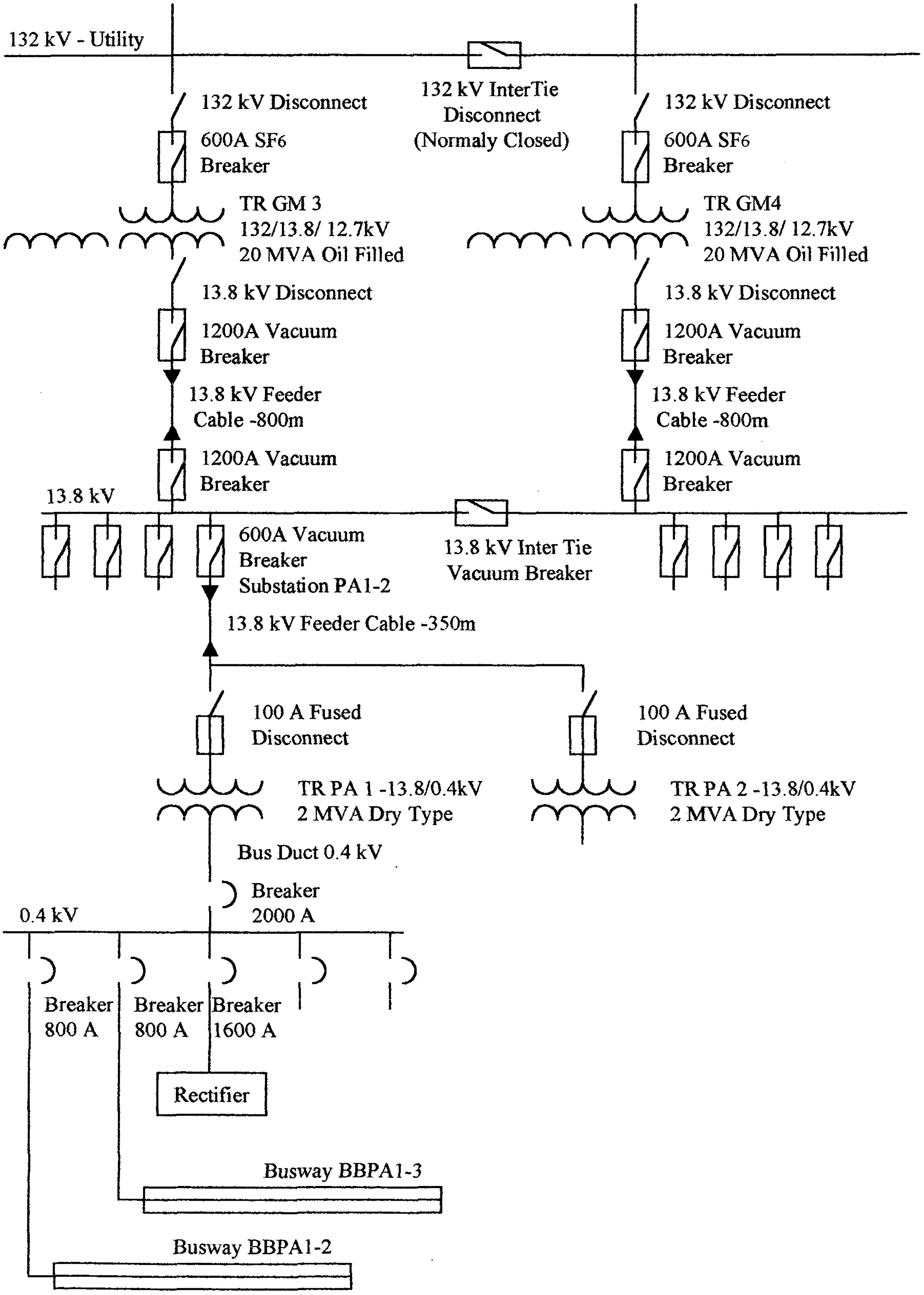


Figure 4.24. GM Rosario Plant Power System one line diagram

The GM Rosario Plant power system is a double 132 kV line, two 132/13.8 kV, 20 MVA transformers, two 13.8 kV feeders that reach the 13.8 kV distribution center. A 13.8 kV distribution feeder connects the distribution center with the 13.8/0.4 kV, 4 MVA transformer substation PA 1-2. In the low voltage side of the PA 1 transformer substation, a distribution panel feeds the different processes through a system of industrial busways.

Each subsystem main panel is connected through a fused plug-in type disconnect. The elements of the power system that affect only to a particular sub-system were considered previously in the model of each sub-system. The elements that affect the whole Phosphate- Elpo System are considered together, and in a serial logic connection with it because a failure in the Power System will affect the entire Phosphate – Elpo System. The Power System Simulink block diagram from the "Main Power Transformer Station" to the "Low Voltage Distribution Panel" of the PA1 Substation is shown in Figure 4.25.

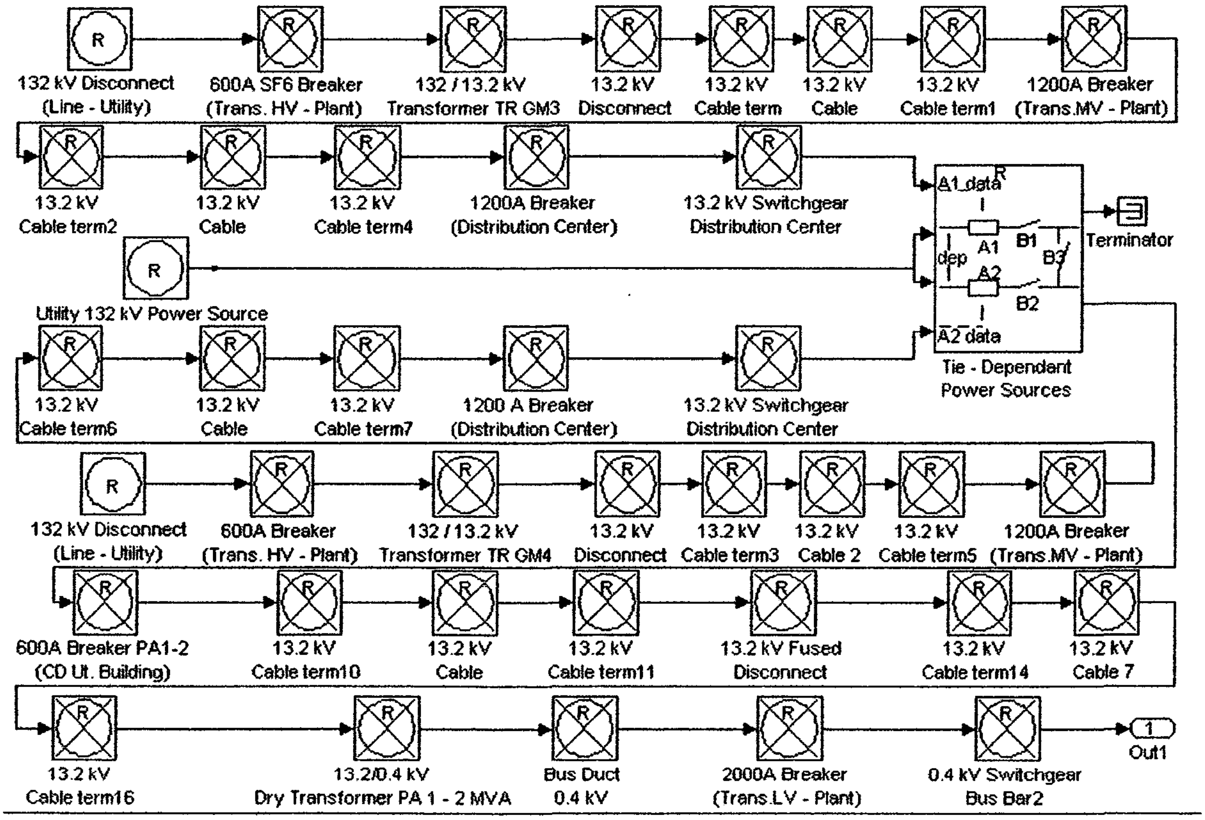


Figure 4.25. Power System Simulink Block

4.4.11 Phosphate Elpo System Model

Now that each subsystem of the Phosphate – Elpo System have been presented, the whole system will be built up. The subsystems are grouped in order to simplify the block diagram and the whole system is presented in Figure 4.26.

