Design and discrete event simulation of power and free handling systems

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Design and Discrete Event Simulation of Power and Free Handling Systems

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By

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This work is dedicated to my dear wife, Elizabeth, for her patience, understanding and support in its completion.

Declaration

I hereby declare that the work reported in this thesis has not been previously submitted for any degree. All material in this thesis is original, except where indicated by reference to other work.

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Abstract

Effective manufacturing systems design and implementation has become increasingly critical, with the reduction in manufacturing product lead times, and the subsequent influence on engineering projects. Tools and methodologies that can assist the design team must be both manageable and efficient to be successful. Modelling, using analytical and mathematical models, or using computer assisted simulations, are used to accomplish design objectives. This thesis will review the use of analytical and discrete event computer simulation models, applied to the design of automated power and free handling systems, using actual case studies to create and support a practical approach to design and implementation of these types of systems. The IDEF process mapping approach is used to encompass these design tools and system requirements, to recommend a generic process methodology for power and free systems design.

The case studies consisted of three actual installations within the Philips Components Ltd facility in Durham, a manufacturer of television tubes. Power and free conveyor systems at PCL have assumed increased functions from the standard conveyor systems, ranging from stock handling and buffering, to type sorting and flexible product routing. In order to meet the demands of this flexible manufacturing strategy, designing a system that can meet the production objectives is critical. Design process activities and engineering considerations for the three projects were reviewed and evaluated, to capture the generic methodologies necessary for future design success. Further, the studies were intended to identify both general and specific criteria for simulating power and free conveyor handling systems, and the ingredients necessary for successful discrete event simulation. The automated handling systems were used to prove certain aspects of building, using and analysing simulation models, in relation to their anticipated benefits, including an evaluation of the factors necessary to ensure their realisation.

While there exists a multitude of designs for power and free conveyor systems based on user requirements and proprietary equipment technology, the principles of designing and implementing a system can remain generic. Although specific technology can influence detailed design, a common, consistent approach to design activities was a proven requirement in all cases. Additionally, it was observed that no one design tool was sufficient to ensure maximum system success. A combination of both analytical and simulation methods was necessary to adequately optimise the systems studied, given unique and varying project constraints. It followed that the level of application of the two approaches was directly dependent on the initial engineering project objectives, and the ability to accurately identify system requirements.

Abbreviations

AGV	-	Automated Guided Vehicle
AMS	-	Automatic Magnetising System
CAD	-	Computer Aided Design
CIM	-	Computer Integrated Manufacturing
DBR	-	Drum-Buffer-Rope
FCS	-	Flexible Conveyor System
FMS	-	Flexible Manufacturing System
GT	-	Group Technology
IDEF	-	Integrated Computer Aided Manufacturing Design Methodology
IMT	-	Integrated Manufacturing Team
JIT	-	Just-In-Time
L-CMS	-	Linked-Cell Manufacturing System
MMI	-	Man/Machine Interface
MN	-	Mini-Neck (Product Type)
MTBF	-	Mean Time Between Failures
NCTF	-	Number of Cycles To Failure
NN	-	Narrow-Neck (Product Type)
OLE	-	Object Linking and Embedding
PCL	-	Philips Components Ltd.
PLC	-	Programmable Logic Controller
SCADA	-	Supervisory Control And Data Acquisition
WIP	-	Work In Process

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1. GENERAL INTRODUCTION AND PREVIOUS RELATED WORK

1.1 Simulation and Design of Handling Systems

Advanced manufacturing and handling systems are increasingly used to accommodate the demanding requirements of a modern production facility, particularly if the facility is manufacturing in relatively high volumes. Flexibility of the manufacturing system to handle such demands as differences in product type, changes in capacity, and the ability to absorb daily production problems, create the need to design systems that can adapt to these issues quickly and effectively. By their very nature of incorporating more flexibility and operational functions, and being controlled by both automated and manual methods, manufacturing systems contain an increase in automated equipment and logistical interactions. This increase in complexity, in turn, heightens the potential for unanticipated occurrences while in operation. These can take the form of many types of negative outcomes such as unscheduled blockages, loss in throughput, or incorrect product routing, all of which generally lead to a loss in system utilisation. It is the responsibility of the systems designer to address such problems either in the design or production stages of the system implementation.

As a result of the increase in operating functions and complex interactions, many of the manufacturing systems to be designed and analysed contain the characteristics of being stochastic (i.e., the presence of random variables) and dynamic.[1] These characteristics have placed more demand on the need for tools that can effectively capture and anticipate potential design flaws and compensate for them, preferably in the earliest stages of a project. There exists many methods for analysing manufacturing systems, of which computer simulation is one. Simulation provides the designer with the ability to test and observe the interaction between various pieces of equipment with random variables and complex interaction rules not possible with traditional analytical methods. Although, in many cases, individual pieces of equipment and their interactions can be best understood using manual analytical methods, when designing an entire system, it is difficult to visualise and understand how those individual interactions significantly affect the overall performance.

Handling systems, in particular, power and free conveyor systems, are representative of potentially complex systems, as they can contain a wealth of random events and variability. At the lowest level, they can be designed to handle products from one point to another. However, their design also includes the ability to queue, sort and route products to various destinations (similar to guided vehicle systems) or depending on equipment design, products can be processed without removing them from the system. Due to these flexible handling and queuing capabilities there can arise in their design and construction, operational issues relating to system capacity, logistics, and undesirable queuing or traffic problems, that will limit system performance if they are not fully identified, understood and eliminated. Attempting to solve design problems such as these requires an understanding of random events, and the ability to visualise operational interactions. Simulation can offer a means by which these can be captured and analysed in a relatively painless environment, in the Design Stage, rather than encountering them on the production floor.

1.2 Simulation in Industry

Simulation and modelling is already used in industry in a variety of areas such as equipment operations design, process design, logistics and supply chain management. Currently, it provides the only method that allows people to solve problems in areas where:[2]

- It is not possible to observe all necessary system activities or interactions;
- The observation needed to adequately perform the analysis of the real system is too expensive;

- Time is not available for a required analysis of the actual system;
- It is not possible to formulate a solution using traditional analytical techniques;
- Analysis would be too disruptive to the production activity.

Once the decision has been made to install an automated handling system, the primary focus for its design and implementation is on cost, efficiency and quality. Any tool that will increase design confidence for "getting it right the first time", is significant, consequently, simulation is taking an increasing role in these stages of Engineering Projects.

Philips Components Ltd (PCL), located in Durham is, in this case, no exception to industry. Over the past several years, there have been a number of automated system installations and improvements to existing manufacturing and handling systems. Simulation has been playing an increasing role in the design and optimisation of these systems. This study will focus on engineering design and Discrete Events Simulation within a production environment, and its application to Automated Power and Free Handling Systems Design, with specific examples at the Durham facility to identify successful criteria for the uses of simulation and analytical models within the design process.

1.3 Systems Modelling and Computer Simulation

1.3.1 General Modelling and Simulation

Modelling is a form of evaluation, mimicry and analysis that can take many forms but generally falls into one of two categories: physical or mathematical.[3] When a system is modelled, it is replaced by something that is, "simpler and/or easier to study, and equivalent to the original in all important respects." [1] It is building a system that is as identical to the original as possible in all relevant aspects so that given its exposure to certain kinds of external inputs or interactions between elements within itself, it can produce results that can be interpreted as though they were of the original system. Using these results, an approximation of the behaviour of the system can be analysed.

Manufacturing systems modelling is primarily concerned with capturing dynamic, time-based events, such as, processing times, product transfer rates, or routing activities, which can then be used in the determination of equipment requirements and planned operating or control rules. Although static modelling can be done manually, through the use of both physical and analytical techniques, such as, state diagrams, operational algorithms, and probability theory, these methods do not effectively capture time-based systems design problems, as discussed by Chapman (et al.).[4] Time-phase diagrams can capture time based applications, however, they are not practical for relatively large systems due to the vast amount of operations and statistical variables involved. Such complex systems modelling is thus facilitated by the aid of computer.

Computer simulation involves the use of a digital computer to input system data, calculate and display predicted outcomes. Using the computer for simulation, one can take advantage of two benefits: speed of handling many variables virtually simultaneously, and the ability to dynamically display the many component interactions that may occur. Manufacturing system simulations created and reviewed in this document are classified as dynamic (i.e., outputs are required for the system performance over time), stochastic (i.e., with the presence of random variables), and discrete (i.e., variables will change only at defined points in time).

1.3.2 Discrete Event Simulation

To model the "discrete" manufacturing systems as defined previously, a form of simulation, called Discrete Event Simulation, is identified as an appropriate tool. Discrete event simulation is used for modelling systems in which variables change only at defined, separate points in time. For example, the number of products on a conveyor changes only when one is created from a manufacturing process or scrapped when the part leaves the area concerned. The modelling is performed by identifying and capturing all relevant operating information, such as, process activities, lead times, product types, and labour/maintenance requirements, and combining them to form a working "picture" of a system and its components. These components can then be analysed using defined operating rules as the system progresses through a specified time period.

Discrete event simulations utilise numerical methods or "computational procedures" for model operations.[3] A simulated history of events is recorded and, given specific commands within the model, these events can be tabulated and manipulated depending on the objectives of the user. Therefore, these types of simulations require running with the user defined actions over distinct time periods and rely on the periodic checking of the model state for output.

1.3.3 Computer Simulation

Generic language simulation packages are specifically designed computer languages with tools for creating models, possessing the capability to conduct experimentation and report results. They are designed to make model building and analysis on the computer relatively quick and easily understandable by common terminology in the simulation definition, benefits identified by Mitrani and Thompson.[1 5] A more advanced "simulation system" as defined by Askin[6], improves user-friendliness, including supporting tools such as graphical editors, statistical analysis, and animation capabilities. Generally, these are divided into two types: advanced simulation languages and simulators. Simulation languages require the modeller to create a model by programming, using the language's internal constructs, in contrast to a simulator, which provides a more user friendly, albeit less flexible, interface requiring a limited amount of programming.

An advantage of using a simulation system is the provision for standard manufacturing object classes, such as, conveyors, machines, and buffers, including their expected state possibilities such as broken down, running, waiting, or blocked from downstream processes. Some systems provide the ability to create user-defined, generic object classes, which can substantially improve the efficiency of simulation activities. Generally, simulation systems can be used for any actual system that can be distilled into individual standard components and event states, their application within the Manufacturing arena, an appropriate one.

1.3.4 Physical and Logical Elements

Physical elements are *tangible* components of a system and can include any real part of that system. For general manufacturing handling systems, physical elements include, Parts, Buffers, Machines, Conveyors, and Labour. Logical elements represent *conceptual* aspects of a model. For example, a machine may break down with the characteristics of a Negative Exponential distribution. The distribution would be a logical element of the machine and would be used to approximate its break-down behaviour. Logical elements include, Attributes, Variables, Distributions, Files, Functions, Shift Patterns, and Reporting Functions.

1.3.5 Approximating the Real System - Actual vs. Simulated

One of the more important features of successful modelling, is identifying and translating the relevant aspects of the real system to the simulated system. In most cases, all physical components of a system can be captured under the definition of elements or "entities" within the computer simulation; components that define the system can be graphically displayed and modelled. However, in some cases, there will be elements that are significant (system behaviour is sensitive to their particular event states), but are not in the standard package offered by the software. To model these aspects, it is necessary to create an alternative method, known as *logical* modelling. Components are not modelled as the physical elements, but their relevant behaviour and approximated effect on the system is captured. Certain elements of Power and Free Handling

Systems fall in this category, in particular, elements for transporting products between system operations or the devices providing release criteria for products. These logical sequences and the resulting issues with their usage will be discussed in the subsequent case studies.

1.3.6 WITNESS

A simulation program called WITNESS has been used for all simulation activities reviewed in this thesis. It is a Windows-based, graphical, interactive simulator which enables the user to design and build a wide range of systems on the computer through the identification of generic, individual components and processes as discrete events. System dynamics can then be graphically displayed and animated to visually and statistically evaluate interactive process activities. The process of designing and building a simulation model on the WITNESS package consists of three basic steps; Define, Display, and Detail.[7]

During definition, the primary stage for model building, the names and quantities of system "elements" are identified. An element can be defined as a physical or logical, as noted above. Once defined, elements can then be displayed on the computer screen. Once the elements are displayed, their states of operation can be viewed while the model is operating or "running". The animation is especially necessary for those elements or subsystems that might require dynamic observation of operating conditions and event states, such as a machine running unimpeded or being blocked, for potential problem analysis. Once displayed in the appropriate layout, elements require detail, or rules which control element interaction and operation within the system. Defining, Displaying and Detailing are all simulation activities resulting from a customer requirement. Identification of a methodology to organise these activities is a fundamental step in successful simulation, and is addressed in subsequent chapters.

1.4 Automated Handling Systems Design

1.4.1 Common Issues in Automated Handling Systems Design

A general system is defined as, "a group of objects that are joined together in some regular interaction or interdependence toward the accomplishment of some purpose." [3] Systems are usually described as being discrete or continuous. Discrete systems have been described previously. Continuous systems are those systems in which the states of the components within the system can change continuously over time, for example, the flow of chemicals in a pipe. Most manufacturing systems, in particular automated handling systems, can be approximated as discrete systems.

General requirements for automated systems design as with any system design include:[4]

- Functional Requirements (e.g., product types, process speeds, etc.).
- Technology Requirements (e.g., equipment available, capable, and acceptable to the Customer).
- Performance Requirements (e.g., measures for the success of the functional aspects of the system).
- Resource Utilisation Requirements (i.e., how well the equipment is specified and used).
- Testing/Commissioning Requirements or accurate operation, such as control functions, interactions with other machines, and with the human element.

Automated systems can be both large and complex, being defined characteristically with a substantial number of functional requirements, not necessarily being satisfied simultaneously, as researched by Suh.[8] Power and free systems can be complex as they can contain a number of operational requirements, such as routing and sorting, that do not necessarily occur in a fixed routine or sequence. Two systems addressed in this study are classified as complex. Even though they contain a large number of components and span great distances, it is the operation and characteristics of the functional requirements which make them complex. Further, due to the flexibility of power and free systems, the system range or the number of possible states the solution can provide to satisfy customer requirements is large, having an incremental effect on the design range or the number of functional requirements. This creates potentially complex systems or a potential for complex systems design, which require effective and communicative tools to produce an efficient design.

1.4.2 Automated Power and Free Conveyor Systems

A power and free conveyor system is an automated handling system that transports products on a fixed track in which the products can either be moving or stopped, while the main transport media, usually a linked chain, is continuously moving. Examples used in the case studies include overhead power and free conveyor systems with hanging carriers that can be "latched", under *power* of the main driving chain, or "delatched", *free* from the powered movement. Although there are many different kinds of power and free systems in industry, the common components include:

- Devices to stop (delatch) and hold a product for processing or routing.
- Track creating routes on which the products will be transported.
- Products being held on some sort of carrying device or frame.
- Switching points or areas where products coming from different areas can be routed.
- Interfacing manufacturing processes that utilise or alter the product being carried.

Due to the added flexibility over a traditional indexing conveyor, the function of a power and free system is to transport products between processes *in the desired sequence and at the precise time they are required.* Where a traditional conveyor would need the sorting, sequencing and variable delivery controlled either by manual or alternative automated methods, the power and free system contains all of these functions within the system.

1.4.3 Design Considerations - the Use of Systematic Approaches

What are the critical success factors when designing and installing a power and free system? A useful method of identification and definition of these factors has been idenitified and used for the design process at PCL Durham, which is based on the Integrated Computer Aided Manufacturing Definition Methodology ($IDEF_0$)[9] diagram, the format of which is shown in figure 1.

With links to the more general Structured Analysis and Design Technique (S.A.D.T.), IDEF is a graphic method, traditionally used for analysing manufacturing systems, however, its use in the design stages of projects has been the subject of much investigation in recent years.[10] [11] The methodology is a form of structured analysis by "decomposing" a process into its related elements and graphically displaying them to facilitate communication and potential improvements. This method of "manufacturing enterprise modelling" was introduced as a technique for modelling systems incorporating hardware, software and people for functional performance.[12] The structure contains several characteristics which make it desirable for modelling the power and free systems design, as identified by Ang and Mandel.[13] [14] Further, the methodology has been used to illustrate improvement opportunities for concurrent project engineering design, similar to the concurrent engineering product design as has been the subject of similar studies.[15] [16] Ideally, the concurrent engineering technique is intended to improve the understanding of the processes used in manufacturing systems to reduce the time taken for their implementation. This document will not attempt to improve on the existing design process, but rather identify and pull together the set of existing, albeit fragmented, tools for manufacturing systems design already in place at Philips; a process definition tool (added to project planning tools, graphical layout tools, and the discrete event simulation tool) into a systematic approach to Power and Free Systems Design.

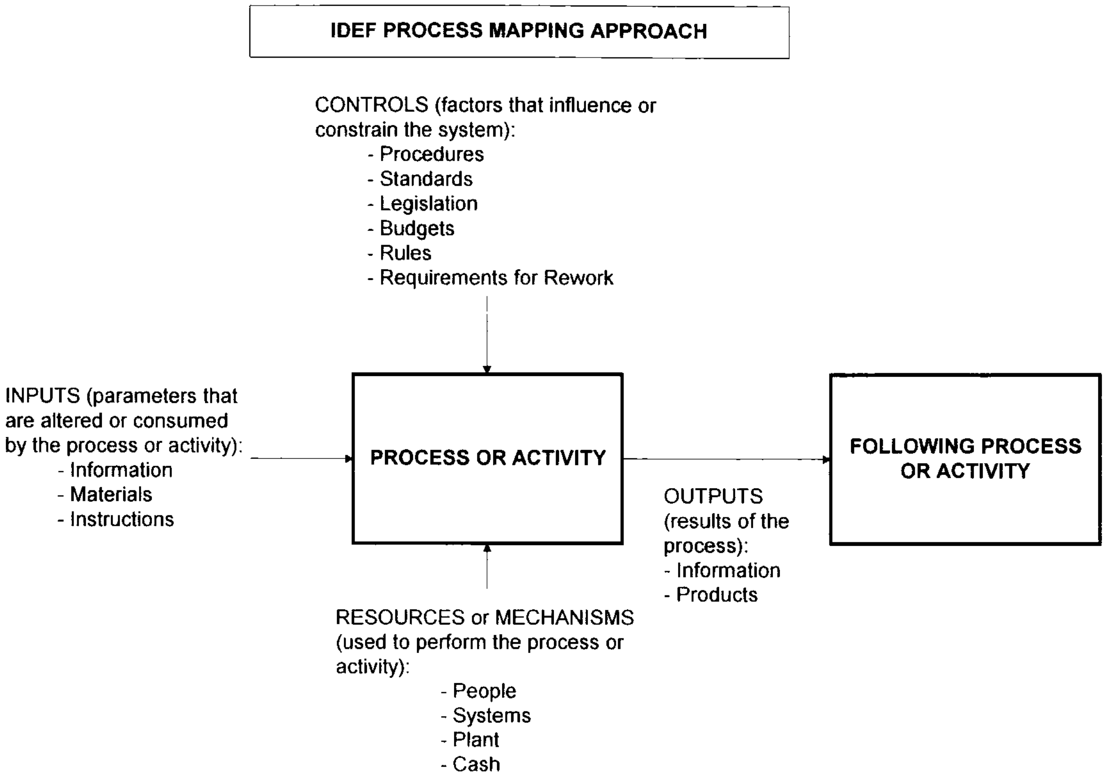


Figure 1. IDEF Process Mapping Methodology

Using this approach, both the design factors unique to the particular organization and design criteria required for general design of power and free systems can be identified and recognised, in order to facilitate the design process and improve its cost-effectiveness by making it more efficient. This can form the basis for a more generic approach in the future for quickly creating IDEF models of other engineering systems, which has been the topic of recent research.[17] It is the purpose of the defined process to assist with questions that can arise during the design stage, for example:

1. Should the system contain buffers and what would be their ideal size?
2. How can the equipment utilisation be improved and affect criteria for the total system?
3. What is the required throughput for the handling system alone?