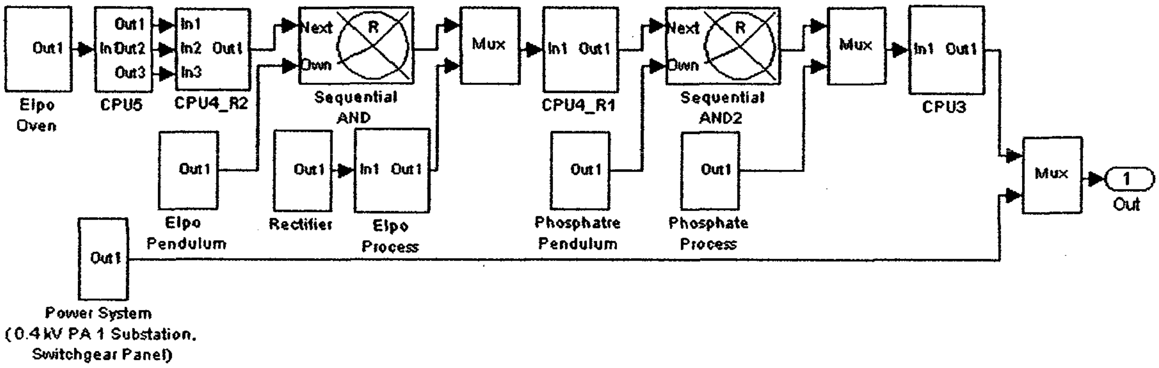


Figure 4.26. Phosphate - Elpo System Simulink block diagram

The links between sub-systems depends on the logic that interconnects them and it is sequential among conveyors, and “and” conditioning among conveyors and chemical systems, oven and rectifier.

At this point, the Phosphate–Elpo System is fully modelled and represented in Figure 4.26. The simulation was run and the results will be presented and analyzed in the next chapter.

CHAPTER 5. RELIABILITY ANALYSIS

5.1 Introduction

The Phosphate-Elpo System of the Paint Shop Plant, General Motors Rosario, Argentina modelled in Chapter 4 was simulated with the proposed method for different case studies and the results analyzed. Some particular sub-systems and improvement proposals are also analyzed in order to show the effectiveness of the proposed reliability analysis method. The system modelled with the designed Simulink Reliability Blockset and represented in Figure 4.26. is the basis for the different case studies simulated in this chapter. It is also simulated with the reliability indices obtained from the survey conducted by the GM Rosario Plant Maintenance Department. The data is shown in Appendix D. For some elements, because of the data unavailability from the plant survey, data from the IEEE Std 493 –1997 [1] was used.

Because of the production cycle of the plant which as it was previously explained is organized in weekly shifts of production and non production, the downtime was limited to the end of the productive shift, assuming that the failure started at the middle of the productive shift. This is a realistic approach for the cases studied.

5.2. Case Study 1. Phosphate - Elpo Process Reliability indices calculation

To analyze the reliability of the Phosphate–Elpo System, the point selected for analysis is the entrance gate of the Phosphate Machine, it is point P3 in Figure 4.1. Point 3 was selected because there is a checking point where a visual inspection is done on each bodyshell and the load to the phosphate pendulum is enabled manually. From P3 to P8 the system is automated. If a car is loaded in the Elpo Pendulum during the production shift it will finish the process at P8 sooner or later. The car that was not loaded in the Elpo Pendulum before the production shift ended, will not be loaded until the next production shift. Because of the limited processing speed of the systems involved, the load rate (cars / hour) on the phosphate pendulum is controlled and limited by the

Phosphate PLC. It is assumed for the present analysis a constant rate of load on the phosphate pendulum, which represent the real case. It means that if the system is unavailable to load for any reason for a period of time equal to: 1car/Rate of load a "car not produced" will be accounted.

The system in the GM Rosario Plant is simulated for a production rate of 20 cars / hour and the reliability indices calculated for each individual subsystem and the whole system are shown in Table 5.1. In order to perform a comparative study the subsystems of the Phosphate-Elpo System were linked in series and the results are shown in the last row.

Table 5.1 Phosphate – Elpo System (and it subsystems) Reliability indices

Subsystem / System	Annual Downtime [min/yr]	Failures per year [failure/yr]	Average Downtime per failure [min/failure]	Reliability
Conveyor Sys. CPU3	91.4585	2.4388	37.5010	0.999211
Phosphate Process	98.1153	1.2437	78.8881	0.999154
Phosphate Pendulum	578.7759	74.0178	7.8194	0.995007
Conveyor Sys. CPU4R1	218.9978	21.7724	10.0589	0.998111
Elpo Process	38.9053	0.9312	41.7785	0.999664
Elpo Pendulum	492.0940	68.7035	7.1626	0.995755
Elpo Rectifier	96.7101	2.6188	36.9292	0.999166
Conveyor Sys. CPU4R2	255.3589	29.8569	8.5528	0.997797
Elpo Oven	146.2059	6.2845	23.2646	0.998739
Conveyor Sys. CPU5	577.1262	62.8469	9.1831	0.995021
Power System	319.8586	12.5883	25.4092	0.997241
Phosphate–Elpo seq. System (whole system)	**1616.6250**	**109.9307**	**14.7059**	**0.986054**
Phosphate-Elpo serial System (whole system)	2913.6064	283.3028	10.2844	0.974865

The Reliability of the Phosphate-Elpo sequential system of 0.986054 is acceptable. The number of cars not produced is calculated as follows:

$$Cars\ not\ produced = \frac{Total\ Annual\ Downtime}{Cycle\ Time}$$

$$Cars\ not\ produced = \frac{1616.6250\ min/year}{3\ min/car}$$

$$Cars\ not\ produced \approx 539\ cars$$

This number is very important for the financial analysis of the productive facility, if we consider that the cars are produced upon the demand schedule. It means that these "Cars not produced", in order to satisfy the demand, will be produced in overtime with a increase in cost.

The results obtained for the hypothetical case of linking the subsystems in series instead of in sequential way as it is proposed in this thesis show very distorted results. The Total downtime for the series linking shows and excess error of 80.23% and for the numbers of failures per year the excess error is of 157.51%. These distortions and the differences in the resulting average downtime for the series system can lead also to a very inaccurate reliability analysis and it shows the importance of performing the sequential modelling of the car manufacturing system. Moreover, if the conveyors for each conveyor subsystem were linked in series the errors observed would be significantly larger than for this case.

5.3. Case Study 2. Phosphate Process scrap cars prediction

The Phosphate Pendulum, as it is explained in Chapter 1 is a machine of continuous cycle. It means that it never stops, except due to failures, or is in the no – productive shift. In the Phosphate Process, there are several pools, some of them with acids, where the bodyshells carried out by the pendulum are submerged. The submersion time is proportional to the speed of the pendulum and the action of the acids limited to that time is appropriate for the metal treatment. If the time of exposure to the acid is extended by any reason, the bodyshell will be severely damaged and depending on the damage, it may be scrapped. The occurrence of a scrap bodyshell depends on the acid concentration, the exposure time and the position of the car in respect to the dip.

The company responsible for the operation, which is Henkel Argentina, based on technical and survey data developed an estimation table in order to predict the relationship between the time that the phosphate pendulum stops and the expected number of scraped body shown in Table 5.2.

Table 5.2. Time Phosphate Pendulum Stopped vs. Number of Scrap Bodyshells

Time Phosphate Pendulum Stopped [min]	Expected Number of Scraped Bodyshells [unit]
3	0.1
5	0.9
9	1.0
10	1.6
12	1.7
15	1.9
≥ 20	2.0

In order to predict the scrap bodyshells that we can expect for one year, it is not accurate to work with average values of the downtime because the relationship between downtime and the number of scraped bodyshells is not linear, as we can see in Table 5.2. The spectrum of downtime vs. failure per year, given by the vectors Λ and Γ given by the Simulink Reliability Block "Lambda-Gamma" were used. These vectors were analyzed according to the Table 5.2, and for a regular year with a production rate of 20 cars/hour, the expected annual rate of scrap bodyshells per year is: 46 scrap bodyshells/year.

Although theses bodyshells will go throughout all the states of the Phosphate - Elpo System, they will be scrapped, and then have to be added to the "Cars not produced" previously calculated in Case Study 1. The total number of cars not produced + cars scrapped for a regular production year will be: 539 + 46 = 585 cars

There will be an additional cost of producing the 585 cars "not produced" to meet the production schedule plus the additional cost of replacing the 46 scrapped bodyshells.

5.4. Case Study 3. Variation of the reliability of the system with the production rate

Because of the process of fault transfer among conveyors, for the same system, the reliability will be dependant on the rate of production, that is, the cars produced per year. The Phosphate – Elpo System was simulated for different production rates in order to determine the relationship between the Elpo System Reliability and the Number of Cars produced per hour. The results are shown in Table 5.3. and the most representative indices are plotted in Figure 5.1.

Table 5.3. Reliability indices for different Production Rates (Phosphate Elpo System)

Production Rate [Cars/Hour]	Total Downtime [min]	Failure per Year [Failure/year]	Average Downtime per Failure [min/failure]	Reliability [p.u.]	Cars not produced [cars/year]
10	1401.6666	94.1745	14.8837	0.987908	234
12	1448.0948	95.2201	15.2079	0.987508	290
14	1495.3720	106.3663	14.0587	0.987100	349
16	1538.6034	106.8345	14.4017	0.986727	410
18	1578.3920	109.7851	14.3771	0.986384	474
20	1616.6250	109.9307	14.7059	0.986054	539
22	1653.3613	113.7754	14.5318	0.985737	606
24	1685.5575	115.2879	14.6204	0.985459	674
26	1717.9799	123.5048	13.9102	0.985180	744
28	1747.7969	125.1670	13.9637	0.984922	816
30	1775.4700	125.4663	14.1510	0.984684	888

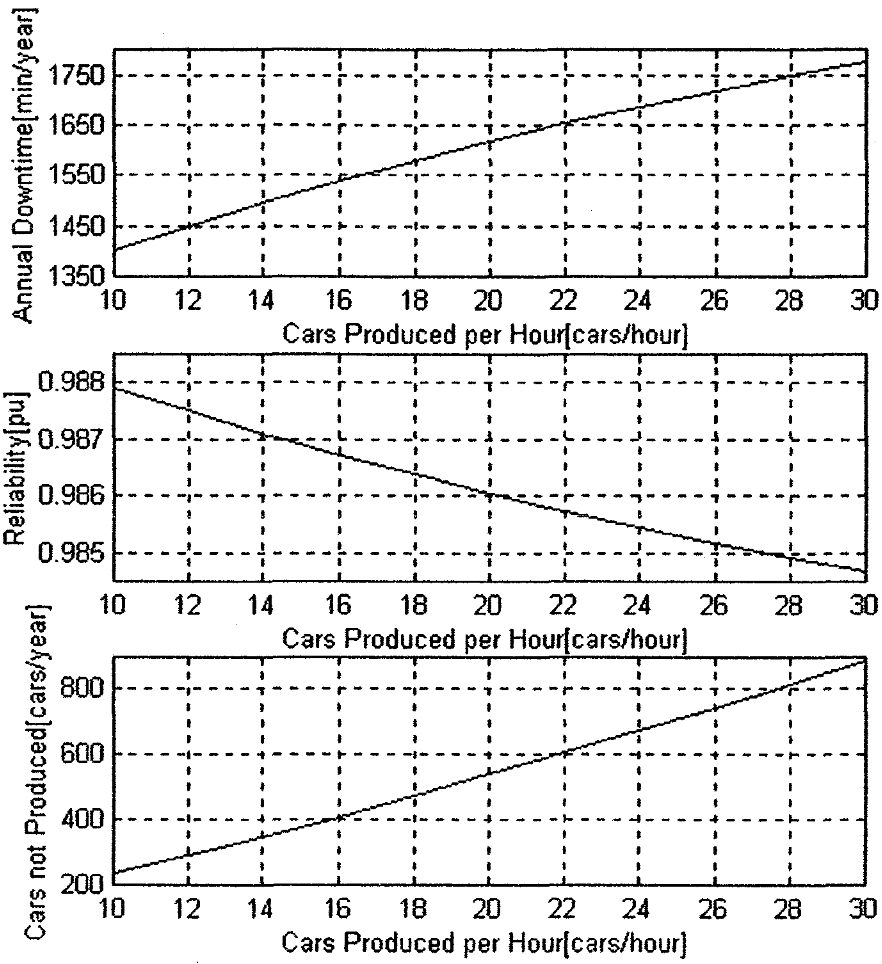


Figure 5.1. Downtime, Reliability and Cars not produced vs. Production Rate

The numbers shown in the last column of Table 5.3 have a significant impact on the financial planning when the business year is planned because those cars not produced during a regular shift will be produced in the overtime or over-shift periods with associated costs. This data is not available in the industry, and the provisions are based on average values, that make the prediction very inaccurate because normally during the year the production rate changes and then it is not possible to provide a precise estimation of the cars not produced.

The increase of the down time is also very important if we consider that the cost of operating the plant. For example operating at 30 cars / hour will cost more than operating the plant at 20 cars/hour, not just because of the manpower increase but for other costs associated to materials handling and stock, and energy consumption, among others.

Normally reliability is calculated for a system , independently of the production rate. It can be seen in Figure 5.1 that the reliability can be used to analyze maintenance strategies and the development of the maintenance department.

Perhaps the most important tendency that can be observed from Figure 5.1 is the increase of "Cars not produced" with a change with the production rate that varies from 234 cars not produced for a production rate of 10 cars/hour to 888 cars not produced for a production rate of 30 cars/hour. This means an increase of 280% in the cars not produced for an increase of 200% in the production rate.

5.5. Process Improvement proposals by Reliability Analysis

In order to apply the proposed reliability analysis method, some improvement proposals will be analyzed by modelling with the Simulink Reliability Blockset. Some of them were proposed by the GM Rosario Paint Shop Plant Maintenance Department.

5.5.1. Case Study 4. Phosphate Machine Buffer

From the previous analysis, it can be concluded that one of the most critical stages in the system is the Phosphate Process and its associated conveyor, the Phosphate Pendulum.
If a buffer at the output gate of the Phosphate pendulum was present in such a way that, when a fault in one of the conveyors that follows the Phosphate pendulum happens (it normally stops the Phosphate pendulum) it could be possible to deviate the bodyshells to that the buffer and empty the Phosphate machine. In this case, the scrap units produced by the stop of the phosphate pendulum will be as a result of pendulum failures.

The modified system was simulated and the Λ and Γ vectors processed according to Table 5.2.

The expected annual rate of scrap bodyshells per year with the modified system is 27 bodyshells per year, a reduction of 41.3 % in the scrapped units and this for the plant operating under a schedule of one productive shift. If the plant operates with two or 3 shifts, the number of no scrapped cars would be significantly higher. Another improvement with the proposed buffer is that the cars that otherwise would be produced under the regular schedule with no extra costs.

5.5.2. Case Study 5. Twin Sensor logic for the Phosphate pendulum

The most important cause of downtime in the Phosphate Pendulum is proximity sensors failure. It is proposed to add to the Pendulum Control, parallel sensors, in such a way that each position is detected by any of two "twin sensors". That the first sensor detects, then the position is recognized. If the second sensor does not detect the position after a predefined time, an alarm signal starts, but the pendulum continues running.

The reliability indices of a system consisting of parallel sensors with in a production rate of 20 cars/hour is shown in Table 5. 4.

Table 5.4 Existing Phosphate pendulum vs. proposed "Twin sensors" model.

Case Studies for Phosphate Pendulum	Total Downtime [min]	Failure per Year [Failure/year]	Average Downtime per Failure [min/failure]	Reliability [p.u.]	Cars not produced [cars/year]
Basic System	1616.6250	109.9307	14.7059	0.986054	539
Basic System with Twin Sensors	1525.5747	103.1454	14.7905	0.983747	509

Installation of twin sensor logic results in a reduction of 5.6% in the cars not produced compared to the existing system configuration. Quantified in terms of money, it would justify the investment which would be very low.

5.5.3. Case Study 6. Power System Failure Influence on the total down time and improvement analysis by sag mitigation

Examining Table 5.1 it is realized that the power system is responsible for approximately 319 minutes per year of downtime in the Phosphate – Elpo Process, what means 19.74% of the total annual downtime. The most frequent problems that produces important losses to the productive system are voltage sags and short time interruptions. Particularly in the Paint Shop Plant the voltage sags and short time interruption were recorded and are shown in Table 5.5.

Table 5.5. Voltage Sags and short time interruptions for the Paint Shop Plant

Failure	Occurrences per year [Failures /year]	Failure Reposition Time [min / failure]
Voltage Sag	7.6	12
Short Interruption (~ 1seg)	4.1	40

These failures have been considered in the model system previously analyzed in Case Study 1.

The effect of applying some of the methods for sag mitigation will be analyzed next. In the GM Rosario Plant a "combined" method has been successfully implemented. This consist of a UPS for the PLC CPU and Control Power Source, instantaneous undervoltage relay and some modification in the PLC Ladder Logic to enable a quick restart of the system after a failure. A system with these proposed characteristics is modelled and the results are shown in Table 5.6.

Table 5.6 Actual Phosphate-Elpo System vs. proposed Sag resistant model.

Case Studies for Phosphate Elpo System	Total Downtime [min]	System Outages per Year [Failure/year]	Average Downtime per System outage [min/failure]	Reliability [p.u.]	Cars not produced [cars/year]
Basic System	1616.6250	109.9307	14.7059	0.986054	539
Basic System with Sag Mitigation Method	1366.5061	98.3308	13.8970	0.988212	456

By including the proposed improvement, the number of cars not produced will decrease by 83 units per year, which means a reduction of 18.2% for the operating conditions of the plant. In this case, the investment in the proposed solution is also justified.