The process and general design criteria, of which simulation is a part, for implementing a power and free system will be discussed in subsequent chapters.

Further, there has been investigation in the use of IDEF techniques applied to the design of relatively large systems and simulation projects.[18] [19] Conveyor systems, as designed at PCL, fit within the category of the production systems reviewed, particularly by Wu, in studies that recommend a combined analytical and simulation approach to successful design. Research has shown an effective link from analysing the system using functional techniques to effectively creating analytical models or computer simulation models.[20] The case studies to be discussed were conducted to identify an effective methodology, combining the recent findings, for future use at PCL.

1.4.4 Time-Based Events and Randomness - The Detailed Operational Levels

The $IDEF_0$ tool allows the designer to begin at a relatively abstract level of systems definition to the operational aspects of the system. However, its format is not well suited to the issues required for simulation of the system, namely, time-based events and randomness in system operations and components. Random events in power and free conveyor operations include:

- Pusher dogs - used to transport carriers in the system.
- Certain "automated" interface processes - the availability of a carrier when required.
- Manual interface processes.
- Carrier flow in various areas of the system (depends on layout and production schedules).
- Operator intervention for routing carriers (off-line stock building/loading).

Alternative design tools are required to facilitate the link from systems design to simulation model design.

1.4.5 Man/Machine Interface - "Human Centred" Design

A common question in manufacturing systems design is whether or not to automate and then given the decision to automate, how comprehensive the automation should be. Designing a system that increases integration of the operator, one that is automatically controlled in certain modes, but whose modes can be determined by the operator, can have distinct advantages, particularly in design time reduction, ownership, system utilisation via complexity reduction, and overall quality of the system performance. The dual approach with emphasis on the user, supports recent studies into the implementation of "anthropocentric" manufacturing systems, or designs that aim to effectively incorporate human and technical aspects of the system; a "human centred" approach. [21] [22] By providing increased control to the operator and improving the man/machine interface, the goal of this approach is to increase operational flexibility, system robustness, productivity, and skill levels.

When the automated system is relatively complex, significance should be placed on the users' information requirements. If emphasis is placed on the functional only, such as providing information only to serve the primary objective of the system, opportunities will be missed to improve upon the system utilisation and intended design efficiency. If too much information is provided, it can adversely influence system performance, as the correct information will not be there when needed. In the case of the first two power and free systems installed, required demands on the system for functionality and flexibility were so great that it was decided to design the system with the operator as the primary controller of the system logistics. Thus, the system would run automatically in many different modes, but the operator could control these modes. In order to perform the function effectively, the immediate interface between the operator and the system control had to be as transparent as possible, still containing the necessary information to handle complex activities, requirements for a "usable system", as discussed by Genter and Grundin.[23]

1.4.6 Use of Push/Pull Methodologies

A goal of every manufacturing systems design is to improve or optimise the system utilisation; the amount of time the system operations are available for production requirements. As the equipment and people interactions increase in a system, so does the potential for lower performance. Therefore, reducing the complexity or the amount of interactions for a system should be one of the goals for improving the overall performance. Studies have been carried out to evaluate the performance of using a push/pull type philosophy in which the push policy is used at the initial stages of the process, with the pull policy being used in latter stages.[24] From these studies, it has been shown that a combination push/pull strategy for manufacturing systems produced improved results in inventory levels and shortages, in comparison to either a push or pull strategy alone. This approach to design was recognised and applied to a subsequent installation, the results of which will be discussed in the 225/226 System Case Study.

Design of the system must take into account the third law of manufacturing systems as identified by Askin in order to improve the system performance.[6] Increased reliability can come about by separating key processes to improve overall performance; introduction of a mechanism to reduce interdependency increases the probable system uptime for local areas. Manufacturing cells were designed to reduce the complexity and improve uptime and it has been shown that use of a "decoupler" (the name given to the mechanism) in manufacturing systems has been utilised to break dependencies in critical processes.[25] Design of power and free systems should use this complexity reduction philosophy and apply its advantages to the flexible conveyor systems.

Further, a power and free system that contains many manual workstations attached to the system can have the characteristics of an unpaced line[6] in which case, buffers and their location and size need to be considered and incorporated. Without such consideration, the system might contain internal blockages that could affect overall system performance. Reservoirs that are undersized will inhibit line performance in a local area, that could eventually spread to the remaining system operations.

1.5 Simulation in an Industrial Environment

1.5.1 Successful Simulation Project Methodology

It is generally accepted that simulation can provide many benefits to systems design. Within the industrial environment, however, it is important that focus and communication of purpose is maintained, in order to realise these benefits. Traditionally established steps to most simulation studies include the following activities:[3 26 27 28]

1. Formulate the problem or area of study.
2. Set *(and agree)* objectives and overall project plan.
3. Collect data.
4. Build the model.
5. Verify coding and validate operations.
6. Design and perform experiments.
7. Document and report results.
8. Implement findings.

Practically, while these are presented in a sequential format, the activities will not run in that manner, although, meeting certain criteria is essential for each stage in order to progress. During the simulation activities, a need for a visual, generic methodology, adaptive to design of engineering systems was recognised.

1.5.2 Generally Accepted Benefits

Standard tangible and intangible benefits for using simulation include, risk reduction, minimisation of project equipment costs, increased understanding of system components, operating cost reduction, increased understanding of component or process interactions (system dynamics)[29], and improved system acceptance and ownership when used as a dynamic training tool. The research also explored specific potential benefits such as:

- The ability to prototype during the Design Stages of a Manufacturing Systems Project - an activity usually reserved for Product Design or for the latter stages of Build Stage of a manufacturing systems project, if sufficient time and money is available.
- Maintaining design validity throughout the Project Lifecycle.

1.5.3 Apparent Limitations and Possible Pitfalls

When implementing simulation for manufacturing systems design, and more specifically when using simulators, limitations exist, which need to be considered or at least recognised. In general, these could include:

- Specific training being required on both modelling and the use of the specific packages.
- Development time can be quite lengthy.
- It is used when more traditional methods would be adequate.[3]
- Errors can be made in translating actual operating rules of the system to the simulation logic.

Investigation in the area of simulation reveals two requirements for success: adequate knowledge and sufficient time.[30] Adequate knowledge refers to relevant familiarisation with statistics, experimental design, logic, and more practically, the manufacturing process being simulated. Once these have been attained, it is necessary to use each one of these requirements to the correct level of significance to complete the original objectives. Sufficient time refers to the allowance for proper data collection, and experimental runs, again to the level of detail the project requires.

Translating actual operating logic of the system to the simulation is of particular interest when modelling power and free systems. It is the assumptions used when building a model (particularly of a new system) that go into validation of the model, and capturing them incorrectly can cause many of the problems associated with confidence and subsequent success in the model build. Further, if the objectives of the simulation are not clearly identified, the detail that goes into building the model could be greater than necessary, thus lengthening the design and build time with limited benefit. It is important to recognise the causes of these problems and be clear on methods to avoid them. While efficiency and effectiveness are requirements for success of simulation applications in industry,[6] an effective simulation, one that is used to reveal critical factors in the actual system, modified to show improvements in those critical factors, and tempered against real world issues not captured in the simulation to find a very good but not necessarily the most optimal solution, will be the most favourable and practical application of simulation in industry.

1.5.4 Project Influences on Simulation Building - The Need for Objectives

Due to the fact that building and analysing a simulation model could be a potentially time consuming activity, identification of the project objectives prior to any further activities is critical. For example, graphically showing an operator dynamically carrying out activities on a model may not be necessary if the objective is to focus on numerical analysis of system throughput. Therefore, from the formulation of the project objectives, the guidelines on the level of model detail can be derived. Typical objectives for simulating a manufacturing system include:

- To determine optimum operating rules (an optimisation tool).
- To determine optimum manning levels (an optimisation tool).
- To identify capacities of individual components or process areas (a results tool).
- To determine the configuration of facilities/operations (a results tool).
- To identify areas for contingency planning (an interactive tool).
- To determine optimum storage or buffering requirements (an optimisation tool).[31]
- To use as a training tool (an interactive tool).
- To test the effects of policy changes (an interactive tool).
- To determine daily production parameters (an on-line troubleshooting tool).

While primarily a tool to address the design and operations of a system, most of the objectives, as they have applied to systems at PCL, assumed various meanings depending on the level of detail required, consequently it was important to identify the context.

1.5.5 Validation

To ensure the accuracy of experimental results from the model, there must exist a certain level of confidence that those results would match results of the real system. Validating the model could assume varied meanings depending on the objectives of the model, as will be illustrated in the individual case studies. In all cases, it is an iterative process[3] of comparing the model results to the existing measures of the actual or proposed system until an accepted level of accuracy is reached. A difficult challenge in simulation is validating a model of a proposed system for which there are no existing measures.

On a more general level, validation is an activity to be considered at every stage of a simulation project, in contrast to the methodology described previously. Alternative methodologies (based on the spiralling software development process) have been investigated that incorporate validation into a phased approach, aimed at improving the overall communication and acceptance of the simulation study more effectively.[32] Consequently, validation should not seen as a "step" in a process, but rather an underlying requirement at every stage. This is true in the actual design of a system, as well as simulation. Potential problems made at the intermediate stages of design might not necessarily be rectifiable at the detail levels as proposed by Suh[8], therefore, every stage should include validation.

1.5.6 IDEF for the Simulation Modelling Process

The previously mentioned modelling requirements and associated issues require a common format from which to base project activities. To assist, the IDEF tool was applied to simulation activities of power and free systems, due to the fact that simulation requires good communication, as well as the correct results. IDEF, being a communication and analysis tool, was expected to capture the benefits of both traditional and alternative simulation methodologies, and complement those for actual system design. The use of IDEF models has been investigated, historically, to improve the performance of model building, particularly in the areas of specification and validation.[33] They have also been integrated into a overall structure to support modelling and simulation on several levels to improve implementation of a factory-wide design as well as detailed system design.[34 35] However, these approaches must also incorporate other tools that capture the dynamic behaviour, in order to be successful in the context of the detailed process and modelling package used; no one process/methodology is best for all cases. On a detailed simulation level, complementing techniques such as decision flowcharts, event mapping[36], activity cycles and Petri-net design[37 38 39] may be necessary.[10]

Using these concepts, a methodology for simulation on three levels at PCL Durham for power and free system design, including, Factory Level, Overall System Level, and Detailed System Level, was devised to improve the current process. The underlying objective was to use simulation and the IDEF models of the power and free design process to span the communication gaps and thus avoid some of the pitfalls associated with simulation and system design. It was noted that problems could arise if logistics design of the intended system and its control design are not synchronised, the results of which have been reviewed by Koonge.[15] Thus, integrating and sharing information relevant to the various activities in the Design Stage would be necessary for effective design and efficient use of resources.

1.5.7 Simulation Influences and Applications in the Design Process

Clearly identifying the role of simulation and its expectations within the design stage is important to its effectiveness. Because the design process requires the ability to test and evaluate many options, simulation is an obvious choice if used effectively. The ability to generate accurate models quickly relies on a base of knowledge for the system under investigation. Identifying common aspects between models and formulating a modular approach to reduce the design time and improve customer validation has been the subject of past studies.[40 41 31] It has been shown that the functions of conceptual model development,[42] translation of the concept to a simulation model, data analysis and experimental design can be improved by generic, pre-determined methods. Specific simulation models can then be quickly constructed by modifying the generic models, provide guidelines on experimental design and analysis requirements, and aid in conceptual model development, thus reducing the time and effort.[43] While it was not the intention of this study to identify comprehensive generic user models for all handling systems, it was intended to work within the essence of the Group Technology (GT) scheme to gain as many of its proposed benefits as possible. Simulators, and in particular, WITNESS facilitates the GT philosophy, inherently, by its use of generic descriptions for manufacturing entities, however, its current interface does require specific training, a quality that the pure GT approach attempts to reduce or eliminate.

Previous research has also been done to bring simulation to the next level of integration in the design process and work in, or close to, an actual control environment.[44 45 46] Using the general concept of simulating the Programmable Logic Controller (PLC) code structure for operating rules, an opportunity exists for reducing design and implementation activities. Historically, these simulations have been created with general purpose software, such as Pascal or C, due to their flexibility in comparison with simulators. While it would be impractical to use a simulator such as WITNESS to mimic a PLC and the intricacies of system component operation, such as, sensor performance (impossible to simulate a multi-tasking PLC controlling a power and free conveyor system due to the source programming configuration of WITNESS), it can be used to a level of detail that can capture logic rules that will eventually be incorporated into the system controller. General design of simulation models with this structure have been reviewed and demonstrated successfully by Fuh (et al.).[47] However, the effectiveness at this level is limited due to the fact that true robustness of a control system is based on all aspects of the control which cannot be simulated practically using WITNESS; e.g., system safeties, and interfacing emergency occurrences within the system.

Further, when designing a manufacturing system, it is important to obtain the acceptance of the end "users" or customers. It has been shown that an effective way to illustrate the operation of new concepts or systems is through simulation.[48] The ability to illustrate the results of certain operator actions on the system before it is installed benefits both the design and the implementation. The approach introduces and facilitates a basic, often neglected, part of systems design - participation of the end user as a key to system success, a concept illustrated in the case studies.

1.5.8 Simulation Influences and Applications in the Production Process

The front end interface on a simulation model can be set up for three distinct types of people:

1. Simulation model expert with knowledge of the simulator language.
2. A general computer user with no in-depth knowledge of the simulator.
3. A user unfamiliar with a computer interface, but familiar with systems operation.

Depending upon how the user interface of the model is configured, there exists the potential to use the model on a daily basis to evaluate either current or immediately planned production schedules, and integrate the results into production operations.[44 49 50 51] For success, it is important that the simulation results and the data manipulation requirements are considered by effectively identifying the needs of the end user prior to model build. Typically, within an industrial environment, the users are not trained in simulation. To train them in the simulation language would be an inefficient use of resources. However, extensive training might not be necessary if the model interface is configured appropriately. The criteria for capturing this benefit from the model become directly dependent on production activities and objectives, all of which affect reporting and outputs, which were explored in the case studies.

As mentioned above, although it can support certain data interfaces, such as spreadsheet/database information, and built-in menu interfaces, it is not practical to connect WITNESS to a multi-tasking control system. However, it can be used off-line with similar results, using the existing data links, if the scheduling dynamics and processing uncertainties in the system occur at rates that allow minimum response delays. In this case, the production engineer performs the duties of the data manipulator and interpreter.

1.6 Research Objectives

Based on practical and theoretical areas reviewed, the objectives of this research were twofold:

- To explore the science and requirements of manufacturing systems design and simulation of automated handling systems using analytical techniques and the WITNESS simulator for three actual engineering design projects in an industrial environment, to identify the practical uses and potential misuses of simulation for future industrial applications.
- To examine, in detail, the design of power and free conveyor systems and the role simulation plays in their design process, in order to identify both general and specific design criteria when undertaking the implementation of such a system.

The goal of the design and simulation studies was to identify common design models that could be used repeatedly to solve future design requirements or problems with existing power and free systems. Several areas required investigation to accomplish this goal:

1. A method of communicating the basic components and functions of power and free systems needed to be identified and presented.
2. Power and free systems design and simulation required dissection into its core constituents on as many levels as is necessary (keeping to a GT approach at all times), with the objectives and benefits of each of these levels identified.
3. A method of communicating the basic simulation models with their generic criteria required development and implementation. The case studies were used to illustrate these generic components as well as create guidelines for the use of simulation; i.e., the appropriate level of detail.

2. INDUSTRIAL BACKGROUND

2.1 Philips Factory Design

2.1.1 Manufacturing Process and Product Structure

Philips Components Ltd (PCL) located in Durham, UK is a manufacturer of high quality colour picture tubes for supply to external television set makers. Primary components for the television tubes include:

1. **Glass Screen** - front face of the tube, on which the reflective coatings (e.g., phosphor, aluminium, graphite, etc.). are applied.
2. **Shadow** Mask - thin metallic sheet containing small holes through which the electrons are directed to the back screen face.
3. **Inner Cone** - thin metallic cone-shaped piece used to shield the electron beam from stray magnetic fields.
4. **Glass Cone** - back section of the tube used to house the electron guns.
5. **Electron Guns** - used to project electrons onto the screen face, exciting the phosphor.
6. **Deflection Coil** - used to ensure uniform application of the electron beams onto the screen face and thus, the phosphor.

The product is relatively mature, and the facility is primarily configured for high volume, continuous manufacturing, as illustrated in figure 2.

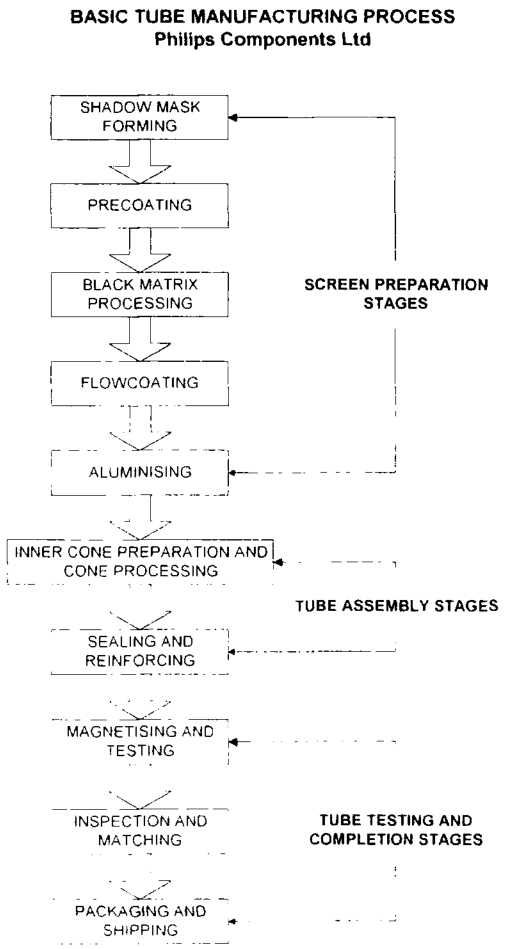


Figure 2. Tube Manufacturing Process

While there is not a definitive line structure for manufacturing process flow at PCL, as the illustration might indicate, it shows the general requirements for tube manufacture, relevant to the study. The areas of study included the Black Matrix/Flowcoating areas and the Magnetising/Testing areas. Each of the stages indicated on the above chart corresponds to areas of the factory called Integrated Manufacturing Teams (denoted as IMTx). IMT1 is designated for the screen preparation stages, IMT2 for the tube assembly stages, and IMT3 for the tube testing and completion stages. The television tube manufacturing process is a multi-disciplinary one, requiring knowledge in mechanical, chemical, thermal and electrical processes at various stages of production. The basic television tube products manufactured are identified in Table 1.