Discussion

Many other cases can be analyzed for the Phosphate – Elpo System of the Paint Shop Plant with the model used, but are beyond the scope of this Master of Science Thesis, which is focused in the development and implementation of the proposed reliability methodology. At this point, the author considers that the cases presented, involving over 15 case simulations, have proven the usefulness of the proposed methodology.

CHAPTER 6. CONCLUSIONS

The use of traditional parallel-serial reliability methodologies is not suitable for manufacturing systems where the products are carried by sequential conveyors systems or the products are processed in sequential stages. The direct application of these methods can lead to totally inaccurate results.

To perform a reliability study of a complex manufacturing system with a large amount of elements like the case analyzed in this M. Sc. thesis where over 5000 individual elements were identified, it is necessary to provide a methodology that enables the creation of sub-systems by grouping of elements in the block diagram. Otherwise, such a study is practically impossible to perform.

In order to perform an accurate reliability study for sequential conveyors, it is not possible to use the average reliability parameters for individual components because the way in which a fault in a conveyor affects the rest of the conveyors in the manufacturing line and can not be modelled with average parameters. The method proposed in this Master of Science thesis works with reliability vectors and is accurate accounting for the fault transferring between consecutive conveyors. It is possible to determine the total down time of a particular conveyor, not only by considering its own faults, but accounting for the effect of the faults in the conveyors downstream that will force it to be in a idle state.

The Matlab – Simulink environment that is designed to deal with vector, matrixes and block diagrams, appropriately customized, is a powerful and versatile tool to perform reliability studies of systems with a large number of elements and diversity of configurations. Eventually any kind of logical relationships between elements can be modelled and represented with customized blocks. For this particular system, many case studies that could not be solved accurately by the traditional methods and available tools are solved by a customized solution using Simulink Reliability block diagrams.

The case studies analyzed are:

- Conveyor sequential systems
- Conveyor systems with alternative parallel paths
- Inter tie breakers with independent and dependent power source
- Switching to alternative systems (Ovens, Pumping Systems, Rectifier Zones)
- Switching to alternate operation mode (Automatic to Manual)
- Multiple Parallel Systems
- Effect of Automatic control Systems (PLC and DCS)
- Representation of logical and no logical fault modes

Although this study is performed for a particular system, the methodology developed in this M. Sc. Thesis is potentially applicable to any manufacturing line or other industrial facility, and perhaps it would be necessary to develop new Simulink Reliability blocks in order to solve particular cases.

The method proposed seems to be very complex and time consuming but for a trained eye in automation and with a good industrial background it is not and the modelling process can be performed quickly. The level of detail with which the production system was modelled is very complex and detailed and could logically be reduced depending on the accuracy expected.

To perform an accurate reliability study of a manufacturing system it is necessary to have a detailed knowledge of the systems involved, accounting for automation, mechanical, electrical and chemical systems, power distribution, normal and emergency operation modes and other components that could produce failures or provide alternative operative modes. All these components have to modelled and included in the reliability model of the system under study.

By using the reliability methodology developed for this Master of Science thesis some information from the manufacturing line was obtained that otherwise would not be possible . Particularly some trends like Cars not produced (because of downtime) vs. cars produced per hour have not been previously studied and is very important for the business plan of a manufacturing industry.

By applying the methodology proposed in this thesis it is also possible to assess the impact of particular elements on the reliability of the whole system and to study improvements on the existing systems to decrease its impact, for example, by changing maintenance strategies or by performing system modifications. The proposed methodology is also flexible and can easily be modified to account for aging components in the system.

Future Work

The methodology presented for reliability analysis has proved to be effective for the modelling of a complex process like the Phosphate-Elpo in the Paint Shop Plant. It would be interesting to extend the study to the processes and stages of the Paint Shop Plant not considered in this thesis. Once the whole Paint Shop Plant is modelled, it could be estimated the impact on the Body Shop and General Assembly Shop.

It would be also interesting to study the reliability modelling of other components of a car manufacturing complex like the Body Shop were the process is quite different from the Paint Shop. In that case, several independent production cells produce the panels that conform the car in the Body Shop Assembly line. The modelling of the buffers would probably be the most challenging task for that case. Similar structures are present in the Engine and General Assembly shops but in each case it would be fundamental to include the effect of the cycle time as it was modelled in this thesis.

The modelling methodology developed in this thesis for sequential systems is also applicable to many other manufacturing systems involving the sequential material transport systems. For example, mining, drug and bottling systems all involve sequential transport systems which can be modelled by the methodology developed in this thesis.

It is the intention of the author to perform reliability modelling and analysis studies of other manufacturing systems with the proposed methodology and to continue the development and improvement of the Simulink Reliability Block Set to represent the behaviour of systems that were not studied in this thesis.

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APPENDIX A. Simulink®

Following a brief Simulink overview extracted form the simulink.com web page is presented

Overview

Simulink is an interactive tool for modeling, simulating, and analyzing dynamic, multidomain systems. It lets the user build a block diagram, simulate the system's behavior, evaluate its performance, and refine the design. Simulink integrates seamlessly with MATLAB, providing immediate access to an extensive range of analysis and design tools. These benefits make Simulink the tool of choice for control system design, DSP design, communications system design, and other simulation applications.

Key Features

Creating the Model

- Extensive library of predefined blocks
- Models can be grouped into hierarchies to create a simplified view of components or subsystems
- Model Browser for navigating model hierarchies
- Library Browser for convenient block selection
- Finder tool for searching models and libraries
- Auto-connection and auto-routing simplifies editing
- Customizable blocks that can incorporate existing MATLAB, C, Fortran, and Ada code
- Linear, nonlinear, continuous-time, discrete-time, multirate, conditionally executed, mixed-signal, and hybrid systems
- Supports operations on matrix, frame-based, and complex signals
- Supported data types include 32- and 64-bit floating-point, fixed-point (requires Fixed-Point Blockset), and integer

- Model Discretizer easily converts continuous designs to discrete (requires Control System Toolbox)
- Simulink Data Explorer GUI for viewing and editing data

Running a Model

- Graphical debugger lets you find and correct design errors
- Simulations can be run from the MATLAB command line, either interactively or in batch mode
- Diagnostic Viewer helps you conveniently identify and correct modeling errors
- Model Verification blocks validate design elements during model execution
- Intrinsic fixed-point support lets you switch easily between fixed-point and floating-point representations (requires Fixed-Point Blockset)

Tools for Creating Models

Simulink provides a complete set of modeling tools that can be used to quickly develop detailed block diagrams of your systems. Features such as block libraries, hierarchical modeling, signal labeling, and subsystem customization provide a powerful set of capabilities for creating, modifying, and maintaining block diagrams. These modeling features, together with Simulink's comprehensive set of predefined blocks, make it easy to create concise representations of systems, regardless of their complexity.

In addition, Simulink offers features for creating customized blocks and block libraries. It is possible to customize not only the functionality of a block, but also its user interface, using icons and dialog boxes. Custom blocks can be saved in a block library for future use and can be shared with work groups, vendors, and customers. Changes made to the library version of a block propagate to all models that use that block.

Model Discretization

Discretization is a critical step in embedded digital controller design. However, the designer often relies on continuous design methods, which are supported by Simulink. It therefore becomes necessary to convert such a continuous model to a discrete model. Simulink includes a convenient discretization tool to selectively convert blocks in your model from continuous to discrete form, allowing you to choose the discretization method.

The Library Browser makes it easy to navigate through block libraries and then drag and drop selected blocks into your model. Click on image to see enlarged view.

Integrating Custom Code

It is possible to incorporate a new or existing code (MATLAB, C, Fortran, or Ada) into a Simulink block diagram through Simulink S-Functions (system-functions). An S-Function is a custom code module that defines the behavior of a Simulink block. Simulink provides an S-Function Builder for C-coded S-Functions to help the user to create his own S-functions and include them in your model.

Simulink Data Objects

Simulink data objects can be used to define new MATLAB data classes that are specific to the customer application and then use them as parameters, signals, states, and datastore memory data in the Simulink models. This is particularly useful for specifying implementation details when generating code with Real-Time Workshop. Al Simulink data objects can be viewed or edited with the Simulink Data Explorer.

Data Typing

Simulink supports complex and data-typed signals. Many of the blocks in Simulink support several data types. The ability to specify the data types of a model's signal and block parameters is particularly useful in real-time applications such as microcontrollers and DSPs. With this capability, it is possible to specify the optimal data types required to represent signals, block parameters, and mathematical operations exactly as they are represented on these devices. Additionally, by choosing the appropriate data types for the customer model's signals and parameters, it can dramatically increase the performance and decrease the memory requirements of code generated from the model. Supported data types include double-precision floating-point; single-precision floating-point; signed and unsigned 8-, 16-, and 32-bit integers; and Boolean.

Multi-dimensional Data Support

Simulink supports the modeling of single-input/single-output (SISO) and multi-input/multi-output (MIMO) systems, These inputs and outputs are modeled as signals, and can represent scalar, vector, or matrix quantities.