Table 1. General Television Tubes Tupes Produced.

Tube Type	Description
51FS 90° NN	51 cm Flat Screen (standard) type with narrow cone neck
51FS MN	51 cm Flat Screen (standard) type with mini cone neck
51FS 110°	51 cm Flat Screen with 110° deflection of electron placement
51FS STD BM	51 cm Flat Screen Black Matrix (standard) type
51FS H End BM	51 cm Flat Screen Black Matrix (high end specification) type
51FS CC BM	51 cm Flat Screen Black Matrix (coma corrected) type
51FS Meres BM	51 cm Flat Screen Black Matrix (medium resolution computer) type
41 FS	41 cm Flat Screen (standard) type

Within each of the tube types, the screen contains one of two light transmission rates, 41% or 52%, with the exception of the CC or coma corrected type which contains 41% only.

2.1.2 Operating/Manufacturing Philosophy

Many of the manufacturing processes indicated above require equipment set-up and changeover between the different product types, which is costly and time consuming. Therefore, as much of the equipment as possible, within each IMT, is configured on an in-line process principle with each line being dedicated for specific product types only. Strategically, the plant runs on a Just-In-Time (JIT) materials management philosophy with incoming materials, regardless of the location in the factory, kept at a minimum depending on the delivery capabilities and robustness of the overall process. The following manufacturing rules apply for each of the IMT's:[52]

- Maximum of two screen sizes allowed simultaneously per processing line.
- Maximum of four screen sub-types (e.g., light transmission rates) or size allowed per processing line at one time.
- Volume of product for changeover is dependent on process line capacity.
- Sub-types are changed over in single process line steps, due to limited resources.
- Target batch size is one week of production or the most cost-effective batch size.

Production is normally run continuously, 24 hours per day, seven days per week, with availability for equipment maintenance scheduled in two week intervals, "maintenance windows", for approximately 10 - 12 hours per window. This requires the equipment and overall production systems to be relatively flexible and robust.

2.1.3 Managing the Bottlenecks

As in any production environment, it is necessary to identify and adopt an effective policy for dealing with the overall process bottleneck as well as local bottlenecks. A bottleneck is defined as the process that has the highest cycle time in comparison to available time.[53] General rules for managing bottlenecks include:

1. Guarantee availability of products to the bottleneck.
2. Guarantee availability of capacity after the bottleneck.
3. Limit the amount of products into the bottleneck to what the bottleneck can accommodate.

In order to effectively accomplish the above requirements, the use of "Drum-Buffer-Rope" (DBR) methods are usually employed when possible,[54] requiring systems that produce accurate information for control and prediction of product flow surrounding the bottleneck. Past studies utilising simulation have shown the DBR approach to be an effective tool minimising WIP, and improving general system management.[55 56] At the time of the studies at PCL, the Flowcoat and the Testing/Magnetising processes were the bottlenecks, or "capacity constrained resources", of the process. Discussion in each of the case studies will include how these factors and the nature of the handling systems affected both the project objectives and the system design.

2.1.4 Automation Investment Philosophy - Critical Success Factors

Investment in process and handling equipment is the majority of the total capital asset investment within PCL, therefore, improvement of asset utilisation within the company is focused on cost-effective design in the use of manufacturing systems. Critical factors noted for successful investment in equipment automation include:[57]

- Improvements to the performance or direct product yield of the bottleneck process.
- Improvements to layout, i.e., production capability per m^2 for new or additional equipment.
- Improvements to existing equipment performance by means of adding spare capacity for strategic maintenance, preparation (set-up) and calibration (maintenance of quality systems).
- Improvements in standardisation, including equipment and operating philosophies.
- Improvements in standardisation of engineering design methodologies.

The mature nature of the product manufactured at PCL, of relatively high sales volume and lowering market prices, allows for manufacturing systems with relatively distinct lines for product types (with limited type/volume flexibility), requiring maximised throughput and high equipment performance, thus implying increased mechanisation. This is in contrast to a production environment of low sales volume and higher market prices which favour manufacturing systems that have high type/volume flexibility, accepting lower throughput and equipment performance, implying decreased mechanisation.[58]

2.2 Automation Design at PCL and the Economy of Power and Free Systems

2.2.1 Use of "Pull" Manufacturing Techniques and Conveyors for In-Line Processes

Achieving a cost effective equipment operating structure, makes it necessary to construct production systems that are linked together with pull type systems for the control of both products and information. This is in agreement with a "linked-cell manufacturing system" (L-CMS) as detailed by J.T. Black in several studies.[59] The pull type system, as defined by Black, is one in which products flow to downstream processes, while information or production criteria flow to previous, upstream processes, to manage inventory, production or quality control. The use of conveyor systems, either embedded within a flexible manufacturing system (FMS) or installed to handle products between processes over large distances, can be configured to handle these pull system requirements, and the DBR requirements mentioned previously, transparently within its control structure.

Standard indexing and power and free conveyors play an important role in fulfilling the above mentioned objectives for production operations and investment in automation. For example, conveyors automate the handling process, reducing the need for manual intervention, thus improving product quality. Storage of work in process for strategic management or unforeseen production problems can be done on-line, thus eliminating the need to add extensive storage areas in the facilities layout. They allow the entire tube manufacturing process to be as continuous as possible. However, power and free systems have an advantage over the traditional indexing conveyors, due to their mechanical design and improved control capabilities. They can inherently minimise the amount of products between process points, minimising overall system inventory; objectives of an L-CMS. Further, they improve the layout by eliminating the need for products spaced evenly at fixed pitches through the line, facilitating other auxiliary functions of production, such as, miscellaneous material movement or equipment access.[60]

2.2.2 Flexible Manufacturing Systems - Closed-Loop Processes

The term "closed-loop" process is used to describe a power and free conveyor system that is contained within an FMS having relatively limited and discrete boundaries and little or no human intervention. Even though strict definitions for FMS include high part variety and low volume[61], they can also accommodate relatively high volume, particularly if configured with other conveyor systems. While the function of a power and free system within an FMS is similar to any other conveyor system, influencing factors to consider with these types of systems for design and simulation can be different. For example, in FMS design, optimising product throughput and equipment utilisation by testing placement of conveyor track and control logic can take precedence over other factors of design; a more self-contained approach. Further, buffer zones within the system are of less importance, as equipment cycle times are usually relatively balanced.

2.2.3 Flexible Conveyor Systems - Linking Functions with Open-Loop Processes

The term "linking" is used in this thesis to describe the function of handling products from one distinct manufacturing process to another. These functions are traditionally handled by standard indexing conveyors, either with unidirectional flow as is the case with belt type conveyors or with utilising a loop with a return leg containing empty carriers. However, depending on the requirements of the next process, the linking operation can assume more complicated functionality, not quite becoming a true flexible manufacturing system but taking on much of the characteristics of an FMS, thus the terminology: flexible conveyor system (FCS). The additional functionality could include:

- Flexible sorting.
- Buffering.
- On-Line mechanisation of product inspection.
- On-Line product preparation (e.g., thermal, mechanical or electrical).
- Dynamic routing of rejects back into the process.

Consequently, "open" is used to describe the functions of a conveyor system requiring variable flow of product, not simply unidirectional from one process to the next. It is the need for these alternate functions that push the design of automating the linking functions towards more complicated conveyor designs and more specifically, power and free handling systems.

If a manufacturing process requires a specific pattern of product type in order to continuously utilise the available equipment, sorting, an activity that arranges the products in the correct sequence for processing, is used. Randomness and variable flow rates of product type delivery from the previous process could create the need to either sort manually or automatically, and a combination of the two may be necessary.

Buffering or storing a queue of product prior to the next manufacturing process reduces the dependence between two processes in sequence and can be a requirement due to several factors. Identified buffer types include Flow, for unplanned events, Time, for fixed process operational differences, Drain, for start-up and shutdown operations, Synchronous, for equipment operational differences, and Patterning, for effectively sorting product types.[62] Specific requirements for the systems within the study included:

- Randomness in product delivery rates due to product rejects.
- Unplanned downtime of the previous manufacturing process.
- Planned downtime or set-up time for equipment in the previous manufacturing process.
- Non-synchronous operation of interfacing processes or equipment.
- Product type changeover.

Generally, buffers are used to effectively manage bottleneck processes (whether they are internal to a process or plant-wide). Buffers, as they are defined and used at PCL, are generally organised into two categories: Dynamic and Temporary.[63]

A *dynamic buffer* is one that is planned to be constantly filled, with the quantity depending upon the product yield performance and equipment uptime of the enveloping processes. In general terms, these types of buffers should be sized to accommodate the average downtime of the worst performing process, taking into account the ability to also accommodate the worst anticipated gap in product flow due to a bad yield. A *temporary buffer* is one that is normally run empty ("normal" being defined as greater than 70% of the available production time) and is used to accommodate an unplanned stoppage of the following process. This is required, due to the fact that some tube manufacturing processes involve continuous "batch" production in process equipment lines which, if stopped, could cause an entire batch or line to be scrapped.

The location of a buffer is based on the following criteria:

1. Before and after a local or general bottleneck to ensure that the bottleneck will not be starved or blocked should it produce ahead of the surrounding processes on certain occasions.
2. Prior to every critical or costly process, consistent with variations in equipment performance and product quality.

Design and application of buffers has been shown to be illustrated as a Markov chain problem, which will be reviewed in the next chapter under the subject of analytical modelling.[6] Design of buffers on the power and free systems between reservoirs of random processing times (manual workstations), as mentioned in previous sections, is a type of synchronous buffer, which takes on multiple characteristics of both dynamic and temporary buffers. Reservoirs within a power and free conveyor system can represent several different queuing characteristics. For example, a reservoir containing a process of a robot loading product will have a more constant cycle time (most times, indistinguishable for design purposes), thus assuming the characteristics of a M/D/1/N or (as contingency design would require a second carrier behind the first, ready for processing), a D/D/1/N queuing model (using Kendall notation).[64] In contrast, a reservoir containing a manual process could have a wider variation of servicing time, particularly if the operator is responsible for other indirect functions, assuming the characteristics of a M/M/1/N or D/M/1/N queuing model. It is the combination of these queuing states on the same system that challenge the designer.

2.2.4 The History and Strategy of Simulation at PCL

Due to the costly nature of simulation packages and projects, and lack of sufficient resource, PCL has chosen a "vendor-aligned" approach[65], using outside consultancy to write and analyse simulation models, for the majority of their manufacturing system modelling requirements, using a simulator called WITNESS. Using WITNESS also creates a standard communication tool within the facility for simulation studies. Historically, however, the application of WITNESS at PCL Durham has had mixed success. This was due in part to factors, such as:

- Model design and build times were too long.
- Simulation time was too long to efficiently observe and analyse results.

- Modelers were outside consultants, trained in the use of the simulation package, but not in manufacturing systems design, consequently a "link" between the two was effectively missing.

Further, the design of the model logic in comparison to the actual logic was too great, i.e., too many characteristics of the actual system were deemed necessary to go into the model, thus lengthening the process. Therefore, designing a model build technique or models of specific equipment types that are generic enough to make the model building process as efficient as possible, and implementing standards for future model build, were perceived critical for improvement of WITNESS applications.

2.3 Black Matrix To Flowcoat - Screen Preparation

The Black Matrix process takes place within the screen preparation stages of tube production. During matrix production, screens are coated with a black graphite layer in inverse pattern to the phosphor coatings that will be applied in the following process, called Flowcoat. Its primary function is to reduce glare on the screen and improve picture contrast. Between Black Matrix and Flowcoat, a power and free conveyor system is used for product routing and other functions described under the Handling Process Section. Simulations have been used to analyse the operations of the power and free conveyor in detail, and have not focused specifically on Matrix or Flowcoat, due to the objectives of the modelling. These will be discussed in detail under the appropriate sections.

2.3.1 Products Handled

Products handled by the power and free systems include screens and masks, as illustrated in figure 3. Once in a finished tube, the mask will sit on location pins within the screen, directing electron flow. While the system is designed to handle several type variations, currently it is only handling product sub-types within the same size range of 51 cm. Note, "sub-types" refer to the variations within the same size range as identified previously.

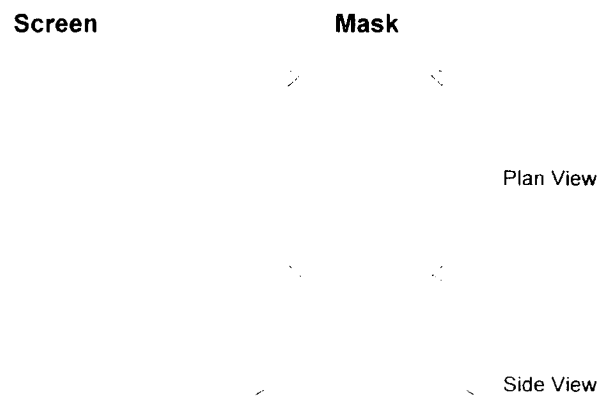


Figure 3. Screen and Mask Combination

Due to the tight tolerances needed for directing electron flow to the correct areas inside the screen, it is necessary that mask and screen combinations, once processed in the front end of the facility, stay together as a paired combination throughout the entire remaining manufacturing processes. This is a factor in design of the handling system.

2.3.2 General Black Matrix to Flowcoat Handling Process

The product handling and manufacturing process from Black Matrix to Flowcoat are illustrated in figure 4.

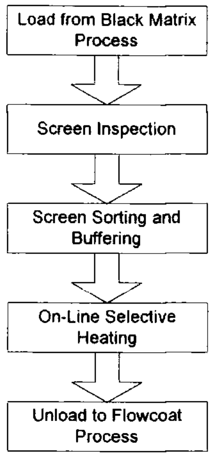


Figure 4. General Black Matrix to Flowcoat Process.

Masks and screens are loaded to a power and free conveyor system, transported to in-line Inspection, Sorting, and Selective Heating processes, then unloaded for Flowcoat processing. Two separate power and free system installations, corresponding to handling requirements for two separate installations of the Black Matrix Processing Lines, have been the subject of the simulation projects. Detailed handling schematics relevant for the design and simulation activities are reviewed in the subsequent chapters.

2.3.3 General Equipment and Manning

In addition to the actual power and free conveyors, general equipment addressed in the handling process and the simulation models includes:

1. Matrix processing lines - proprietary screen/mask processing systems used to apply the black graphite inner screen coating.
2. Loading robots - anthropomorphic type robots used to load masks and screens to the conveyor system.
3. Inspection System - a separate, floor mounted power and free pallet conveyor system in which screens are loaded to pallets that pass through manual and automatic inspection areas.
4. Selective Heating System - an in-line heating tunnel that selectively heats screens to within a specific temperature range as required for Flowcoating.

The majority of the functions within the handling from Black Matrix to Flowcoat are performed automatically on the system. There are, however, three components of the process that require manning:

1. System operator - responsible for supervising all system functions (full time).
2. Process operator - responsible for assisting in any manual handling requirements should they arise; e.g., in the event of equipment breakdowns or product changeovers (part time).
3. Flowcoat operator - responsible for manually handling products from the conveyor system to the Flowcoating process which is in a self-contained clean room environment (full time).

2.4 AMS Circuit - Tube Preparation

Once mechanically assembled, television tubes require testing and magnetising prior to the final stages of manufacture. This process ensures that the electron guns resident within the tube are landing on the screen with the required accuracy by testing and applying a permanent magnetic field to make corrections. A flexible manufacturing system, called the Automatic Magnetising System (AMS) has been designed to handle this stage in the process. Tubes are loaded to a closed-loop, power and free conveyor system which transports them through a series of on-line testing and magnetising stations before being transferred to the next production stage.

2.4.1 Products Handled and Processed

Products handled by the AMS include television tubes, shown in figure 5. The system is designed to handle two basic type variations, NN and MN type tubes of the same screen size range, 51 cm.

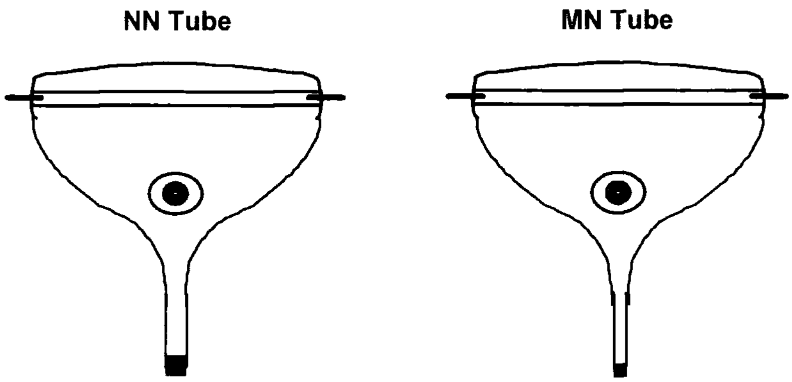


Figure 5. General Tube Types on the AMS Circuit.

Due to the difference in product type, carriers within the power and free system are unique to each basic MN or NN type.

2.4.2 General AMS Process

The manufacturing and handling process is illustrated in figure 6.

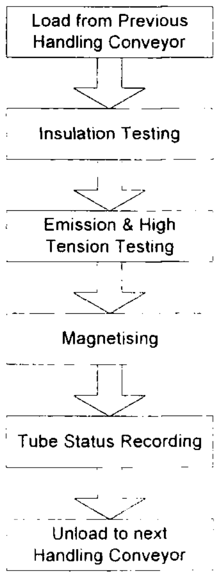


Figure 6. General AMS Circuit Process.

Tubes are loaded to a power and free conveyor system for the entire manufacturing process of Insulation Testing, Emission/High Tension Testing, Magnetising, and tube status recording until they are manually unloaded to another transport conveyor to complete manufacturing. Tubes remain within the confines of their carriers throughout the entire process, travelling through booths or stations that operate like a clamshell for testing and magnetising functions.

2.4.3 General Equipment and Manning

In addition to the integral power and free conveyor system to transport carriers, equipment for consideration in the simulation includes:

1. Incoming Conveyor - a standard indexing conveyor transporting products from the previous process to the beginning of the circuit.
2. Loading Robots - Cartesian type robots used for loading products to the AMS Circuit.
3. Insulation Stations - Process machines connected to the power and free system used to test the insulation properties of the tubes.
4. Emission/High Tension Stations - Process machines connected to the power and free system used to test emission and high tension properties of the tubes.
5. Magnetising Stations - Process machines connected to the power and free system used to magnetise the tubes.
6. Tube Status Read Station - Process machine connected to the power and free system used to read and record quality data from the tubes.

The AMS Circuit is virtually an unmanned operation. All manufacturing functions occur automatically within the system. The only requirements include a full-time process operator who is responsible for unloading tubes from the circuit, noting specific quality data, and loading them to the next conveyor. Further duties include resetting any process equipment after a breakdown.

2.5 Comparison of the Systems for Simulation and Design

Creation of the final simulation model depends on several factors. Even though the power and free systems described previously are relatively identical in function, e.g., carriers that can be stopped or transported without affecting the entire system, the building blocks used in the simulation varied, due to some basic differences.

2.5.1 Closed-Loop FMS vs Open-Loop Designs

Closed-loop systems will have fixed, relatively unidirectional paths of travel for products on the system. All junction points that exist come from a common flow in and out of the system. Traffic routing and priority issues will require analysis that is more focused on evenly distributed equipment utilisation and shortest route methods. In contrast, open-loop processes contain subsystem feedback loops, or routing changes for carriers based on varying production operations; paths similar to Automated Guided Vehicle (AGV) type systems. Products from different areas of the process could affect other sections of the system if the routing is not designed and managed correctly. Therefore, traffic issues and priority routing become more complicated, subject to increased variability.

2.5.2 Equipment Differences

While the basic function of the equipment remains identical, specific differences exist in the power and free technology and the method in which the systems are installed. For example, being a closed-loop system, the AMS circuit can be optimised as a single system, designed in unit blocks equivalent to the pitch of a carrier. This means that reservoirs within the system can be designed to contain a whole numbers of carriers with no excess track between process stops or junction points, facilitating model build, using a generic design for conveyor reservoirs. In contrast, the Black Matrix power and free system must adhere to the locations of its surrounding processes. These surrounding process locations may depend on other factors such as ergonomics or internal process optimisation; consequently, the power and free system, which is linking these processes together, is subject to uneven reservoir sizes, adding complications to the model building process.

2.5.3 Flexibility Requirements

The AMS circuit, being an FMS, can accommodate different types of products simultaneously and with little variation in set-up. However, due to the design complexity and the requirements of being connected to two very different processes, the Black Matrix power and free system, ironically, required more design flexibility. Flexibility was needed to handle rejected products, labour and varying product flow, thus the simulation was more interactive, designed for testing a greater amount of "what-ifs". The objectives of the model design were altered to accommodate operational aspects that could be verified visually rather than with statistical analysis.

2.5.4 Project Requirements

Simulation project objectives will depend on the engineering objectives and requirements of the actual system. For example, the Black Matrix power and free systems were green-field installations. Consequently, a wider range of design parameters and process unknowns created a more comprehensive list of actual implementation objectives, which was transferred to the simulations. It further complicated validation due to the fact that there were no baselines for comparison other than analytical models. In contrast, the AMS circuit was an existing manufacturing system, of which a great deal of process information and project limitations were known. The primary objective was to test specific ideas for an increase in throughput, resulting in specific simulation objectives and directly measurable results.

3. POWER AND FREE CONVEYOR SYSTEMS DESIGN

3.1 General Design Process for Automated Systems Using $IDEF_0$ Approach

The $IDEF_0$ approach for the primary stages or Design Process of a Power and Free Systems Project was chosen to compliment PCL Durham's existing project management tools to improve the specific process steps consistent with an iterative life-cycle philosophy.[66] Most of the top level activities are based on an existing project management procedure. For simplicity, it is assumed that the Design Process is the first stage in the Engineering Equipment Project Management Process, thus the two level numbering scheme for sub-processes of the Design Stage, beginning with 1, although, practically, the Project Management Process would probably start with an appraisal of the situation and technology in reference to a company's overall engineering equipment strategy. Using the principle of IDEF process mapping, figure 7 illustrates the first part of an automated systems project, which includes the beginning project feasibility stages to the internal approval of the design, with the Design process shown as the parent task:

Power and Free Conveyor System Design Process

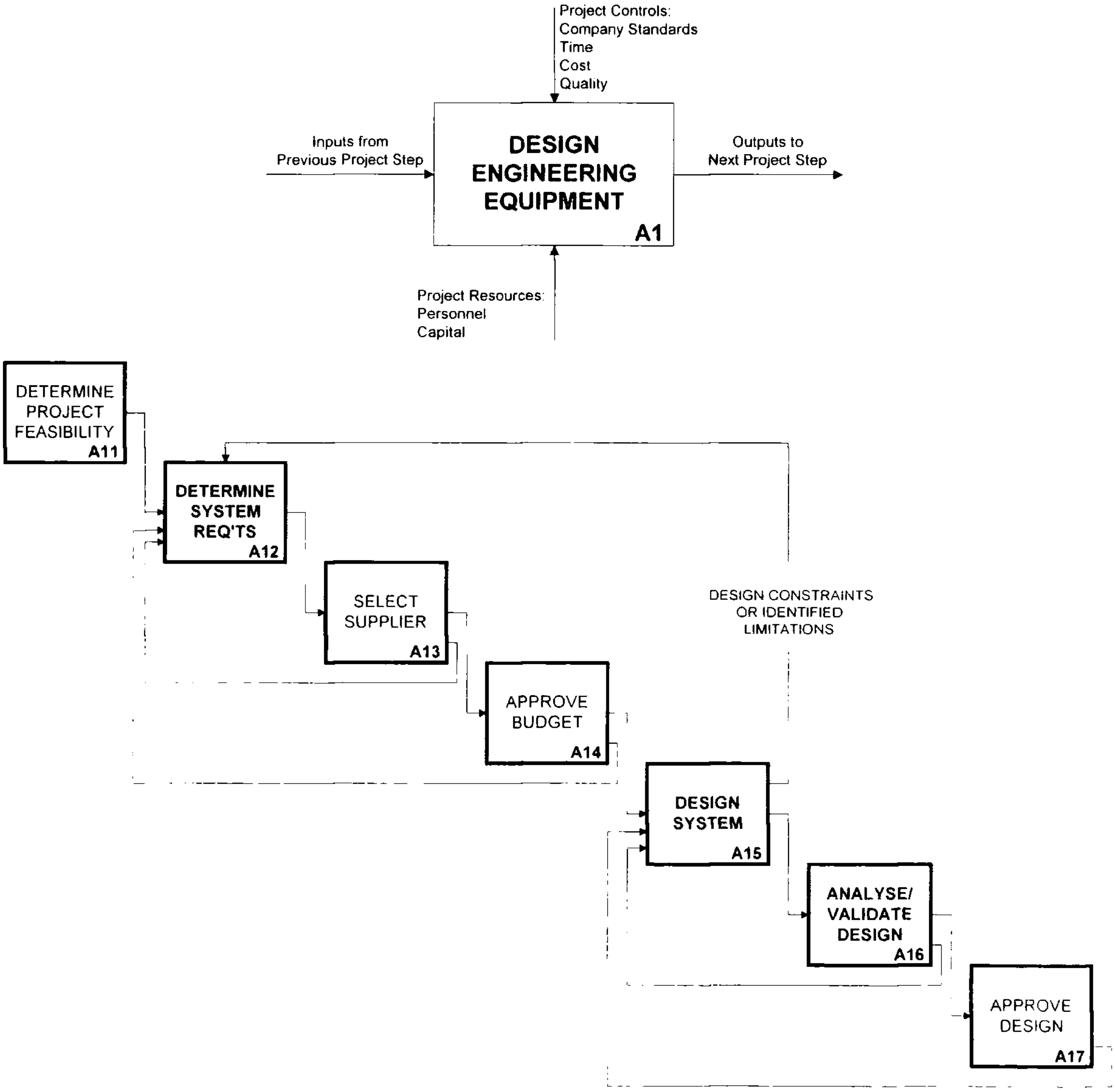


Figure 7. IDEF Map of the Power and Free Handling System Design Process.

As all companies have their own internal customised procedures for the feasibility and commercial aspects of an engineering equipment project, this document will focus on a proposed (to be) method of the more generic design aspects of this stage, which include: Determining System Requirements, Designing the System and Analysing/Validating the Design. Clearly, there will be feedback links from following stages in the Project Management process which could have bearing on the design, however, these will not be addressed. Further, the Mechanisms or Resources within the design stages will not be discussed in detail as these also tend to be variable within each organisation.

3.2 Determining System Requirements

Relevant principles of material handling design for power and free systems as identified by the College Industry Council on Material Handling Education include:[67] Orientation, Production Flexibility (Planning), Unit Load, Space Utilisation, Systems Integration/Interface, Standardisation, Ergonomics, Energy, Mechanisation, Simplification, Safety, Computerisation/Control, System/Information Flow, Layout, Cost (Initial and Future Cost of Ownership), and Maintenance. More specifically, a flow model was developed for this stage in the project for Power and Free System implementation and is illustrated in figure 8.

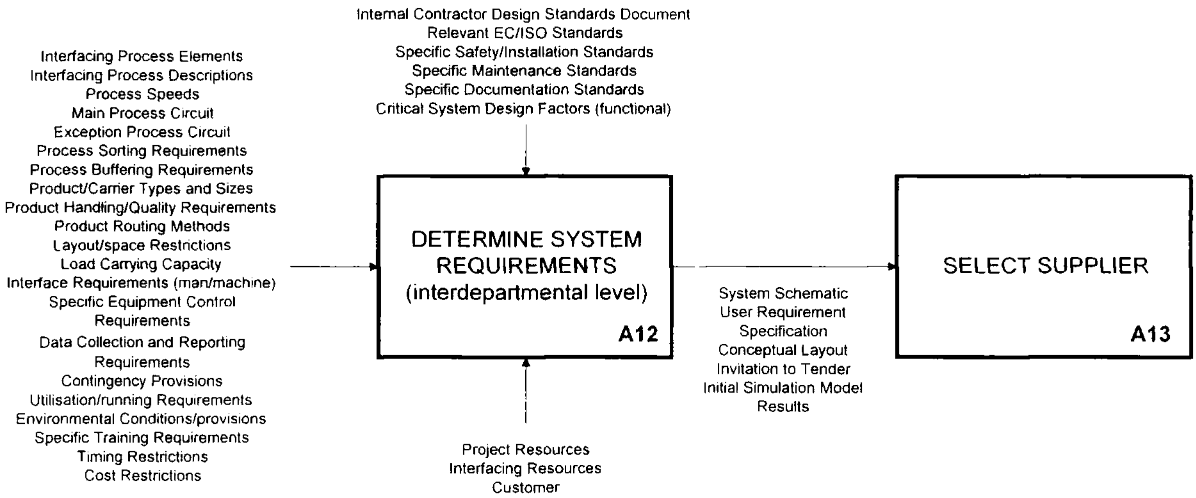


Figure 8. The Process of Determining System Requirements.

3.2.1 Inputs

The inputs to the function of Determining System Requirements correspond in large part to the five general classes of production activities as identified by Engelike (et al.): Make, Move, Wait, Verify, and Store.[68] More generally, they can be classified into the following categories: Interfacing Processes, Handling Functions, Building Factors, Control Factors (Man and Machine), General Requirements or Considerations.

3.2.1.1 Interfacing Processes

Interfacing Processes include, Interfacing Process Elements and Descriptions, and Process Speeds. Interfacing process elements and descriptions are defined as all manufacturing elements (e.g., equipment, manual; workstations, etc.) associated with and interfacing to the system. Process speeds are defined as the times or throughputs associated with each of the process elements. It is important to include the possible range of times, particularly for manual elements as these could have a significant effect on the power and free conveyor calculations.

3.2.1.2 Handling Functions

Handling Functions include: the Main Process Circuit, the Exception (ancillary) Process Circuit, Sorting and Buffering Requirements, Product and Carrier Types and Sizes, Product Handling and Quality Requirements, Product Routing Methods, and Contingency Provisions. The Main Process Circuit is a description of all the process elements coupled in a running loop or all the elements through which the carriers will definitely pass. The Exception (ancillary) Process Circuit is a description of those elements that need to be included for any problems or production requests that may be associated with the system. These could include, feedback loops for empty carriers resulting from rejected products and for products the have failed the previous process, or deposit loops for extra products requiring off-line stocking.

Sorting and buffering requirements include provisions for a system handling more than one type of product, or temporarily holding product or empty carriers. Product and carrier types and sizes are a description of the product and the carrier with drawings, the total combined weight of the heaviest product, if different types are involved, and carrier/clevis arrangement used. These factors are important for calculating carrier spacing and buffer capacities. Product handling and quality requirements include indication of the position of the products on the carrier (e.g., for bar code routing), carrier positioning accuracy requires consideration of fragile components potentially affecting speed of the conveyor chain. Product routing methods are an indication of the method by which carriers will be routed in the system, examples being, bar coding on the product, or routing mechanisms on the carrier, such as switching arms, or premid (magnetic memory) devices.

Contingency provisions should include information on all anticipated potential problems, including, abnormal reject rates, anticipated interface equipment stoppages, and operator intervention requirements. Identification of contingent strategies is based on detailed analysis of the potential problems associated with a particular design. The simulation model and results are an important factor in a comprehensive analysis and will be discussed in the next chapter.

3.2.1.3 Building Factors

Building factors include layout or space availability and existing load carrying capacity. Layout and space boundaries provide information on working heights and routing restrictions from building to building or with interface equipment. Load carrying capacity information includes ratings for surrounding existing support steelwork, such as maximum evenly distributed load, centrally based load, and point load.

3.2.1.4 Control Factors (Man and Machine)

Control factors include Interface Requirements, Specific Equipment Control Requirements, and Data Collection/Reporting Functions. Interface requirements are to provide information on both equipment interfaces (e.g., for safety and control) and manual interfaces, either at the main control panel or remote locations throughout the system. Specific equipment control requirements are those design aspects needed or requested for, individual device, overall system, operational, and maintenance control functions for the system. Examples include, faults created by system operations or by device failure, warnings created by system operations or pre-determined device maintenance schedules, and maintenance controls (e.g., for device sequences or timings). Data collection and reporting functions are descriptions of all data needed from the system for operating, maintenance and reporting purposes. Examples include, the number of products delivered to a process in a given time, chain running time, and product type and quantity in the buffer.

3.2.1.5 General Requirements or Considerations

General requirements or considerations include, Utilisation and Running Requirements (System Availability), Environmental Provisions, Specific Training Requirements, Timing Restrictions, or Cost Considerations.

Utilisation running requirements are measures of system availability and utilisation criteria specified that will be used to measure the performance of the system. Generally, availability on a system is expressed as a ratio of available time divided by total production time, or:

System Uptime/(Uptime + Downtime) = Productive Cycles/(Productive Cycles + Nonproductive Cycles)

Therefore, availability should be expressed in terms of two primary criteria: target uptime and acceptable downtime or repair time. This will give an indication of how the system should operate in terms of mean time to failure which will be used to describe the system performance requirements. Required availability for the conveyor system should, therefore, be specified in terms of average acceptable repair time, or the time that Production can accommodate with contingency planning either in extra manpower or additional equipment requirements and operating rules, and the target uptime rate or availability (expressed as a % $<$ or $=$ 100). Once these criteria have been identified, the calculations are based on the following equation:

[6] Availability = $1/(1 + \sigma b)$

Where,

σ = Rate of Failure (in cycles).

b = Average acceptable repair time (in machine cycles).

= $DT_{MIN}(T_C/60)$

with,

DT_{MIN} = Average acceptable repair time (in minutes).

T_C = Throughput required of the conveyor system (products/hour).

Therefore, it follows:

Rate of Failure (σ) = $1/NCTF$

Number of Cycles to Failure (NCTF) = $T_C\,(MTBF/60)$

Mean Time Between Failures (MTBF) = $60/(T_C \times \sigma)$ = $(Availability(DT_{MIN}))/(1-Availability)$

For example, if a conveyor system running at 250 products per hour is allowed to go down for an average of 3 minutes per occurrence (3 minutes being whatever Production personnel can accommodate as a contingency for interfacing equipment), and the target uptime rate is 99.5%, the maximum number of minutes it has to be running for is calculated as follows:

b	=	3(250/60)	=	12.5 cycles
MTBF	=	(.995 x 3)/(1 -.995)	=	597 minutes
NCTF	=	250(597/60)	=	2487.5 cycles
σ	=	1/(2487.5)	=	0.00040201

The above calculations will put descriptive constraints on the system depending on the specific running rates which can be used in the specification to the supplier. In the case above, the number of equipment stoppages should not exceed one every 2487.5 cycles, equivalent to 597 minutes or 2.41 in 3 shifts (24 hr production) timescale. Note that, in this case, the conveyor is treated as an extension of the interfacing processes to determine the required throughput. If the actual time for repair goes up, so does the acceptable interval in stoppages accordingly, critical when the system is physically installed. If the actual time for repair goes down, the acceptable interval in stoppages theoretically goes down, however, there will be a tolerance limit for Production as to when the stoppages (although small) will become a nuisance. Performance specification to the supplier should address this potential problem.

A boundary on the time to measure performance should also be provided to reflect certain anomalies that may occur when running under real conditions. For example, the likelihood that a system will run at 99% every week is remote, therefore, relaxing the time scale (say to one month) will relax the requirements and more realistically reflect operations. A lower boundary on it should be included, based on the time unit used for the total performance figure.[69] Additionally, provisions for a potentially higher than expected repair time must also be anticipated and addressed. Typically, for power and free conveyor systems, the uptime or performance will be specified with the following additional criteria, an example of which is shown below:

System uptime or availability must be at least 99%. 99% is defined as:

- One (1) month average availability at 99%.
- One (1) weekly average down not less than 96% (based on the assumption that the best the system will do in any one week is approximately 99.9% - on a four week month, to achieve the required 99%, one week cannot go below 96%).
- Given a repair time lower than average, the number of equipment stoppages in x consecutive shifts (e.g., one weeks production) is not to exceed "y" per shift ("y" being the minimum acceptable number to operations, given that the repair time could be consistently below average).
- Note for expected equipment servicing schedules (from a customer perspective of available time for maintenance).