Graphical Signal Management

Because Simulink blocks support vectored operations, it is possible to greatly reduce the number of blocks needed to model your system. This results in clean, simple, and easy-to-read block diagrams. Simulink provides blocks to multiplex and demultiplex signals, create data busses, merge signals, and perform switching.

Simulation

After building your block diagram in Simulink, it is possible to run interactive simulations and view the results live. The powerful suite of fixed-step and variable-step solvers available in Simulink makes simulation results extremely accurate.

State-of-the-Art Solvers

The Simulink simulation engine offers numerous features for simulating large, challenging systems. Foremost among these is the set of integration algorithms, called solvers, which are based on the MATLAB ordinary differential equation (ODE) suite. These solvers are well suited to continuous-time (analog), discrete-time, hybrid, and mixed-signal simulations of any size. They provide fast, reliable, and extremely accurate simulation results.

The solvers offer support for certain differential algebraic equations (DAEs) with multichannel algebraic loops. An algebraic constraint block facilitates the solution of a system in which an algebraic constraint applies to the governing set of equations. The solvers also support stiff systems, and systems with state events (such as discontinuities, including instantaneous changes in plant dynamics).

Integration with MATLAB

Simulink is built on top of MATLAB, providing a unique development environment. This gives the user access to the powerful analysis and graphics capabilities of MATLAB, and lets the user run simulations either interactively, using Simulink's graphical interface, or systematically, by running in batch mode from the MATLAB command line.

APPENDIX B. MATLAB FUNCTIONS

Matlab Code for Lambda Function

```
function[L]= lambda(u)
i = 1;
j = 1;
k = 1;
n = size(u);
r = n(1);
L=zeros((r/2),1);
G=zeros((r/2),1);
L0=zeros((r/2),1);
G0=zeros((r/2),1);
LP=zeros(r,1);
GP=zeros(r,1);
while i < r
   L0(j)= u(i);
   i = i + 1;
   j = j + 3;
 end
i = 2;
while i <= r
 G0(k) = u(i);
  i = i + 2;
   k = k + 1;
end
G1(1)=0;
L1=zeros(r,1);
[G1,I] = sort(G0);
L1=L0(I);
```

```
d1sc=size(G1);
max1=1;
min1=0;
b=1
a=2
LL=0
GG=0
c=0.1
mx(1)=1
while max1 <=( max(G)*60+1)
while b<=d1sc(1)
LL=0;
GG=0;
while mx(c)>=(60*G1(b))
while mx(c)>=(60*G1(b))
L0 = LL;
G0 = GG;
LL=L1(b) + LL;
GG=(G1(b)*L1(b)*60 + L0  * G0)/(L1(b)+L0);
b=b+1;
if b>d1sc
else
end
end
LP(a)=LL
GP(a)=GG
a=a+3
if b>d1sc
else
end
end
```

```
mx(c+1)=mx(c)+1;
c=c+2;
end
max1=max1+1;
end
L=LP;
```

Matlab Code for Gamma Function

```
i = 1;
j = 1;
k = 1;
n = size(u);
r = n(1);
L=zeros((r/2),1);
G=zeros((r/2),1);
L0=zeros((r/2),1);
G0=zeros((r/2),1);
LP=zeros(r,1);
GP=zeros(r,1);
while i < r
L0(j)= u(i);
i = i + 3;
 j = j + 2;
end
i = 2;
while i <= r
G0(k) = u(i);
i = i + 2;
k = k + 2;
```

```
end
G1(1)=0;
L1=zeros(r,1);
[G1,I] = sort(G0);
L1=L0(I);
d1sc=size(G1);
max1=1;
min1=0;
b=1;
a=1;
LL=0
GG=0
c=1
mx(1)=1;
while max1 <=( max(G)*60+1)
while b<=d1sc(1)
LL=0;
GG=0;
while mx(c)>=(60*G1(b))
while mx(c)>=(60*G1(b))
L0 = LL;
G0 = GG;
LL=L1(b) + LL
GG=(G1(b)*L1(b)*60 + L0  * G0)/(L1(b)+L0);
b=b+2;
if b>d1sc
else
end
end
LP(a)=LL;
GP(a)=GG;
```

```
a=a+1;
if b>d1sc
else
end
end
mx(c+1)=mx(c)+1;
c=c+1;
end
max1=max1+1;
end
G=GP;
```

Matlab code for transffa function

```
function[LG]= transffa(u)
T = u(1);
M = u(2);
i = 2;
j = 1;
k = 1;
G(1)=0;
L(1)=0;
n = size(u);
r = n(1);
L2=zeros(1,M);
G2=zeros(1,M);
LG=zeros(1,M);
while i <= r
L(1,j)= u(i);
i = i + 1;
j = j + 1;
```

```
end
i = 4;
while i <= r
G(1,k) = u(i);
i = i + 2;
k = k + 1;
end
[G1,I] = sort(G);
L1=L(I);
d1sc=size(G1);
G2(1,1)=0;
L2(1,1)=0;
f=1;
d=1;
while f <= d1sc(2)
if (G1(f)*60)> T;
G2(d)= G1(f)*60-T;
L2(d)= L1(f);
d = d + 1;
end
f = f + 1;
end
LG=zeros(1,M);
e=1;
g=2;
while e<= (M-1)
LG(e)=L2(g);
e=e+2;
g=g+1;
end
h=2;
```

```
m=1;
while h<=(M-1)
LG(h)=G2(m)/60;
h=h+2;
m=m+1;
end
LG;
```

Matlab code for crp function

```
function[Rel]= crp(u)
s=size(u)
n=s(1);
i=1;
j=1;
x=0;
y=0;
l=0;
while i<= n
l=u(i)*u(i+1);
x=x+l;
i=i+1;
end
Ltot=x*60;
while j<= n
y=y+u(j);
x=x+1;
j=j+2;
end
AvgDT = Ltot/y;
Rel=[Ltot,y,AvgDT];
```

Matlab Code for 2squeue function

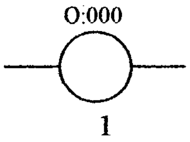
```
function[LG]= 2squeue(u)
T = u(1);
M = u(2);
Ts = u(3);
i = 2;
j = 1;
k = 1;
G(1)=0;
L(1)=0;
n = size(u);
r = n(1);
L2=zeros(1,M);
G2=zeros(1,M);
LG=zeros(1,M);
while i <= r
L(1,j)= u(i);
i = i + 1;
j = j + 1;
end
i = 6;
while i <= r
G(1,k) = u(i);
i = i + 2;
k = k + 1;
end
[G1,I] = sort(G);
L1=L(I);
d1sc=size(G1);
G2(1,1)=0;
```

```
L2(1,1)=0;
f=1;
d=1;
while f <= d1sc(2)
if (G1(f)*60)> 2*T;
Y=2*T+(Ts-T)/Ts*G1(f);
G2(d)= G1(f)*60-Y;
L2(d)= L1(f);
d = d + 1;
end
f = f + 2;
end
LG=zeros(1,M);
e=1;
g=1;
while e<= (M-1)
LG(e)=L2(g);
e=e+2;
g=g+1;
end
h=2;
m=1;
while h<=(M-1)
LG(h)=G2(m)/60;
h=h+2;
m=m+1;
end
LG;
```

APPENDIX C - PLC INSTRUCTIONS AND ADDRESSING

1. PLC Ladder Logic Instructions

1.1. OTE – Output Energize instruction



Type - Bit

Description

Use the OTE instruction to control a bit in memory. If the bit corresponds to an output module terminal, the device wired to this terminal is energized when the instruction is enabled and de-energized when the instruction is disabled. If the input conditions that precede the OTE instruction are true, the processor enables the OTE instruction. If the input conditions are false, the processor disables the OTE instruction. When rung conditions become false, the corresponding device de-energizes.

An OTE instruction is similar to a relay coil. The OTE instruction is controlled by preceding input instructions; the relay coil is controlled by contacts in its hard-wired rung.

Sample Output Address

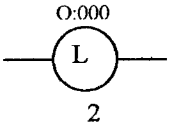
In an output address, such as O:12/03:
"O" indicates output-image table
"12" represents word twelve (octal) in the output-image table
"03" represents bit three

Note: The "12" also indicates rack one, module group two (output-image table addresses correspond to output module locations).

Output addresses are specified to the bit level.

Note: When using SoftLogix 5, this instruction supports the Long-integer data table type. Example: L10:0

1.2. OTL – Output Latch Instruction



Type - Bit

Description

This instruction functions much the same as the OTE with the exception that once a bit is set with an OTL, it is "latched" on. Once an OTL bit has been set "on" (1 in the memory) it will remain "on" even if the rung condition goes false. The bit must be reset with an OTU instruction.
When the processor changes from Run to Program mode or when the processor loses power (and there is battery backup), the last true OTL instruction continues to control the bit in memory. The latched output device is energized although the rung conditions that control the instruction may have gone false.