In addition to availability requirements, utilisation (or how well the system is used) should be considered. While identifying System Utilisation in theoretical terms is relatively straightforward, practically there can be other considerations that could make measurement accuracy for power and free systems difficult to obtain. It is critical to identify the differences between equipment utilisation and system utilisation. This is important for both effective problem analysis and commercial obligations to the supplier, with the objective of separating the equipment performance from its effective use. For example, System Utilisation as a fractional percentage, is equal to the Total Time the System is running without problems for Production operations divided by the Total Time the system is needed for Production operations, or how well the equipment performs on its own merit plus how well the equipment is used by personnel. Quantifiably, System Utilisation = Equipment Utilisation - Operational Efficiency Offset, or:

$$U_{sys} = U_{equip} - O_{opeff}$$

Addressing the latter measure,

$$O_{opeff} = \text{Operational Efficiency / Total Time System needed for Production}$$

$$= O_{eff} / T_{prod}$$

Further,

$$O_{eff} = \text{Actual Response Time + Actual Repair Time - Acceptable Response Time - Acceptable Repair Time}$$

$$= T_{actresp} + T_{actrep} - T_{accresp} - T_{accrep}$$

Therefore,

$$O_{opeff} = (T_{actresp} + T_{actrep} - T_{accresp} - T_{accrep}) / T_{prod}$$

Equipment Utilisation is equal to the total time the system is automatically running with no fatal faults or warnings that would abnormally affect operations plus the total time the system should have been running after such a fault or warning, with the sum divided by the total time the system is needed to run for Production operations. I.e., U_{equip} = (Total Time the system is automatically running as detected by the PLC - Total Time self-generated System Warnings are present that disrupt carrier flow but do not stop the system from automatically running - Acceptable Response Time - Acceptable Repair Time + Actual Response Time + Actual Repair Time), divided by the Total Time the system is needed for Production operations, or:

$$U_{equip} = (T_{auto} - T_{cfwarn} - T_{accresp} - T_{accrep} + T_{actresp} + T_{actrep}) / T_{prod}$$

This equation is what would be used for determining practical Equipment Utilisation. It is only valid if the Actual Repair and Response Times are greater than their Acceptable counterparts. If not, this part of the equation should be left null. By addressing Actual and Acceptable Response and Repair times, the equation is designed to take out any "inefficiencies" on the part of the Customer. An example of a self-generated warning that would abnormally affect running or operations but still run the system automatically can be observed if a problem with control safeties is encountered. In this case, if an area safety is not reset appropriately by the last carrier through a common area, the next carrier will be inhibited, thus affecting carrier flow. It is assumed that all faults, self-generated or otherwise, will stop the system. The calculation does not consider performance of processes that are directly connected to the conveyor system or processes where the carrier is held until the process activity is completed. Combing the equations for System Utilisation yields:

$$U_{sys} = (T_{auto} - T_{cfwarn} - T_{accresp} - T_{accrep} + T_{actresp} + T_{actrep}) / T_{prod} - (T_{actresp} + T_{actrep} - T_{accresp} - T_{accrep}) / T_{prod}$$

Simplifying,

$$U_{sys} = (T_{auto} - T_{cfwarn}) / T_{prod}$$

Although appearing to be a relatively straightforward calculation to perform, automatically capturing the data that goes into the calculation, could be difficult. For example, If an operator turns the system on (panel on signal), but does not need the system right away, the system will not be activated and if the panel on time is used as the base line for T_{prod}, it will be overestimated. Currently, T_{auto} is defined as the time the system is running automatically, usually identified by the PLC, with no distinction between fault types. As a result, it could represent something worse than the actual auto running time, e.g., someone intentionally pulling an emergency stop. However, these occurrences should be rare, therefore, statistically insignificant. T_{cfwarn} is defined as the time any self-generated warning is present on the system that inhibits normal carrier movement, implying that timers have been installed on the control system to measure warnings.

As with any measurement, activities are more efficient if they can be done automatically, although, there are issues with automatic calculation of the utilisation figure for power and free systems. The exact time for when T_{prod} starts is not known and varies, therefore the baseline could be incorrect. For example, if the control panel "on" time is used to start the measurement for Production Time, actual production might not start until some time later (could be hours). Any assumptions are just those and could be inaccurate. When calculating T_{auto}, self-generated faults (caused by the system running) and faults that are caused by operator intervention are not known. When calculating T_{cfwarn}, there is a need to ensure that all warnings that the system has created without operator intervention are captured. Actual and Acceptable Response and Repair times would be complicated to include in the calculation, therefore, it must be assumed that these numbers are identical. This would cancel out part of the equation and make it easier to capture. The above assumption means that Equipment Utilisation becomes System Utilisation. If the measurements are recorded on an hourly basis, they can then be filtered, with the aid of an external software package, for any inaccuracies in the Production Time; i.e., start-up and shutdown.

Environmental conditions or provisions require a description of the operating environment and any extra considerations needed as a result of the environment, such as, clean room working. Specific training requirements should consider all training groups anticipated with a list of suggested training topics. As with contingency provisions, it is anticipated that results of the simulation model and the model itself can be used to train personnel in the operations of the system. Timing restrictions include information on the anticipated project plan and any potential problems associated with timing on any stage of the project; e.g., installation windows due to interface equipment or projects. Cost considerations require the identification of any known restrictions on available money that could affect design; e.g., extra capacity of the control or other items that may not be vital.

3.2.2 Controls

Controls represent standards for engineering and operation that will influence the activity of determining the system requirements and subsequent design. These are identified as External, Internal and Handling System Standards. External standards include established specifications or control documents for general engineering systems. These can include relevant industry-accepted specifications for equipment build, safety and documentation. They are general guidelines, in most cases, therefore, internal definitions controlling system design are required.

3.2.2.1 Internal Design Standards

Internal design standards can include, Contractor or Supplier Guidelines, Specific Safety or Installation Guidelines, Specific Maintenance Criteria, or Documentation Structures. Contractor guidelines are normally resident with all suppliers employed by the customer. Information specified could include: Product Data, Contract Information, Design Standards, Preferred Manufacturers/Components, Restricted Materials, Machine Performance criteria, Project Support standards, Documentation Requirements, and Factory Services information. Specific safety and installation standards should provide information unique to the project not generally covered in external standards. Specific maintenance criteria should include maintenance issues not specifically called off in the relevant customer internal documents that could be unique to the project. These standards are usually specific to the location and anticipated operation of the system and its unique technology. Specific documentation should specify standard internal structures required when capturing information about the handling system(s) to be installed.

3.2.2.2 Handling System Standards (Significant Design Factors)

Handling system standards include those general areas of design relevant in the Requirements Process that can be addressed on a conceptual level to form the boundaries of system capabilities, and thus the detailed design requirements. These include Buffering, Fixed Design Areas, and Decoupling principles. Buffering in a handling system should identify quantities and locations, considering all types of buffering mentioned previously which could involve, internal areas on the system (synchronously between reservoirs), interfacing equipment (temporarily between processes attached to the system) or general operations (dynamically between manufacturing processes). "Fixed" design areas in a system are those aspects of a Customer requirement that are absolute, containing no flexibility of requirements. Generally, these areas will include, layout restrictions, and system options in functionality and control. Identifying these aspects will inevitably reduce the amount of options available, thus improving the design efforts for a power and free system.

"Decoupling" system areas refers to dividing the system into two or more "sub-systems" that can run independently of each other for limited periods of time. Justification for introducing decoupled areas in a power and free system include:

- An improvement in the utilisation of equipment feeding a bottleneck process. A large power and free system will contain many devices, each with their own performance. As this is combined into a complete system, the performance of these devices must be factored into the system utilisation. As the number of devices increases, the expected utilisation decreases. If the number of components factored into the system performance can be reduced, particularly around a bottleneck operation, its utilisation should improve accordingly. Decoupling would reduce the number of devices thus improving the "local" system performance.

- Improvement in the management of operations for the sub-systems by reducing the amount of connected equipment, thereby reducing the complexity and interacting effects of downtime. The need for increasing automation requires systems to have improved utilisation in all areas, as there is no longer a contingency of personnel address problems. Most of the benefits in this case are intangible, but could represent a substantial hidden cost to operations. For example, if two areas are in distinct remote locations with limited communication facilities to address breakdowns or changes in production, the system should probably be decoupled.
- Desire to improve the customer "ownership" if the system spans two or more areas separated by distinct functional areas of the production facility. Obviously, this is not a primary reason for decoupling, however, splitting large power and free systems has shown an improvement in production team ownership due to the fact that the split makes them directly responsible for a breakdown or change in production requirements.

3.2.3 Outputs

Outputs from the Requirements Stage can assume several forms. The general items or design tools created and used for power and free systems at PCL include, the System Schematic, the User Requirement Specification, and the Conceptual Layout.

The system schematic is created from the process or network chart of the overall system. It is a flowchart of the system which includes, process descriptions (with relative locations within the process flow), process speeds, a main process loop, exception process loops, sorting lanes, process stops, buffer sizes and locations, junction points, and any relevant process statistics. The system schematic sits between the top level requirements, the actual layout and the detailed process flow charts created for product and decision logic. The schematic is also the basis from which the simulation build process is initiated. The User Requirement Specification is a document that, when compiled, is sent out to Suppliers for tendering. Content will vary, but generally, most items mentioned in the "Inputs" section above should be included.

The Conceptual Layout is an initial layout to be sent out with the information packet to suppliers for tendering, illustrating, anticipated conveyor routes, interface equipment and process stop points, anticipated rise and fall sections and available free-space or flexible areas. Initial simulation model results include those findings and recommendations from the model built to analyse the top level manufacturing process requirements for the system or general area. Results for the system requirements would not be detailed at this stage, and could include factors such as buffering contingencies, and potential problem areas given expected process utilisations, handling system utilisation requirements, and minimal insight into system operating rules. The various levels of simulation build detail will be discussed in the context of an overall simulation methodology for power and free systems, in the following chapter.

3.3 Designing the System

Designing the system is a process jointly undertaken by the project team and chosen supplier(s) to identify system requirements to the required level of detail for approval and eventual implementation. With regards to power and free systems, design is divided into two distinct, albeit related, areas: Mechanical characteristics and Control characteristics, illustrated in figure 9.

Designing the Mechanical and Control aspects of the system are shown concurrently to illustrate that the two activities can happen simultaneously provided the control factors are considered and effectively managed, and to justify how concurrent design can reduce the overall system design time. Inputs have been discussed in the previous section.

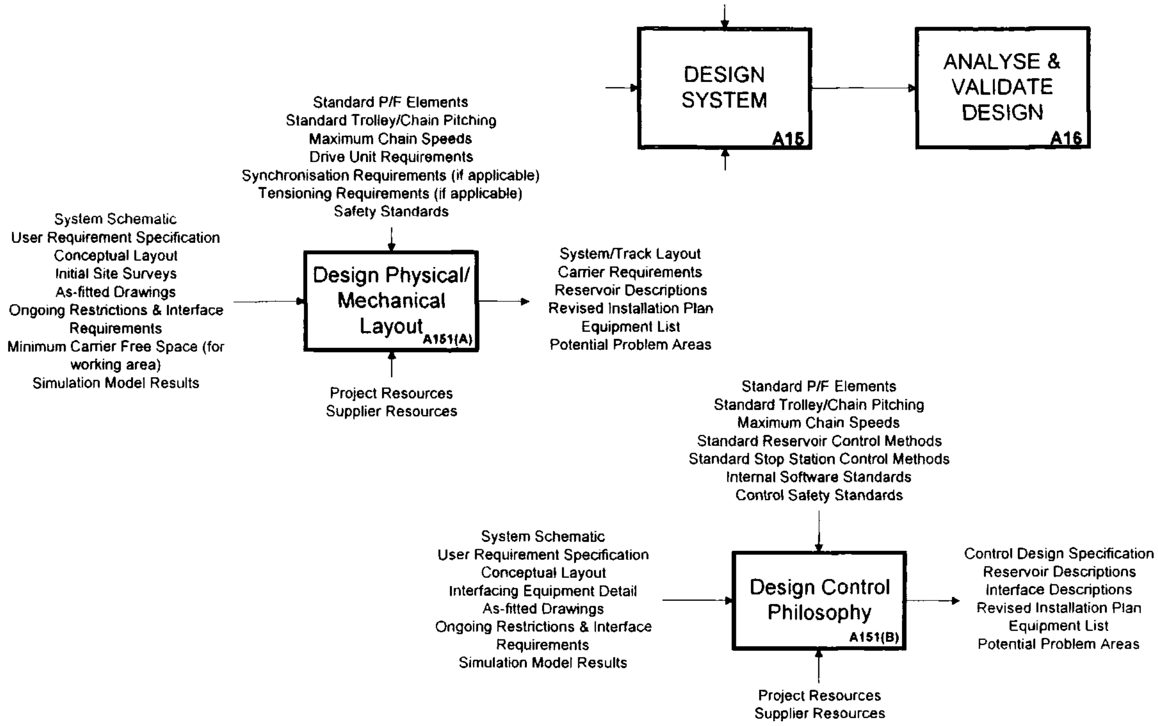


Figure 9. The Process of Designing the System.

3.3.1 Mechanical Design Standards (Controls)

This section introduces generic power and free system mechanical elements with the intention of laying a foundation from which to understand the detailed design requirements, particularly for the simulation models. These include standard power and free elements and devices, standard drive chain and carrier factors, and safety standards (proprietary technology used to ensure the safe operation of power and free devices).

3.3.1.1 Standard Power and Free Elements and Devices

Prior to discussion of the individual components, it is important to understand the system from a wider view, along with the relevant critical parameters used at that level for design. A standard hanging carrier power and free handling system configuration is illustrated in figure 10.

Hanging carriers are attached to a two-level track system in which the top track contains the main driving chain which is constantly moving. The lower track contains carriers with trolleys that can be either latched to the main drive (under power) and carried by pusher dogs attached to the main chain or delatched (free) for on-line processing, queuing, etc. When in a queue, carriers are either stopped by a mechanical stop station (first carrier in queue) or contact the back of the next trolley and are automatically delatched. The configuration above should be taken as a general description. There will be differences in the method of carrier latching and delatching. For example, some power and free systems use resistance pusher dogs which always contact the trolley, whereas others (like the one shown in figure 10) have fixed contact faces, whereby the trolley has to drop down to be free.

GENERAL POWER AND FREE SYSTEM COMPONENTS and CRITICAL PARAMETERS (with hanging carrier)

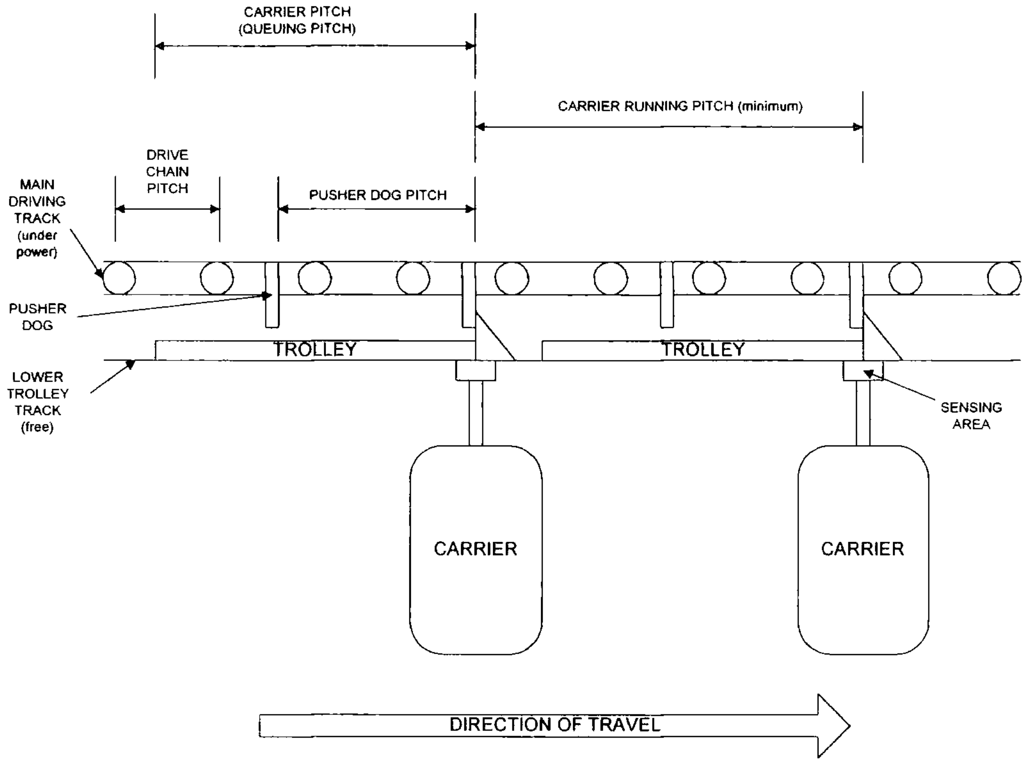


Figure 10. General Power and Free System Configuration.

Carriers are "controlled" in the system through the use of sensing devices attached to the track, identifying the sensing area of the carrier and trolley. When mechanically and logistically designing the system, the following parameters are critical:

1. Drive Chain Pitch - The distance between two chain links
2. Pusher Dog Pitch - The distance between two pusher dogs on the main chain
3. Carrier Pitch - The length of one carrier and trolley (also the queuing pitch)
4. Carrier Running Pitch - The distance between two carriers under power

Stop Stations

Stop stations are used to hold a carrier in position and control its release. They are usually indicated as shown in figure 11, denoting the centre stopping position of the carrier, and its length of standard track.

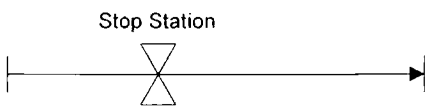


Figure 11. Stop Station Layout Configuration.

Junction points

Junction points are normally called **merges** or **diverts** depending on function. Merges are used when two or more lanes route down to one. Diverts are used to route carriers from one lane into two or more. Every junction point generally has a straight direction and a curved direction. There are right and left handed merges and diverts which correspond to the direction of flow on the curve, as shown in figure 12.

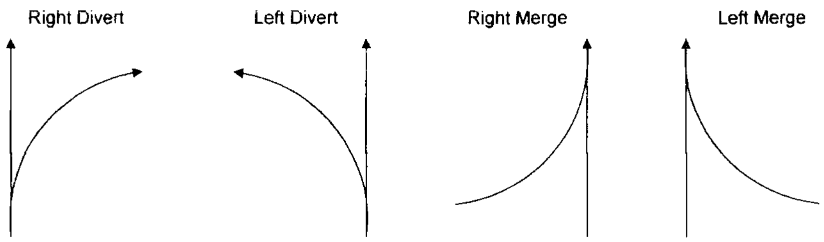


Figure 12. Junction Point Configurations.

The standard configurations are used to make up more complicated junction points if more than two lanes are required.

Decoupler Mechanism

When it is necessary to physically split or decouple a large system into two or more separate subsystems, carriers from one conveyor need to be automatically transferred to the second system by means of what is called a **Decoupler**. The general configuration appears in figure 13.

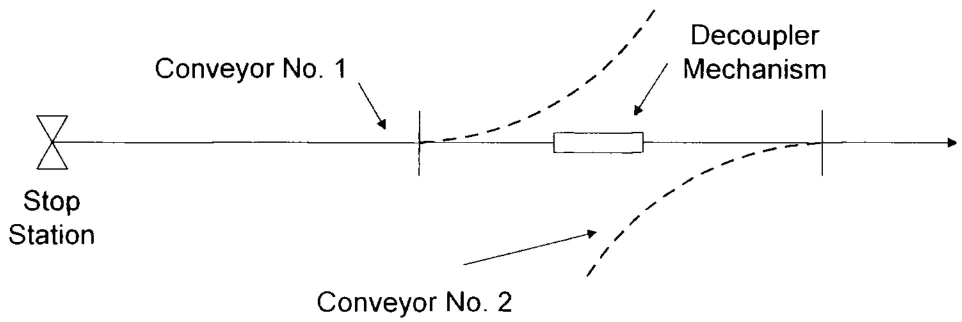


Figure 13. Decoupler Configuration.

The decoupler section can be configured into the standard sections of power and free track. The chain from Conveyor 1 breaks out of the main track just before the mechanism and the chain from Conveyor 2 breaks into the main track just after the mechanism. A second decoupler arrangement would be located for carriers coming from Conveyor 2 to be transferred to Conveyor 1.

3.3.1.2 Standard Drive Chain and Carrier Factors

Drive chain and carrier factors include Standard Trolley Sizes, Chain Pusher Dog Pitches, Maximum Acceptable Chain Speeds, Drive Unit Requirements, Synchronisation, and Tensioning Requirements. Choice of trolley size or "pitch length" depends on the size of the product or carrier conveyed. Trolleys are usually of identical length to maintain consistency of design calculations. Pusher dogs, located on the main driving chain, are also pitched at identical lengths. Pusher dogs are of relevant concern to the logistics of the system as they determine pitching between carriers and thus system throughput. Maximum chain speed for the main driving chain must be identified in relation to the robustness of the product being transported. Drive unit requirements include standard criteria for driving the main chain and are dependent on the proprietary technology.

Some types of power and free systems run using a single driving chain. Consequently, when running through junction points, the chain section from one track passes as close as possible to the chain section from the second track. This causes the pusher dogs to mesh, which is known as synchronisation. Examples of chain positioning through junction points (merges/diverts) are shown in figure 14.

Chain Movement Through Junction Points
(3 cases)

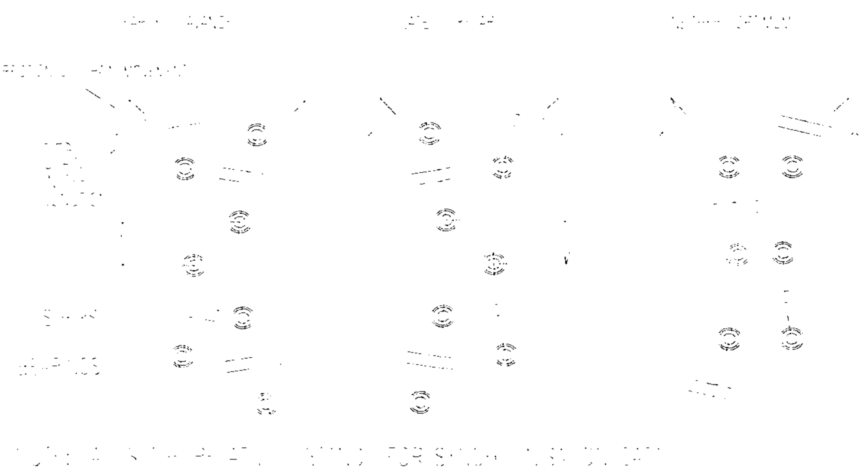


Figure 14. Illustration of Chain Synchronisation.

Maintaining synchronisation is a time-consuming, variable adjustment, critical when carriers are travelling through junction points due to the fact that carriers from one section will have to change over to the other chain, losing a pusher dog pitch and decreasing the throughput. Other types of power and free systems avoid this potential design problem in one of two ways, both eliminating the mesh design. The trolley and track can be designed such that as it is transported into the junction, the back of the trolley is raised and "pushed" into the next chain section. Alternatively, a separate transfer device transports the carrier onto a separate chain; i.e., the chain is not continuous. Tensioning refers to the tightening of the main driving chain and is required to maintain system handling performance by eliminating the slack as it stretches over time and by creating optimum synchronisation.

3.3.2 Control Design Standards

This section introduces generic power and free system control methods to create a foundation from which to understand the actual and simulated device logic requirements. These include standard device control methods, trolley and pusher dog control considerations, standard reservoir control methods, and general control considerations.

3.3.2.1 Standard Device Control Methods

All control methods utilise sensors that pick up the sensing area on the carrier for tracking throughout the system. Individual devices requiring controlled operations include stop stations and junction points.

Stop Stations

These are used control the release of carriers between reservoirs, and contain the following characteristics, illustrated in figure 15.

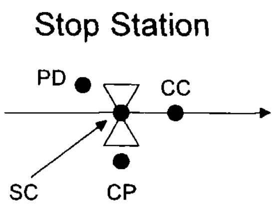


Figure 15. Stop Station Control Points.

CP	=	Carrier Presence Detector (reading a carrier present at the stop).
CC	=	Carrier Clear Detector (reading a carrier clear of the stop).
SC	=	Stop Closed Detector (reading if the stop arm is properly shut).
PD	=	Pusher Dog Detector (reading the position of the passing dogs on the main driving chain).

Standard Stop Station release sequence (open) criteria is as follows:

- Open requirement exists (i.e., request from the following reservoir).
- No carrier is detected between the stop and the carrier clear detector.
- System is running in automatic.
- Stop station is closed (i.e., in a safe position).
- No operational (manual) inhibits are present.
- A carrier is detected at the stop station.
- A minimum pitch has been counted from the last carrier released.
- A pusher dog is in the correct position to pick up the carrier.

It should be noted that release logic is based on the type of layout and not all devices on the system require the amount of release criteria mentioned above.

Junction Points (merges/diverts)

Junction devices control areas where carriers are diverted to several lanes or merge into one. Two functions concern the control in junction points: Safety and arm position (if an arm is used for the switching). In a merge, the arm directing the carriers is not under power, therefore only safety is needed. For a divert, the arm is under power so both safety and the arm being in the correct direction are under control, as noted in figure 16.

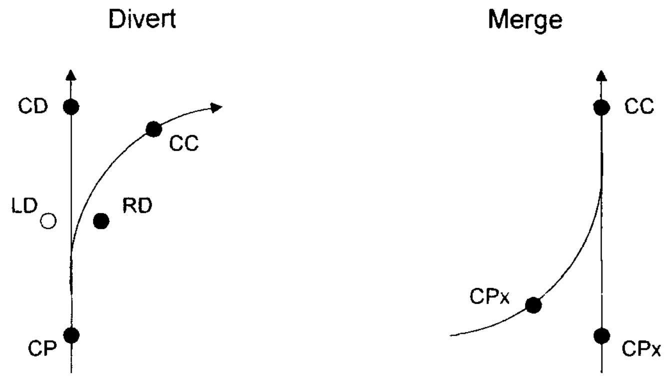


Figure 16. Junction Control Points

CP	=	Carrier Present in the divert.
CPx	=	Carrier Present in the merge from direction x.
CC	=	Carrier Clear of divert (on a curved section) or merge.
CD	=	Carrier Clear of divert (on Direct or straight section).
LD	=	Divert arm in left position.
RD	=	Divert arm in right position.

3.3.2.2 Trolley and Pusher Dog Considerations

As mentioned previously, identical trolley lengths are used throughout the system. In principle, the only trolleys that need to be controlled on the system at any one time are those:

1. At all stop stations.
2. Used for direct reservoir control (i.e., back end of reservoirs).
3. Moving down rise/fall sections (for safety).
4. Moving through junction points (for safety).

Pusher dog and chain pitching are also on standard, fixed lengths, respectively. Sensors mounted on the track to detect passing dogs and chain links can be used for the control system to monitor for both broken pusher dogs and a broken or jammed chain. Broken dogs can either limit the throughput in a minor case or cause safety problems if too many are consecutively broken by causing the second carrier affected contacts the first, delatching, thus their appearance requires detection. A problem with jammed chain is obvious.

3.3.2.3 Standard Reservoir Control Methods

Normally, for the controlled supervision of carriers flowing from reservoir to reservoir, a method called Counting can be employed (explained in detail below). This method is not ideal for two reasons. It relies heavily on a combination of software and device accuracy, and it requires more attention from operators, maintaining the correct counts in the reservoirs after a stoppage, which is often times, overlooked. As a result, other types of control methods have been devised that are more robust. Currently, four basic types of reservoir control exist, each designed to optimise the utilisation of the system and reduce the need of operator vigilance. These include: Presence Carrier, Modified Presence Carrier, Saturation, and Counting.[70] It should be noted that there are specific variations on these control methods, however, only the general methods are presented.

Presence Carrier

Referring to figure 17, showing a reservoir bounded by two stop stations, this method incorporates the use of a sensor at the end of the reservoir to act as a trigger for controlling carriers from Stop Station no. 2 (S2) into Reservoir 1 (R1):

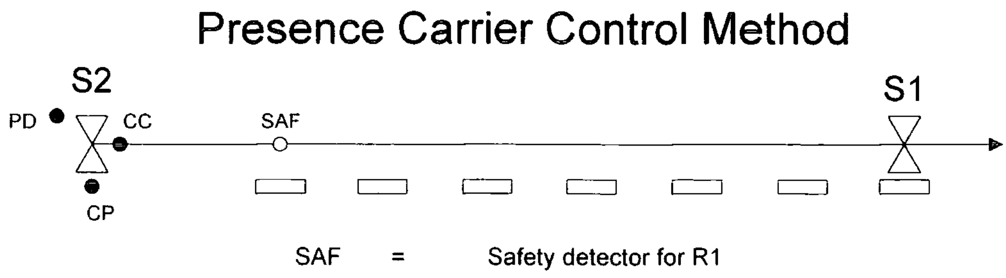


Figure 17. Reservoir Utilising Presence Carrier Control.

If a carrier is detected at S2, and the SAF detector is clear, it releases the carrier using the standard stop station release sequence. The second carrier at S2 is held until the first carrier passes the SAF detector in Reservoir 1. Therefore, the throughput for this type of reservoir is determined by the distance between the CP detector and the SAF detector plus an extra pusher dog pitch (for worse case having to wait for a full pusher dog pitch to pick up the carrier). The second carrier is released once the SAF detector has been cleared, again using the standard release sequence. Carriers are continually released from S2 in this manner. The SAF detector is pitched so that the last carrier sent (in this example, the 7th carrier) covers the detector, inhibiting S2 from any further release. The Presence Carrier method cannot be used if the distance between the CP detector at S2 and the SAF detector plus one dog pitch is greater than the running pitch required for system throughput.

Modified Presence Carrier

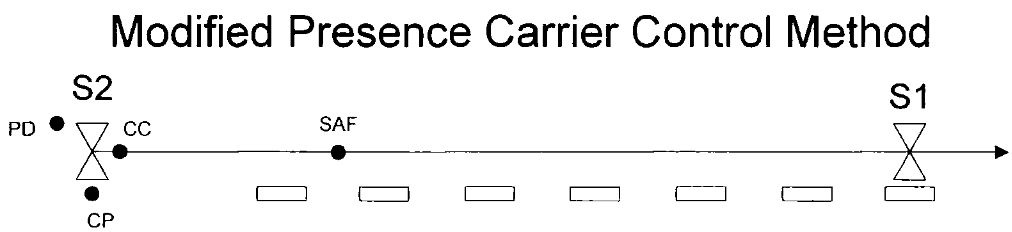
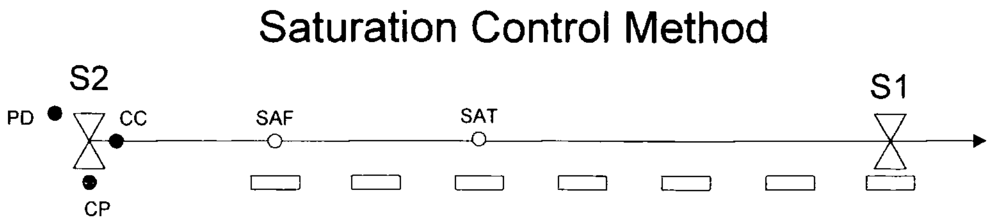


Figure 18. Reservoir Utilising Modified Presence Carrier Control.

Identical to Presence Carrier control with the exception that the last carrier in the reservoir does not cover the SAF detector, Modified Presence Carrier Control is illustrated in figure 18. S2 is still inhibited because the Area Control has not been reset by the last carrier. Throughput is again similar to Presence Carrier, although slightly worse based on the SAF position being farther away from S2. Modified Presence Carrier was devised for use with relatively long reservoirs. Due to the tolerance stackup on queuing carriers, for long reservoirs, it is difficult position the SAF detector so that it is covered by the last carrier. As with Presence Carrier, this method cannot be used if the distance between the CP detector and the SAF detector plus one dog pitch is greater than the required running pitch.

Saturation

Due to the fact the Presence Carrier control methods were reliable but limited in throughput, a third method is available that does not rely on carrier counts but increases the throughput capabilities within a reservoir, called Saturation Control, shown in figure 19.



SAT = Detector for indication of Saturation of the reservoir

Figure 19. Reservoir Utilising Saturation Control.

If a carrier is detected at S2, and SAT detector is clear, a carrier is released using standard stop station release sequence. The second carrier at S2 is held only until the control monitors a safe distance from the first carrier (measured by counting the pusher dogs past the stop station S2). The minimum distance in most cases is defined by what is accepted to be a "safe" distance. With the technology used in the first two case studies, the safe pitch was five pusher dogs. In other words. it counts four dogs and releases on the fifth. Therefore the throughput for this type of reservoir is dictated by the safe distance between carriers.

Carriers are continually released from S2 until the SAT detector is covered. The SAT detector is pitched so that a carrier (in this example, the 5th carrier) covers the detector, thus inhibiting S2 from any further release. When S2 stops releasing, there could still be carriers on the way into the reservoir. Therefore, the SAF detector has to be pitched far enough back to accommodate all remaining carriers in transit. For throughput speed, the method is equivalent to the Counting method, therefore, if Presence Carrier cannot be used, this is the next alternative. However, reservoirs that contain areas in which carriers cannot queue (rise/falls, complicated junction points, etc.) will have more carriers in transit when the SAT detector is covered. This means that the distance between the SAT and SAF detectors becomes greater. On small reservoirs, this could place the SAT detector in a position that reduces the number of carriers below what is required for throughput. Note that throughput dictates a specific running pitch between carriers, thereby dictating the minimum number of carriers needed in a reservoir while running. If this occurs, the only method left to use is Counting.

Counting

The Counting reservoir, illustrated in figure 20, contains the same devices as a Presence Carrier reservoir, however, the method is more reliant on software, not hardware devices.

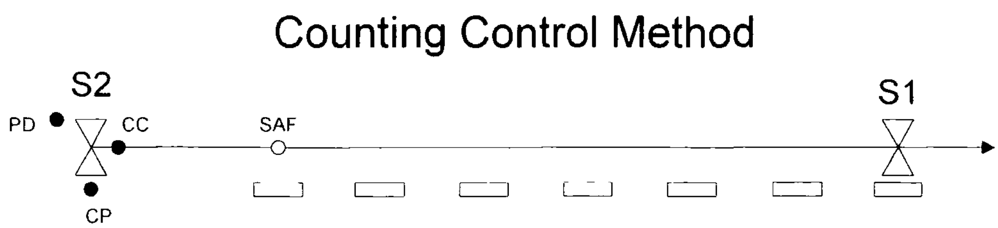


Figure 20. Reservoir Utilising Counting Control.

If a carrier is detected at S2 and the preset number for R1 (in this example, 7) has not been reached, S2 releases a carrier. R1 count is immediately incremented and R2 count decremented. Similar to Saturation, the second carrier is not released until the control has monitored the safe distance from the first carrier (by pusher dog count). Once the preset number has been reached, S2 stops releasing until the number drops below the preset number. The method is required primarily for reservoirs of high throughput containing large rise/falls or complicated junction points that extend the distance between the last carrier in the reservoir and the previous stop station.

3.3.2.4 General Control Considerations

General control considerations should include Internal and External Software Standards, and established Control Safety Standards for the particular devices and system operations. Software standards should adhere to all existing internal documentation relating to software projects and control software development. External software standards, if they exist for the equipment, should also be considered. In general, for the power and free systems, standard documents have been developed, maintained and provided with the System Control Software. These include, Program Listings with cross references to I/O addresses, Sequence Flow Charts (device process logic) showing the flow of decisions for every controlled system device, and English Language Descriptions of the decision criteria. Control safety standards are the guidelines for safe operation of carriers and interfacing equipment for the overall system. As these will vary depending on circumstances and are not particularly relevant to the objectives of this document, they will not be addressed further.

3.3.3 Outputs

Outputs from the Design System step in the process should include all deliverables necessary to make a comprehensive judgement on design feasibility and user-friendliness for the customer (i.e., those items needed to validate the design). Generally, these should include a System or Track Layout, Carrier Requirements, Reservoir Descriptions, a Revised Installation Plan, Equipment Listings, a Control Design Specification, an Electrical (and Pneumatic if appropriate) Design Specification, and a Potential Problem Analysis.

The system or track layout should illustrate, the location of all track routes, including rise/fall sections, the location of all devices (i.e., stop stations, junction points, etc.), recommended chain speed, and interfacing equipment and building items. The carrier requirements should be identified in the form of a calculation of the total number of carriers needed for the system. Guidelines for evaluating the carrier calculation are provided under the Analysing/Validating Design section. Reservoir descriptions should provide, reservoir quantities, individual reservoir lengths, maximum storage length (carrier capacity) per reservoir, calculated maximum throughput, the location of control detectors and the type of reservoir control method employed. The Control Design Specification should be a comprehensive interpretation of the methods/rules used to operate all particular devices on the proposed system. Basic elements in this document should include, standard device operation (stop stations, junction points, reservoir supervision), individual stop station release sequence criteria, Operational and Maintenance interface descriptions, interfacing specifications (covering all equipment outside the immediate conveyor system), conveyor drive control specification, fault and warning conditions and controls, and initial Operator and Maintenance control display designs.

Potential Problem Analysis is an established method of design analysis conducted to identify potential problems, expected related causes, risk analysis (by identifying the potential occurrence and level of seriousness), preventive actions to eliminate or contain the problem, and contingency plans should the recommended remedies fail.[71] It is preferably a joint effort between the customer and the supplier in which potential problem areas should be identified for as many aspects of the design and the project as possible. Regarding power and free conveyor systems, standard areas to be considered for analysis should generally include, System Design Issues, such as tensioning considerations and drive unit capacity, Operational/Control Issues, such as carrier availability for interfacing processes, Manufacture/Installation Issues, such as practical timing problems, Commissioning/Handover Issues, such as excessive equipment stoppages, Layout Issues, such as access and manual interface problems, and General Project Issues, such as limited supplier or customer resource availability.

3.4 Analysing/Validating the Design

Analysing and validating the design is a process undertaken by the project team, customers and external suppliers to evaluate and accept the design against appropriate criteria prior to equipment manufacture, in order to minimise the amount of exception activities during the system installation and commissioning phases. The process flow requirements are illustrated in figure 21. Inputs have been reviewed in the previous section.