Note: The OTL instruction is retentive. When the processor loses power, is switched to Program mode or Test mode, or detects a major fault, outputs go off; but the states of retentive outputs are retained in memory. When the processor resumes operation in Run mode, retentive outputs immediately return to their previous states. Non-retentive outputs, such as OTE outputs, are reset.

Sample Output Address

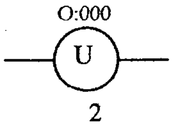
In an output address, such as O:12/03:
"O" indicates output-image table
"12" represents word twelve (octal) in the output-image table
"03" represents bit three

Note: The "12" also indicates rack one, module group two (output-image table addresses correspond to output module locations).

Output addresses are specified to the bit level.

Note: When using SoftLogix 5, this instruction supports the Long-integer data table type. Example: L10:0

1.3. OTU – Output Unlatch Instruction



Type - Bit

Description

The OTU instruction is a retentive output instruction that can only turn off a bit (it cannot turn on a bit). This instruction is usually used in pairs with an OTL instruction, with both instructions addressing the same bit. The OTU instruction turns off the bit that was turned on (latched) by the OTL instruction.
When the processor changes from Run to Program mode or when the processor loses power (and there is battery backup), the bit is retained in the state set by the last rung of the latch/unlatch pair that was true.

The OTU instruction tells the processor to turn off the addressed bit based on the rung condition. Thereafter, the bit remains off, regardless of the rung condition, until it is turned on, typically by an OTL instruction in another rung.

Sample Output Address

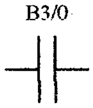
In an output address, such as O:12/03:
"O" indicates output-image table
"12" represents word twelve (octal) in the output-image table
"03" represents bit three

Note: The "12" also indicates rack one, module group two (output-image table addresses correspond to output module locations).

Output addresses are specified to the bit level.

Note: When using SoftLogix 5, this instruction supports the Long-integer data table type. Example: L10:0

1.4. XIC – Examine if Closed Instruction



Type - Bit

Description

Functions as input or storage bit.
If the corresponding memory bit is a "1" (on), this instruction will allow rung continuity and outputs will be energized (other factors may affect rung continuity).
If the corresponding memory bit is a "0" (off), this instruction will not allow rung continuity (it assumes its normally open state) and outputs on the rung will be deenergized (other factors can influence rung continuity).
If used as an input bit, its status should correspond to the status of real world input devices tied to the input-image table by the identical addresses.

XIC - Addressing Help

Sample: I:12/03
In the sample address, "I" indicates input-image table; "12" represents word twelve (octal) in the input-image table; after the slash "/" the "03" indicates bit three.

Note: The "12" also indicates rack one, module group two for input addresses.

Input addresses are specified to the bit level.

Note: When using SoftLogix 5, this instruction supports the Long-integer data table type. Example: L10:0

1.5. XIO- Examine if Open Instruction

Type - Bit

Description

Functions as input or storage bit.
If the corresponding memory bit is a "1" (on), this instruction will not allow rung continuity and outputs on its rung will be de-energized (other factors may affect rung continuity).
If the corresponding memory bit is a "0" (off), this instruction will assume its normal status and allow rung continuity and outputs on the rung will be energized (again, other factors can influence rung continuity).
If used as an input bit, its status should correspond to the status of real world input devices tied to the input-image table by the identical addresses.

XIO - Addressing Help

Sample: I:12/03
In the sample address, "I" indicates input-image table; "12" represents word twelve (octal) in the input-image table; after the slash "/" the "03" indicates bit three.

Note: The "12" also indicates rack one, module group two for input addresses.

Input addresses are specified to the bit level.

Note: When using SoftLogix 5, this instruction supports the Long-integer data table type. Example: L10:0

Database File Type

The following list describes the different data table file types. Default data table file types 0-8 cannot be redefined.

File # - Type	File Description	Comments
O0 – Output	This file stores the state of output terminals for the controller.	--
I1 -I Input	This file stores the state of input terminals for the controller.	--
S2 – Status	This file stores controller operation information useful for troubleshooting controller and program operation.	Status file 2 is fixed at 32 words for PLC-5/10, -5/12, -5/15, and -5/25 processors and at 128 words for PLC-5/11, -5/20, -5/30, -5/40, -5/40L, -5/60, -5/60L, and -5/80 processors.
B3 - Binary Bit	This file stores internal relay logic.	This file can be 1,000 words maximum.
T4 – Timer	This file stores the timer accumulator and preset values and status bits.	T4 is the default file number. For this file type, you can assign any file number from 3 thru 999. This file cannot exceed 1000 structures.
C5 – Counter	This file stores the counter accumulator and preset values and status bits.	C5 is the default file number. For this file type, you can assign any file number from 3 thru 999. This file cannot exceed 1000 structures.
R6 – Control	This file stores the length, pointer position, and status bits for specific instructions such as shift registers and sequencers.	R6 is the default file number. For this file type, you can assign any file number from 3 thru 999. This file cannot exceed 1000 structures.
N7 – Integer	This file is used to store numeric values or bit information.	N7 is the default file number. For this file type, you can assign any file number from 3 thru 999. This file can be 1,000 words maximum.
F8 – Floating Point	This file stores a # with a range of 1.1754944e-38 to 3.40282347e+38.	F8 is the default file number. For this file type, you can assign any file number from 3 thru 999. This file can be 1,000 float words (32-bit words) maximum.

Address Type	Description	Example
Logical address	Alpha-numeric coded format to specify the data location.	N23:0 addresses an integer file 23, word 0.
I/O image address	Logical address format, but relates physical locations in the I/O chassis to memory locations in the I/O image file.	I:017/17 addresses input file word 017 (octal), bit 17 (octal), which corresponds to rack 01, module group 7, and terminal 17.
Indirect address	Logical address format, but allows you to change address values in the base address with your ladder logic program.	N[N7:6]:0 has the file number as the variable The file number is stored in integer file 7, word 6.
Indexed address	Index prefix (#) is followed by a logical address format, but it adds an index value (offset) from processor status file (S:24) to the base address.	When #N23:0 is the indexed address and the offset value stored in the processor status file (S:24) is 10, then The base address is integer file 23, word 0 The offset address is integer file 23, word 10
Symbolic address	ASCII character string that relates the address (file, structure, word, or bit) to a descriptive, meaningful name that you assign.	For example, a floating point address F10:0 could be given a symbolic address of Calc_1. Guidelines for setting up an address are as follows: The symbol can have up to 10 of the following characters: A-Z (upper and lowercase), 0-9, underscore (_) and @. The symbol cannot consist of only numbers.Extended ASCII characters may also be used in the symbol. They can be entered using the ALT key in association with the numeric keypad, or they can be pasted into the Address/Symbol editor.You can substitute a symbolic address for structure, word, or bit addresses.Record the symbols you define and their corresponding logical addresses.

Address

Delimiters

PLC-5 addresses use delimiters between the characters to specify the data file types and number (fn), the file element (e), and the file subelement (w) or bit number (b) within that file. When you enter addresses or symbol names during ladder programming or program documentation, the input is parsed to check it for validity.

Delimiters between file numbers and elements

To facilitate address entry, the colon (:) semicolon (;) and underscore character (_) are valid delimiters between the (fn) and (e) portions of a data table address (spaces are parsed as underscores when entering addresses).

For example: T4:0 T4;0 T4_0
are all parsed as T4:0.

Delimiters between elements and subelements

To specify subelements use a period (.) or a slash (/). The underscore character is not a valid subelement delimiter.
For example: B3:1/4 B3:1.4 B3/20
are all valid bit delimiters.

You can assign symbol names to word or bit addresses and use them instead of the addresses. For example, if SYM_1 is assigned to address N7:0, you can address bits within that word as SYM_1.11 or SYM_1/11, both would be the equivalent of N7:0/11.

Words and Bits

Certain PLC-5 data file elements are made up of multiple words. For example, Timer and Counter elements use 3 words each, where PD file elements use 82 words each. In order to address individual sub-elements or bits within these multi-word data types, you must use word or bit mnemonics. These mnemonics fall into two categories, reserved and non-reserved.

Non-reserved mnemonics can be accessed only by using the (.) period or (/) slash delimiters. For example, if the symbol PIDLOOP1 is assigned to address PD21:0, then the set point sub-element would be addressed as PIDLOOP1.SP or PIDLOOP1/SP but not as PIDLOOP_SP.

Reserved mnemonics may be delimited in the manner described above for sub-element words or bits.