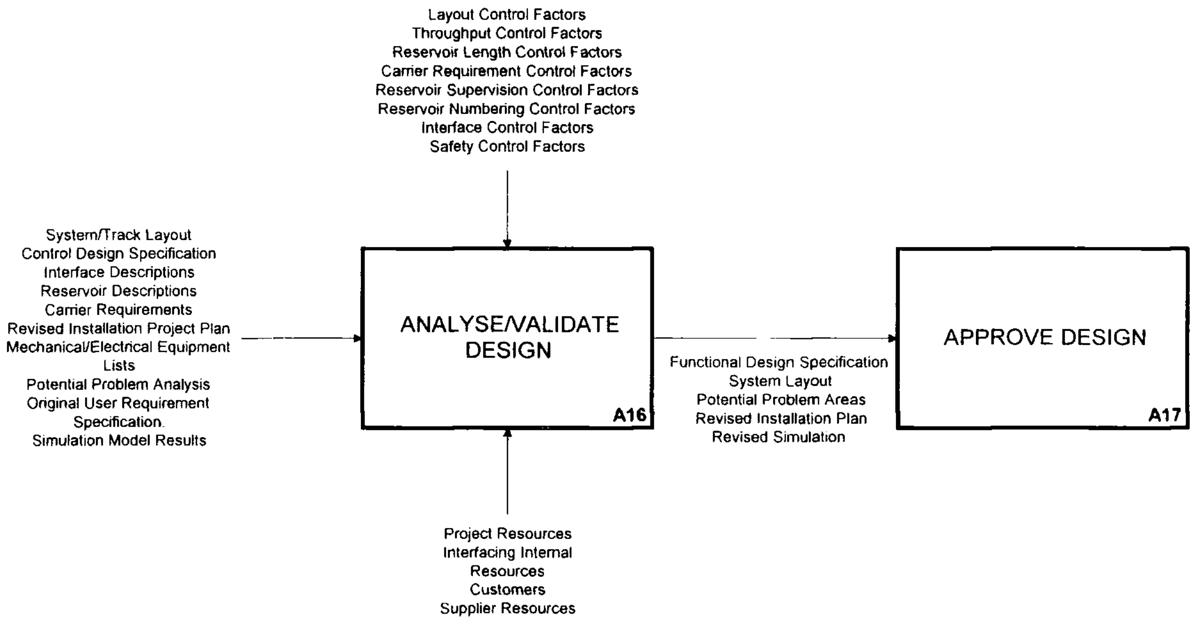


Figure 21. The Process of Analysing and Validating the Design

3.4.1 Controls

Controlling factors for analysing the system design include factors relating to layout, system throughput, individual reservoir length, carrier requirements, reservoir supervision (control), interfacing (automatic and manual) and safety.

3.4.1.1 Layout Control Factors

All power and free systems contain standard devices that are configured into sections as building blocks for a layout. In principle, when designing junction points using merges or diverts, basic components should be used within the layout, as shown in figure 22.

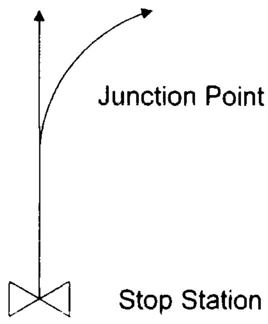


Figure 22. Standard Stop Station and Junction Point Configuration.

Simple junction points (as shown above) should be used wherever possible. These place the stop station as close to the junction point as possible, thus ensuring maximum throughput. When designing more complex junction points, such as, several sorting lanes in sequence, replicating the simple building blocks should be the method used if possible. Stop station positions prior to junction points should be placed for maximum throughput, noting that carriers from one stop prior to a merge might be delayed by changing over to the main track if a single chain system is used. Complex junction points that cannot use simple building blocks must consider two potential problems:

- Increased complexity in the control and safety logic due to the increased distances to travel through "non-queuing" sections, particularly if the speeds are high.
- A potential for undesired carrier flow. Complex junction points are areas for potential traffic problems and priority routing issues. The more complex the junction point, the more complex the issues. This was discovered, in practice, with the systems at PCL.

3.4.1.2 Throughput Control Factors

Throughput factors include considerations for carrier running pitch, inter-reservoir throughput, and decoupler capacity (if appropriate) in the determination of overall system throughput.

Determining Minimum Carrier Running Pitch Requirements

Carrier running pitch or the distance between two carriers when the system is operating, is one of the most important factors when analysing the performance of a power and free system. The calculation is as follows:

$$P_R = (S_{CH} \times 60)/(T_{SYS})$$

Where,

P_R = Running pitch (m/carrier).

S_{CH} = Speed of the main driving chain (m/min).

T_{SYS} = Throughput Required of the System or Reservoir (carriers/hr).

Carriers are transported through the system on pusher dogs that are on a specific pitch. This means that while the above calculation will give a figure for system throughput, in most cases, it will be an average throughput, because the number does not correspond to an even pitch in the pusher dog spacing. When setting up the system, therefore, it is important to design the components such that carriers can at least be released on the minimum acceptable average dog pitch.

For example, if P_R is calculated at 2.6 m, and the dog pitch is .406 m, this is equivalent to an average of 6.4 dogs per carrier (2.6 m / .406 m per dog). Therefore, carriers will sometimes be spaced at 6 dogs or less, and some will be spaced at 7 dogs or more. However, this means that controlled system devices such as stop stations must at least be able to regularly release carriers into the next reservoir at 6 dogs per carrier or 2.436 m, or the system might not meet throughput requirements. Generally, for an adequate design margin, the system design should include calculations for throughput based on a recommended chain speed that produces even dog pitching.

Determining the Minimum "Unaffected" Throughput from Reservoir to Reservoir

A generic reservoir is shown in figure 23. Illustrated are all minimum requirements for a reservoir, but also those optional items that might be necessary, depending on the type of control method and where in the layout the reservoir resides.

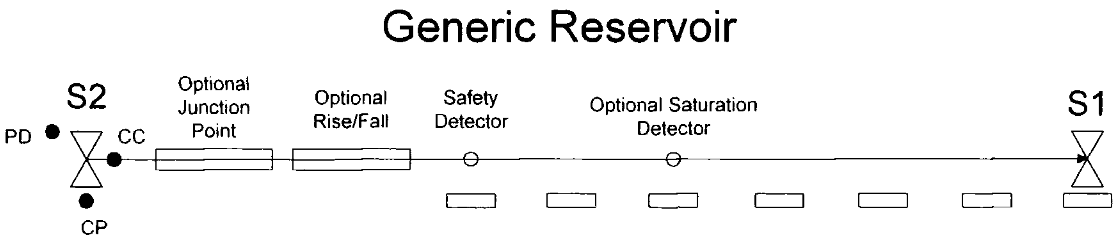


Figure 23. Generic Reservoir Configuration.

"Unaffected" throughput refers to the throughput of a reservoir if there were no direct influences by interfacing equipment, which would have the affect of decreasing carrier flow. Throughput for all types of reservoirs is generally identified, theoretically, by running pitch (as indicated previously) and practically, by pusher dogs. This is due to the fact that while system throughput is dependent on running pitch, stop stations will control the release of carriers based on the location of a dog to transport the carrier. As mentioned in the Control Design section, release of a carrier from a stop station is dependent on certain criteria or "triggers". Depending on the control method, these triggers could be:

- The safety detector (e.g., Presence Carrier).
- The safe pitch between carriers (e.g., Saturation or Counting).
- Carrier free of junction point (e.g., any reservoir containing a junction point).
- Carrier free of controlled area (e.g., through non-standard junction points).

Minimum (worse case) throughput is determined from the trigger point back to the stop station. The exception to this is when the trigger is the safe pitch between carriers, in which the throughput is known (e.g., 5 pusher dogs), assuming no other safety factors, such as, junction points come into play. The general equation is as follows:

$$T_{MIN} = (S_{CH} \times 60)/(D_{TS} + P_D)$$

Where,

T_{MIN} = Worse Case Throughput (carriers/hr).

S_{CH} = Speed of the main driving chain (m/min).

D_{TS} = Distance from the trigger point back to the stop station (m).

P_D = Waiting for next pusher at stop station once trigger is given (m).

__Example 1:__

A Presence Carrier reservoir containing a rise or fall section is shown in figure 24.

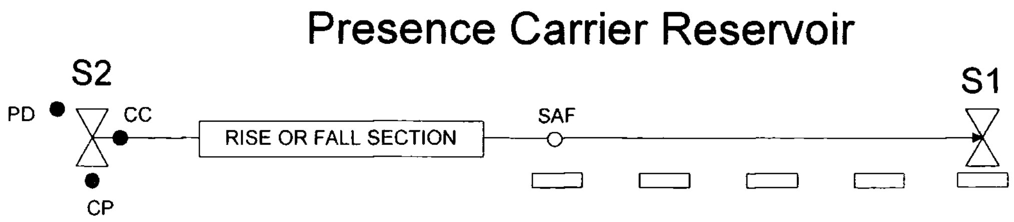


Figure 24. Example Presence Carrier Reservoir Containing a Rise/Fall.

$$T_{MIN} = (S_{CH} \times 60)/(D_{TS} + P_D)$$

Given,

S_{CH}	=	13.5 m/min
D_{TS}	=	Distance from SAF Detector through the rise/fall section to S2 = 4 m
P_D	=	.406 m
T_{MIN}	=	(13.5 x 60)/4+.406
	=	183 carriers/hour (rounded down)
	=	4.406/.406 = 10.85 dogs/carrier

Therefore, the reservoir should be capable of shuttling carriers at that average or at least 10 dogs for safe design.

__Example 2:__

A Saturation reservoir containing a merge is shown in figure 25.

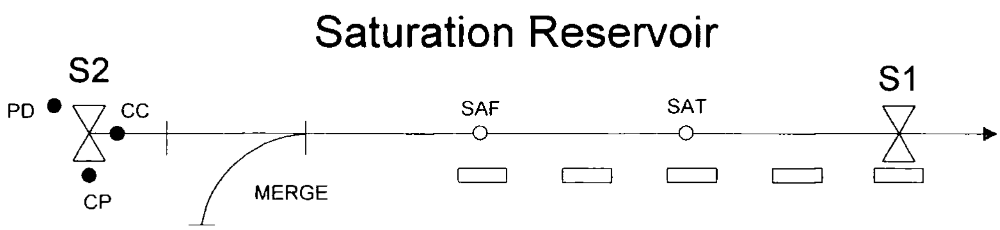


Figure 25. Example Saturation Reservoir Containing a Junction.

Given,

S_{CH}	=	13.5 m/min
P_D	=	.406 m
P_C	=	.750 m = Carrier pitch
L_M	=	.622 m = Length of the merge
D_{SM}	=	.700 m = Distance from Stop (centre of carrier) to merge
D_{TS}	=	Distance of 4 pusher dogs or from the end of a carrier clear from the merge back to S2 (whichever is greater). In this case 4 dogs (4 x .406 = 1.624) will be less than the latter at 2.072 (D_{SM} + L_M + P_C)
T_{MIN}	=	(13.5 x 60)/2.072+.406
	=	326 carriers/hour (rounded down)
	=	2.478/.406 = 6.1 dogs/carrier

Therefore, the reservoir should be capable of shuttling carriers at that average or at least 6 dogs for safe design.

Determining Throughput for a Decoupler Mechanism

Although the decoupler can have specific characteristics depending on proprietary technology, it should be designed to have maximum throughput for use with as many systems as necessary. Note the following standard layout for the decoupler mechanism between two conveyor systems shown in figure 26.

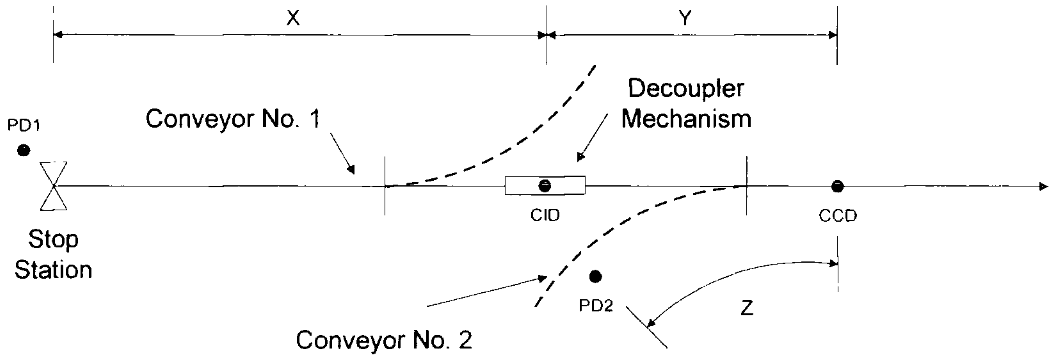


Figure 26. Decoupler Control Points.

Where,

PD1	=	Pusher Dog detector for Stop Station on Conveyor 1.
CID	=	Carrier In Decoupler detector.
PD2	=	Pusher Dog detector for transfer to Conveyor 2.
CCD	=	Carrier Clear of Decoupler detector - OK to send another carrier.
X	=	Distance from centre of the carrier to the CID position.
Y	=	Distance between the CID and CCD detectors.
Z	=	Distance between PD2 and CCD detectors.

Assuming a carrier is at the stop station waiting to be transferred from Conveyor 1 to Conveyor 2, worse case pitch between carriers (P_{MAX}) is calculated as follows:

$$P_{MAX} = P_D + X + D_C + P_D + Z$$

Where,

D_C = Delay time estimated as a small distance (.1 m) for the carrier to settle (for safe control).

P_D is used a second time for worse case waiting for a pusher dog when the carrier is in the decoupler.

Adjusted Maximum Pitch (P_{MAXA}) for actual dog spacing is calculated as follows:

$$P_{MAXA} = (\mathrm{INT}(P_{MAX}/\ P_D) + 1) \times P_D$$

Minimum (worse case) Throughput (T_{MIN}) is calculated as follows:

$$T_{MIN} = (S_{CH} \times 60)/(P_{MAXA})$$

Maximum (best) Throughput (T_{MAX}) is calculated as follows:

$$T_{MAX} = (S_{CH} \times 60)/(P_{MAXA} - 2(P_D))$$

Where,

- $2(P_D)$ is used to represent instantaneous availability of the next pusher dog.

Average Throughput (in carriers per hour), therefore, is calculated as follows:

$$T_{AVG} = (T_{MIN} + T_{MAX})/2$$

It should be noted that all the calculations assume that there is a constant queue of carriers waiting to go through the decoupler mechanism, which is the recommended operation for carrier flow.

Determining Overall System Throughput

In a closed-loop power and free system, or one that does not have any feedback loops for carriers or sorting lanes for carriers to bypass, the overall system throughput is determined by the slowest interfacing process. Even though there will be local increases in throughput for individual reservoirs at certain periods of time, such as start-up, carriers will eventually queue in front of the system process bottleneck and starve the process immediately after this bottleneck. If the speed of the process is reduced long enough, in steady state, it will control the entire system throughput. Examples of this can be seen temporarily on a running system when there is a manual process attached. If the manual process cycle time average runs higher than expected, carriers will build in that reservoir and eventually inhibit the previous process. If this is only a temporary increase in the cycle time, provisions can be made at the design stages to address this potential problem.

Losses in throughput can also be compensated by adding "feedback" or "bypass" loops that can supplement the required areas due to a restricting process. Examples of this will be reviewed in the case studies. Using these loops, it is necessary to identify their local throughput for evaluating their effectiveness.

3.4.1.3 Reservoir Length Control Factors

Reservoir length factors should consider, determining minimum reservoir sizes for fully automatic systems, layouts containing several working heights (rise/fall sections), and reservoirs containing a manual process.

Determining Reservoir Sizes for a fully automatic system

In principle, the size of the reservoir must allow for the distance between the last carrier in the reservoir and the carrier in the previous stop station to be less than, or equal to the acceptable running pitch of the system. The time to transfer the second carrier in the reservoir queue to the process position is a function of the following:

- Pusher dog pitch (to pick up first carrier).
- Minimum running pitch of carrier vs. queuing pitch (I.e., running pitch would be the next highest number of dog pitch from the queuing pitch. For example, if the dog pitch is .406 m and the queuing pitch is .750 m, the running pitch is .812 m).
- Carrier settling time.
- Operation of centraliser or other type of proprietary carrier stabiliser (not applicable if a process is not directly attached to the stop station).

To relate this to overall system design, which includes the process time, the carrier positioning time must be factored into the overall cycle time for a process stop. For example, if the throughput required is 140 products per hour and the carrier positioning time is 10.04 seconds, the process time can be no greater than 15.67 seconds (25.71 - 10.04). It should be noted that these analytical models assume a worse case scenario, an engineering contingency. Further, if a reservoir is only one carrier in length, the distance between the two stop stations will probably be a minimum carrier pitch plus the distance to clear all miscellaneous stop station components. Therefore, the worse case transfer time from one stop station to the next uses the following parameters:

- Operation of centraliser or other carrier stabiliser. Note, the centraliser (if applicable) on the preceding stop is not factored in because it is assumed that it has been released.
- Worse case pitch of the carrier leaving the following stop. Note, if the control method used between reservoirs is counting, this length will be the dog pitch only, because the reservoir is counted down upon opening of the stop station. If it is a carrier presence type of control method used, the distance will be the dog pitch plus the distance for the dog to actually pick up the carrier and go clear of the sensor (length from sensor signal to open stop and the carrier pickup point plus the length of the striking area on the carrier back from the carrier clear sensor) to give the previous stop station the signal to release.
- Dog pitch vs. the length between the two stops (always rounding up to next pitch).
- Settling and centralising the new carrier.

Example:

If chain speed = 14.5 m/min, and distance between stop stations is .900 m, and the method for control is presence carrier (with the pusher dog sensor being .150 m from the carrier pickup point and the carrier presence sensor mounted with .050 m left on the carrier striking area), the time for the second carrier to get in position at that stop station (T_{CR}) is:

$$T_{CR} = T_{DC} + (P_D) \times 60/S_{CH} + P_{LMR} \times 60/S_{CH} + D_C + T_C$$

Where,

T_{DC} = Time to decentralise carrier.

T_C = Time to centralise the next carrier.

P_{LMR} = Roundup$((D_{SS} + D_{PDC} + L_{SRR})/ P_D) \times P_D$.

and,

D_{SS} = Length between two stop stations (centreline of carrier).

D_{PDC} = Distance from the pusher.

L_{SRR} = Length of the sensing range remaining on the first carrier.

Therefore, the greatest time to get in position is calculated as:

$$2 + .406 \times 60/14.5 + 1.218 \times 60/14.5 + 1 + 2 = 11.72 \text{ seconds.}$$

1.218 m was used because it is the least multiple dog pitch, based on the length between the stop stations plus the extra items (.900 + .150 + .050 = 1.100). In other words, the second carrier will be released when it sees the carrier clear as well as the first dog available. As noted previously, the calculation considers the worse case. In some cases, the carrier centralising and settling times have been reduced by loading within their cycle. As with the above example, to relate this to overall system design, this carrier positioning time must be factored into the overall cycle time of the process stop. In comparing the two examples, the positive affects that placing an extra position in a reservoir for buffering have on relaxing the requirements for interface process times, should be apparent. The effect of an extra position in the reservoir is to reduce the trigger length for the carrier release criteria, thus improving throughput.