There are 17 reserved sub-element and bit mnemonics:

Timer	Counter	Control
.ACC (w)	.ACC (w)	.POS (w)
.PRE (w)	.PRE (w)	.LEN (w)
.EN (b)	.CU (b)	.EN (b)
.TT (b)	.CD (b)	.EU (b)
.DN (b)	DN (b)	.DN (b)
.OV (b)	.EM (b)	
.UN (b)	.ER (b)	
.UL (b)		
.IN (b)		
.FD (b)		

2. Review of addressing modes

2.1. Terminology

Chassis

Hardware assembly—physical rack—that houses devices such as I/O modules, adapter modules, processor modules, and power supplies. Chassis are available in six sizes: 1-, 2-, 4-, 8-, 12-, and 16-slot.

Group

An I/O addressing unit consisting of one input and one output word (16 bits each) of the data table. Depending on the density of the I/O module and the addressing mode used, some of the bits in a group may be unused. The group number is included in I/O addresses in the position represented with a 'g' in the format: I:rrg/xx.

Rack

An I/O addressing unit that corresponds to eight input image table words and eight output image table words (8 groups). A rack is a logical entity not to be confused with the physical chassis. 8 groups = 1 full rack, 6 groups = ¾ rack, 4 groups = ½ rack, 2 groups = ¼ rack. The rack number is included in I/O addresses in the position represented with an "rr" in the format: I:rrg/xx.

Slot (physical)

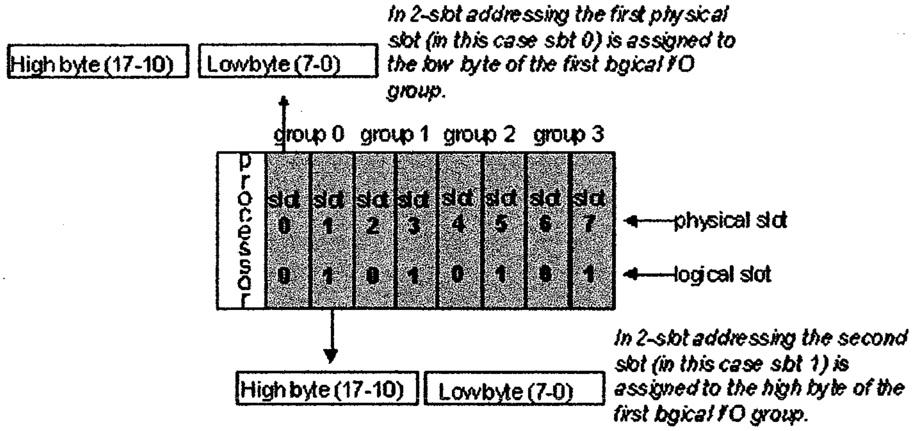
A location in a chassis for installing a module. The number of physical slots per group determines the addressing mode. For example, 2-slot addressing is used when a group contains two physical slots.

Slot (logical)

Applies only to 2-slot addressing. The logical slot is the slot number within the group as opposed to the physical slot number. In 2-slot addressing, each group contains two logical slots, slots 0 and 1 (refer to the drawing below). In all other addressing modes, the logical slot number is always zero.

Two Slot Addressing

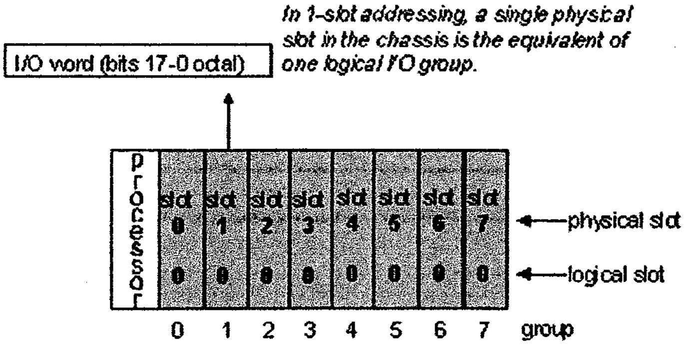
The processor addresses two physical slots as one I/O group. Each physical slot, beginning with slot 0, is sequentially mapped to one byte (8 bits) of the I/O data table. Each terminal on a discrete I/O module is assigned a bit within the byte, beginning with the least significant bit. Two-slot addressing is designed to accommodate I/O modules whose image size is one byte or less. Two-slot addressing is most straightforward with 8-point modules; 32-point modules are not allowed, and 16-point modules must be installed in complementary pairs (of input and output modules).


In 2-slot addressing the first physical slot (in this case slot 0) is assigned to the low byte of the first logical I/O group.

In 2-slot addressing the second slot (in this case slot 1) is assigned to the high byte of the first logical I/O group.

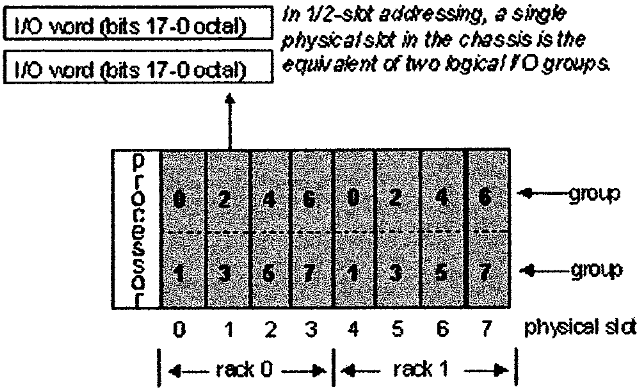
One Slot Addressing

The processor addresses one physical slot as one I/O group. Each physical slot in the chassis, beginning with slot 0, is sequentially mapped to one word (16 bits) of the I/O data table. Each terminal (I/O point) on the I/O module is assigned a bit within the word, beginning with the least significant bit. One-slot addressing is most straightforward with 16-point modules; 8-point modules do not make best use of the I/O data table, and 32-point modules must be installed in complementary pairs (of input and output modules).


In 1-slot addressing, a single physical slot in the chassis is the equivalent of one logical I/O group.

1/2-Slot Addressing

The processor addresses one half of a physical slot as one group. Each physical slot in the chassis, beginning with slot 0, is sequentially mapped to two words (32 bits) of the I/O data table. Each terminal on the I/O module is assigned a bit within the word, beginning with the least significant bit. Half-slot addressing is most straightforward with 32-point modules; 8- and 16-point modules do not make best use of the I/O data table.



APPENDIX D. EQUIPMENT RELIABILITY

1. Survey GM Rosario Paint Shop Plant Equipment Data

Survey Data: 25-aug –2002

Table D.1. GM Rosario Paint Shop Plant Equipment Data

Element Description	**Failure Rate [Failures/year]**	**Downtime per Failure [hours]**
PLC PNP transistor output 24 Vdc	0.010250	1.02
PLC Digital Input(unitary) 24Vdc	0.007038	1.02
PLC Digital Input(unitary) 110Vac	0.007423	1.02
PLC Thyristor Output(unitary) 110 Vac	0.011500	1.02
PLC CPU	0.133333	0.21
PLC CPU Control power Source	0.038000	0.75
Inductive sensor 24 Vdc water environment	0.096203	0.22
Inductive sensor 24 Vdc normal environment	0.127660	0.15
Inductive sensor 24 Vdc alkaline environment	0.316667	0.25
Inductive sensor 24 Vdc 300 ° temperature environment	0.323244	0.16
Inductive sensor 110 Vac alkaline environment	0.316667	0.25
Inductive sensor 110 Vac water environment	0.096203	0.22
Infrared sensor 110 Vca water environment	0.349899	0.14
Limit Switch	0.133333	0.20
Push button	0.004211	0.33
Encoder	0.389560	1.12
Thermal overload relay	0.050000	0.39
Low Voltage Contactor(10-100kW)	0.005932	0.32
Harmonic filter	0.005123	0.62
Variable speed drive	0.133333	1.51
Seq. Conveyor variable speed drive	0.083333	1.51

Table D.1. GM Rosario Paint Shop Plant Equipment Data(cont.)

Element Description	**Failure Rate [Failures/year]**	**Downtime per Failure [hours]**
Soft Starter 0- 50 kW	0.013927	1.96
Current transformer (Softstarter)	0.002667	0.92
Pendulum drive overload protection	0.064945	0.14
Conveyor gearmotor	0.010969	2.13
Seq. conveyor Motor thermal protection	0.005341	0.32
Motor thermal sensor (Thermistor)	0.000522	0.25
Low Voltage induction motor	0.010900	2.11
Low voltage breaker	0.003500	2.20
Maintenance disconnect	0.047619	0.25
Low Voltage Contatctor (0- 10kW)	0.005908	0.30
Fuses low Voltage 0-125 A	0.078590	0.20
Fuses low Voltage 200-600 A	0.068922	0.52
Low Voltage Contactor 600 A an above	0.005911	2.21
24 Vdc Solenoid for blocking	0.033333	1.07
Flexible wiring for lifter, distributor and elevator conveyors.	0.062485	0.97
Pendulum tension bed	0.049751	0.01
Pendulum brake	0.402576	0.48
Seq. conveyor gearmotor brake	0.157530	0.25
Pendulum mechanical drive system	0.875020	4.11
Conveyor belts – rolls	0.024360	0.25
Pneumatic system	0.050000	0.32
Belts – Rolls	0.500000	0.25
Lift Table mechanical drive system	0.028593	1.14
2 level belt Elevator mechanical transmission	0.026904	0.96
Pendulum drive overload protection	0.064945	0.14

Table D.1. GM Rosario Paint Shop Plant Equipment Data(cont.)

Element Description	**Failure Rate [Failures/year]**	**Downtime per Failure [hours]**
Conveyor gearmotor	0.010969	2.13
Seq. conveyor Motor thermal protection	0.005341	0.32
Motor thermal sensor (Thermistor)	0.000522	0.25
Low Voltage induction motor	0.010900	2.11
Low voltage breaker	0.003500	2.20
Maintenance disconnect	0.047619	0.25
Low Voltage Contactor (0- 10kW)	0.005908	0.30
Fuses low Voltage 0-125 A	0.078590	0.20
Fuses low Voltage 200-600 A	0.068922	0.52
Low Voltage Contactor 600 A an above	0.005911	2.21
24 Vdc Solenoid for blocking	0.033333	1.07
Flexible wiring for lifter, distributor and elevator conveyors.	0.062485	0.97
Pendulum tension bed	0.049751	0.01
Pendulum brake	0.402576	0.48
Seq. conveyor gearmotor brake	0.157530	0.25
Pendulum mechanical drive system	0.875020	4.11
Conveyor belts – rolls	0.024360	0.25
Pneumatic system	0.050000	0.32
Belts – Rolls	0.500000	0.25
Lift Table mechanical drive system	0.028593	1.14
2 level belt Elevator mechanical transmission	0.026904	0.96
Chain mechanical transmission oven PRB (chains-bearings -guides)	0.056400	1.93
Oven PRB Mechanical Transmission (chains-rolls)	0.048395	5.00*

Table D.1. GM Rosario Paint Shop Plant Equipment Data(cont.)

Element Description	**Failure Rate [Failures/year]**	**Downtime per Failure [hours]**
Oven Chain Mechanical Transmission (chains-bearings -guides)	0.051537	5.00*
Elevator Counterbalance Guide Wheel	0.184721	1.00
Lateral movement conveyor mechanical elements - SH (Rolls, guides, bearings)	0.113630	0.50
Fan Belt	0.013615	0.25
Fan Bearing	0.005280	0.80
Fan Shaft	0.000425	5.00*
Fan Turbine	0.000400	5.00*
On -Off Solenoid Gas Valve(110 Vac)	0.000535	0.02
Proportional control Gas Valve(110 Vac)	0.038956	0.42
Gas Pressure sensor, min or max	0.000515	0.01
Proportional control Servomotor	0.033227	1.04
Flame Safety Relay	0.023905	0.40
Termocouple Type K	0.015380	1.15
Flame detector (Ultra Violet)	0.098120	1.17
Centrifugal pump	0.016614	5.00*
On of Valve Diam:4 to 12 inches Butterfly Type	0.032462	3.46
Air differential pressure sensor	0.062500	0.25

* For these elements, the Downtime per failure is limited up to an average period up to the end of the shift, because it will be repaired in the no production shift, and then , after the scheduled end of the production shift, it will not affect the production downtime .

2. Survey GM Rosario Paint Shop Plant Logic Faults(PLC Detected) Data

Table D.2. GM Rosario Paint PLC Logic Faults

Conveyor	Logic Fault Description	Failure Rate [Failures/ year]	Downtime per Failure [hours]
PRB2	Stopper Failure	1.200000	0.10
PRB2	Pusher failure	1.951820	0.06
Pendulum	Out of Synchronism	6.194823	0.10
Pendulum	Motor Overload	0.052150	0.01
Pendulum	Skid not on Pendulum	7.894547	0.10
Pendulum	Skid Stuck between E1-E2, E2-E3 or E3-E4	3.249830	0.06
Pendulum	Skid Stuck between E19-E20, E20-E21 or E21	1.666451	0.06
Pendulum	Lubrication System	0.0653721	0.23
Pendulum	Skid on PRB3 and E16 Tripped out	12.392670	0.03
Pendulum	Air Pressure	0.0513562	0.30
PRB3	PRB3 -PRB4 Transfer	1.9174620	0.06
PRB3	Broken Belt	0.500000	0.25
PRB3	Skid Hung up on pendulum exit	12.334142	0.10
Seq. Conveyor	Time Control	6.660000	0.08
Seq. Conveyor	Motor overload	0.062491	0.14
Seq. Conveyor	Brake overload	0.529573	0.08

3. Survey GM Rosario Paint Shop Plant Power Quality Faults

Table D.3. GM Rosario Paint Shop Plant Power Quality Faults Data

Fault Description	**Failure Rate [Failures/year]**	**Repair Time [Hours]**
Utility power Source, 132 kV-----Sag	7.600000	0.20
Utility power Source, 132 kV-----Interruption 1s	4.100000	0.66
Utility power Source, 132 kV-----Interruption 1min	0.800000	1.00

4. IEEE Standard 493 –1997 Equipment Reliability Data

Table Appendix D.4. Power System Reliability Data

Element Description	**Failure Rate [Failures/year]**	**Downtime per Failure [hours]**
Low voltage molded case breaker 0 - 600 A	0.003500	2.20
Low voltage molded case breaker above 600 A	0.009600	5.00*
Low voltage busway plug-in(Fused)	0.064931	5.00*
Medium voltage breaker metalclad drawout	0.003600	5.00*
High voltage SF6 breaker	0.089984	5.00*
Disconnect switch (open)	0.002900	5.00*
Disconnect switch (enclosed)	0.006100	3.60
Switchgear bus, bare, below 600 V(x numb. circuit breaker)	0.000340	5.00*
Switchgear bus, bare, above 600 V(x numb. circuit breaker)	0.000630	5.00*
Low voltage cable in trays(1,000 feet)	0.092300	5.00*
Cable termination low voltage above ground	0.000127	3.80
Medium voltage cable In duct or conduit below ground(1,000 ft)	0.003360	5.00*
Cable termination medium voltage thermoplastic	0.004192	5.00*
3 Phase transformer rectifier	0.003600	5.00*
Transformer dry type 0-13.8 kV	0.003600	5.00*
Transformer liquid filled, above 15000 V - 2500 kVA and up	0.003200	5.00*
Bus duct all types(one circuit ft)	0.000125	5.00*
Voltage automatic regulator	0.142883	5.00*
Voltage measurement loop	0.002805	1.80

* For these elements, the Downtime per failure is limited up to an average period up to the end of the shift, because it will be repaired in the no production shift, and then , after the scheduled end of the production shift, it will not affect the production downtime .

APPENDIX E. CONVEYOR PLC PROGRAM STRUCTURE

1. General

A Conveyor PLC manage a block of conveyors, normally over fifty, and it can be operated in Manual or Automatic mode.
For each conveyor there is a file that performs the control, by calling and auxiliary file called "subroutine". The subroutine file receive the input data and produce the output data by the evaluation of logic functions. The logic equations that control the evolution of the system were implemented in the subroutine file by the method called "Petri Nets". The subroutine file is unique for conveyors of the same type controlled by a same PLC. For example , if we examine a Conveyor System that have six lifter conveyors, there will a file commanding each conveyor, in total 6 files for these 6 conveyors, but only one subroutine file that performs the logic calculations for all of them.

2. Structure

The PLC program consists generally of between 100 and 200 PLC Program Files that performs the conveyors control.

The PLC Program Files are arranged in the way shown in the Table Appendix E1.

Table E.1. PLC Program Files

Ladder number-name	Functions
2-PRINCIPAL	Call Subroutines
3-GENERAL	Restart functions Alarm Concentration(24V CPU, Remote Panels, Master Control Panels) Stop / Run Cycle Manual / Auto Cycle Human Man Interface information exchange
5-GESTION	Upload and download conditions Transitions between conveyors Initialization Conditions Path selection Time management
8-VISUAL	Information exchange between PLC CPU and Human Interface Modules
11 to 22 - MCP	Master Control Panel Auto / Manual mode Cycle Restart Emergency Conditions MCP fail management

Table Appendix E1. PLC Program Files (cont.)

Ladder number-name	Functions
31- 81 CONVEYOR FILE	Subroutine Calling Manual / Auto Cycle Fault Management Restart Protections -Security (Sensors, time, Brake, etc) - Repair breaker Manual Control(Buttons) Upload –Download Outputs control Security(For example, no double commands) MCP Lamps
102 -126 SUBROUTINES	Reading Input information(internal memories that reflects status of inputs and control variables) Processing Input information and assign values to output variables