Determining Minimum Reservoir Size for a Manual Process Stop

In general, when sizing the minimum capacity for a manual reservoir, it is important to identify, the average process time required for the manual operation, the maximum deviation (increase) to the average process time, and the exception activities that may cause the carrier to remain in position, such as, the operator leaving the workstation to reset an alarm.

Reservoir buffering capacity should be great enough to accommodate the number of carriers that would be in transit from the previous process or stop station in addition to the number of carriers that will be transit given the occurrence of an exception activity. This could also affect the number of carriers that are calculated for the system by way of desiring to have a queue of carriers at all times in particular reservoirs with automatic operations that could starve as a result of delayed manual operations. This is essentially a buffering problem for unpaced lines in sequence and must be calculated appropriately.

Determining Minimum Reservoir Sizes containing Rise/Falls

In principle, the minimum acceptable capacity of the queuing section after a rise or fall must be greater than or equal to the number of carriers that could be in transit between the process stop on the straight and the previous stop station, given the maximum throughput. This is to account for a potential occurrence of downstream reservoirs being blocked, requiring the reservoir to be capable of accommodating all the carriers that have been sent to it. Maximum throughput in all cases is based on a stop station releasing carriers into an empty reservoir and on a minimum carrier running pitch (safe distance) of pusher dogs between carriers. Consequently, the equation for determining minimum size of a reservoir after a rise/fall is as follows:

$$L_{MIN} = (INT(D_{SS}/P_R) + 1) * P_Q$$

Where,

L_{MIN} = Minimum Queuing Length of the Reservoir (m).

P_R = Running Pitch (m/carrier).

P_Q = Queuing pitch of the carrier (m).

As a rule of thumb, best practice designs keep an extra carrier position free at the end of the reservoir to accommodate any potential problems with carriers in the previous reservoir. In which case, the equation for minimum reservoir length would become:

$$L_{MIN} = ((INT(D_{SS}/P_R) + 1) \times P_Q) + P_Q$$

The extra carrier positions is not an absolute and is sometimes taken out if space is at a premium.

Example:

A reservoir after a rise is configured with the following data:

Distance between the two stop stations	=	7.565 m
Running pitch	=	2.030 m
Queuing pitch of the carrier	=	0.750 mm

L_{MIN} = (INT(7.565/2.03) + 1) x .750 = 3 m or enough to hold 4 carriers.

3.4.1.4 Carrier Requirement Control Factors

When determining the number of carriers for a system, considerations should be made for the theoretical number per reservoir, total requirements for a fully automatic system, and those for a system containing manual processes and decisions that could affect carrier flow.

Determining Carrier Requirements for Individual Reservoirs

To calculate the number of carriers (N_{CARR}) that should normally be in a reservoir at any one time, the following equation can be used:

$$N_{CARR} = INT(D_{SS}/ P_R) + 1$$

Determining Carrier Requirements for a Fully Automatic System

For a fully automatic system, or one that does not have any regular manual intervention for routing decisions or delaying carriers, the following method, used by Matflex and other designers, is sufficient for calculating the number of carriers required for the system:

$$\sum_{n=1}^{i} (T_n \times D_{SS}/S_{CH} \times 60) \quad + N_{SS}$$

Where,

i	=	Total number of individual reservoirs.
T_n	=	Throughput required for the section under evaluation.
N_{SS}	=	Number of stop stations on the section under evaluation.

Determining Carrier Requirements for a Combination Manual/Automatic System

While the previous method is applicable to fully automatic systems, it may be required to use an alternative method for calculating carrier requirements due to any one of the following criteria:

- Requirement to hold more than the running pitch in a reservoir (e.g., buffer lanes);
- Slight variations in System Throughput between processes that will cause queuing in the reservoirs prior to the bottleneck (e.g., a 280/hr process feeding a 275/hr one).
- By-pass reservoirs that are primarily controlled by manual methods, thus impractical to work on an average throughput (e.g., an off-line stock harbour).
- Reservoirs where it is desired to have "insurance" that there will always be ample supply of empty carriers, in anticipation for process breakdowns.
- Areas of the system where carrier release is restricted by the control system.

All criteria above, with the exception of item 5, will increase the number of carriers required for the system. Those areas of the system where they apply, must therefore be individually evaluated and included into the overall calculation, in which case, the automatic method would result in a baseline but not the optimum number. The quantity in those affected reservoirs will be dependent on, the size of the reservoir, at what level they want to be run at (i.e., half full, full, etc.), what is defined by the control for areas where flow is purposely restricted, and how they will be handled manually. For example, if a reservoir is used for manually loading/unloading stock to/from the system, the Designer should consider the following questions:

- How will the operators handle that function?
- Will they perform the function on average with carrier spaced for the average pitch required?
- Or will they let the reservoir run full, address all the carriers, then release out of the harbour?

These operating methods will affect how many carriers are needed for that function. Analytically, it is recommended to calculate a minimum, maximum and composite value for the number of carriers required in order to gain an understanding of system limits. The minimum carrier capacity is equivalent to the requirements for a fully automatic system. The maximum capacity is the calculation with the system running in a combination of worse case situations, given that there may be operator intervention or process problems. As the system might not run fully automatically and there is very limited chance of many problems occurring at the same time, the minimum and maximum values should be seen as boundaries only. In other words, either value can limit both system flexibility and reliability for interfacing processes. The composite capacity or the "optimum" capacity is a weighted average between the minimum and maximum values based on expected operations.

3.4.1.5 Reservoir Supervision Control and Numbering Factors

Reservoir supervision factors, or methods influencing placement of control devices in the system should consider their placement, relative to the control method used for the reservoir, including the standard control methods previously reviewed. When numbering reservoirs, consideration should be given to real and user-defined counting requirements in the system.

Placement of Detectors for Carrier Presence Reservoirs

Using Carrier Presence reservoir control, placement of the presence detector does not necessarily need to be as far back in the reservoir as possible. Placement in the very back of the reservoir, while improving the throughput, also implies that the maximum number of carriers will queue in this reservoir if there is a problem; carriers that might be better used elsewhere in the system. The detector needs to be placed at the position that gives the desired throughput, provided that the throughput is based on the worse case running pitch release from the previous stop station and the previous process is not adversely affected by placing the detector further into the next reservoir. For relatively long reservoirs, due to the mechanical tolerance stackup of queuing trolleys, the striking area (sensor reading area) on the last carrier might not be positioned on the presence sensor. This can be addressed by using the Modified Presence Carrier method as noted previously, however, another alternative can be used, shown in figure 27.

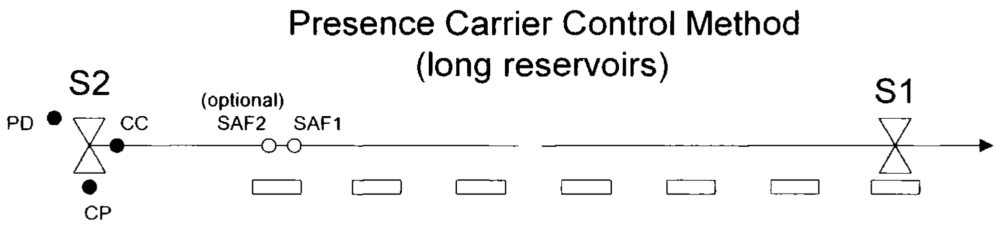


Figure 27. Alternative Sensor Arrangement for Long Presence Carrier Reservoirs.

A second, optional sensor can be used to accommodate the tolerance stackup on the carriers and effectively "create" a larger sensing area. The control system then needs to see both clear to release another carrier into the reservoir. Throughput is based on the detector farthest away from S2. The general rule for placing another detector at the SAF position is as follows:

$$T_{TL} \times N_{RES} \quad > \quad L_{SACARR}$$

Where,

T_{TL}	=	Tolerance of the trolley length.
N_{RES}	=	Number of carriers in the reservoir.
L_{SACARR}	=	Length of Sensing Range on Carrier.

Placement of Detectors for Saturation Reservoirs

Using Saturation control, it is important to get an accurate placement of the detectors so that there is an accurate determination of the minimum size of the reservoir and there are not too many carriers released into the reservoir, creating an unsafe situation. Note the generic saturation reservoir illustrated in figure 28.

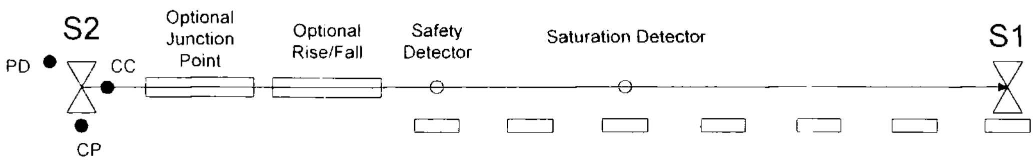


Figure 28. Sensor Arrangement in Saturation Reservoirs.

Location of the Saturation Detector is calculated as follows:

$$D_{SATS1} = (INT(D_{SS}/P_R) + 1) \times P_Q$$

Where,

D_{SATS1} = Distance between Saturation Detector and S1 (m).

D_{SS} = Distance between the two stops stations S1/S2 (m).

P_R = Running Pitch (m/carrier).

P_Q = Queuing pitch of the carrier (m).

$+ 1$ = Rounding up for safety.

Location of the Safety Detector is calculated as follows:

$$D_{SAFS1} = INT((D_{SS} + P_D - D_{SATS1})/ P_R) \times P_Q$$

Where,

D_{SAFS1} = Distance between Safety Detector and Saturation Detector (m).

P_D = Delay of carrier sitting on Saturation Detector.

Some reservoirs may contain areas where trolleys cannot be queued, as would be the case with the optional junction and rise/fall sections shown in the generic reservoir drawing. If the calculated accumulation length ($D_{SATS1} + D_{SAFS1}$) cannot be accommodated within the reservoir (e.g., if two process points don't allow it), then the Counting control method is required. As with long reservoirs and the carrier presence method, an extra detector can be placed at both the SAT and SAF points to increase the sensing area.

Placement of Detectors for Counting Reservoirs

Using the counting control method, it is important to note that for relatively long reservoirs, the safety detector should be placed one pitch behind the last carrier in the reservoir. This is due to the fact that if the traditional method is used where the detector is placed on the last carrier position, as the previous stop station gets the signal to release another carrier (when the count goes down on the next stop open) the last carrier in the reservoir will not have time to move off the safety detector before the next carrier coming in hits the carrier clear sensor, thus creating a control safety fault. Consequently, the safety detector should be put one pitch behind the last carrier in the reservoir if:

$$(P_{MCR} - P_Q) \times N_{RES} > D_{PD\text{-}CC}$$

Where,

P_{MCR} = Minimum carrier running pitch

N_{RES} = Number of carriers in the reservoir

$D_{PD\text{-}CC}$ = Distance between the Pusher Detector and the Carrier Clear Detector of the previous stop station

Example:

A long Counting reservoir is shown in figure 29.

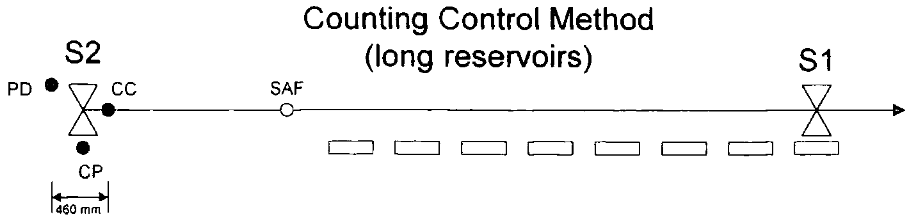


Figure 29. Sensor Arrangement in Long Counting Reservoirs.

If the minimum carrier running pitch = .812 m and the carrier queuing pitch is .750 mm, with the number of carriers needed in the reservoir = 8:

(.812 - .750) x 8 > .460 mm

Therefore, the SAF detector must be placed one pitch behind the last carrier to avoid unnecessarily tripping the safety when another carrier is released from S2. Note, the reason that the SAF detector is not always placed in this position for all reservoir lengths is that sometimes there is not enough room for an extra carrier position (particularly around rise and falls with limited space.

Numbering reservoirs is a necessary part of building the control system for internal carrier management and display to operators. Numbering reservoirs includes physical or real carrier counts in the system and user-defined counts. Physical counts refer to the number of carriers in each reservoir, required primarily for the automatic control of the system. User-defined counts refer to groupings of reservoir counts defined by the operational management and reporting requirements unique to each system. The user-defined counts are used to more effectively manage carrier flow, particularly for systems that are not fully automatic.

3.4.1.6 Interface Control Factors

Interface considerations include those necessary to, maintain a safe system, and manually or automatically operate the system. Applied to power and free systems, three types of interface have been defined for the study: Automatic, Manual and System-to-System (use of a decoupler).

Automatic Interface Standards

Equipment that is "connected" to the power and free system in automatic format generally includes, automatic handling equipment for loading/unloading processes, automatic process equipment directly working within or around the carrier environs, and automatic process equipment indirectly working with the conveyor system; e.g., a batch process that can run in different modes requiring the conveyor control system to alter its carrier flow accordingly.

The basic information required from the interface equipment for adequate conveyor operation both in software and hardware format should include, identification of direct handling or process equipment running or not, in set-up/home position, identification of direct handling or process equipment clear of the common working area, and identification of indirect process equipment running and in a particular production mode or schedule. The basic information provided by the conveyor to the direct interface equipment should include, indication of the carrier in position, identification of whether the carrier is empty or full (depending on which is required), confirmation of the carrier stabilisation procedures being complete (e.g., centraliser operations) and indication of the operator switches in appropriate positions (if applicable). Specific interface information will be dependent on the actual equipment.

Manual Interface Standards (for operations and maintenance)

The function of the machine/human interface is to create a bridge on which to "exchange information" between machines, systems, or system operators.[72] Balint further defines four objectives of the man-machine system, including machine monitoring, supporting management functions in system operations, aiding decision-making, and establishing a certain degree of "error-tolerating operation" of the system. Manual interface methods to the system can include the following:

1. Manual switches for directly controlling carrier release (located at remote process points).
2. Manual switches for controlling carrier flow (located at a central operator point).
3. Operator display for monitoring and controlling system parameters (located at a central point).
4. Maintenance display for monitoring and troubleshooting system operations (usually located at the main control panel).

Actual interfaces will be dependent on the technology available at the time of design. For example, items 1 and 2 mentioned above may not always be applicable. In fact for an automatic FMS, manual interface switches will be rare. Further, an effective operator and maintenance interface will not only be dependent on established, generic dialogue, physical attributes, and ergonomics, it should consider significant aspects of the labour and thought processes associated with operating the system and improving communications amongst the different groups, issues difficult from a pure design perspective.[73] Thus, design of the manual interface should be a "user-centered" one, involving operational and maintenance personnel as early as possible in the design process.[74]

Manual Switching Considerations:

Switches or control over various stop stations in the system are normally used for large, relatively complex systems, where production flexibility is critical. Manual controls should consider all functional requirements and potential problems associated with the interfacing manufacturing processes. Thus, when installing these controls, specific consideration should be given to the following:

- Is the priority at the stop or junction point likely to change?
- Is there a possibility for carrier traffic jams that the control system cannot take care of automatically?
- Will there ever be a need to manually inhibit the flow of carriers from a particular stop station?
- Are there any manual loading/unloading points in the system?
- Are there any contingencies for carrier routing that require manual intervention (e.g., bar code failures for a particular type)?
- Is the system going to be reactive to various Production Modes of running?

If the answer to any of the above questions is positive, than the probability is high that a manual control switch will be necessary.

Display Considerations:

Regardless of the type of system, a display screen is usually installed to monitor critical system parameters. Evaluation of the necessary parameters for display should involve analysis of issues, such as, the type and amount of information, use of standard menus, use of troubleshooting assistance, and internal software controls available to the user.[74] Specific functions or characteristics that have been considered the interface display for power and free systems, include:

- Reservoir Volumes (i.e., number of carriers in individual reservoirs as well as pre-defined sections of the system to improve operational management, with capability to edit).
- Product Throughput Statistics (pre-defined).
- Product Type Identification (internal system designation for routing).
- Routing Mode Selection (for sorting areas of requiring type mix distinction).

- Interfacing Production Process Timers (for reacting to production changes).
- Indication of stop stations inhibited.
- Warnings.
- Faults.
- Watchdog timers for system components.
- Interfacing Systems operating status (particularly for systems that are decoupled).
- Sequence Status for conveyor system components.

The method and design of the displays will be dependent on the customer feedback, ergonomic considerations and the technology available at the time (assuming cost factors have been considered).

Conveyor System-to-System Interface

If a decoupler is used, splitting a large system into two or more semi-independent systems, control and operational design interface functions should be considered.

Control Interfaces:

Normally, the decoupler mechanisms, one for sending carriers and one for receiving carriers, will be controlled by one system for practical maintenance. It will probably be easier for one area to effectively address problems than the other. In a hybrid "push/pull" system design, determination of which system should have control of the decouplers will be dependent on equipment location and the size of the following buffer. Systems installed currently have had the decouplers effectively controlled by the "push" side of the overall design, provided carrier flow is controlled by the "pull" side.

The minimum input/output information required by the control system to effectively operate the decouplers should include, indication of a carrier required, any information used in the display on the interfacing system, interfacing system status (i.e., running in automatic or stopped), indication that the stop station prior to the decoupler is clear to release, and confirmation that the stop station prior to the decoupler has released.

Operational Design Interface:

As a decoupler is normally used to improve the efficiency of the bottleneck, provisions in the design, particularly carrier flow, are required appropriately. The number of carriers sent to the bottleneck side should be of sufficient quantity to keep the system running for as long as possible given a potential stoppage on the other system. The number of carriers should be balanced against the system capacity after the bottleneck process, noting the other system may be down and not able to accommodate carriers. Designing as a pull system with the bottleneck process requesting products when they are needed, a trigger point in the system should be identified, similar to a manual kanban system. The trigger point should be located in a position that allows for uninterrupted flow of the bottleneck process. Once the trigger point is identified, the relative position is used to calculate the number of carriers for uninterrupted carrier flow, given the interfacing system could be down for a specified amount of time.

It is first necessary to determine how many carriers can be queued from the bottleneck process to the decoupler point. Once identified, the number of carriers that will normally be on the run during operations must be calculated and subtracted from the queued number, thus identifying the amount that can be stored after the bottleneck process. This is the limiting factor as to how many carriers can be on the way to the bottleneck (on the bottleneck side of the decoupler). Based on this number and the speed of the bottleneck process, the time to process all of the unit products (T_{PBBUFF}) can be calculated. Using the distance from the stop station on the "push" side to the trigger point on the bottleneck side and the speed of the chain, the travel time to the trigger point (T_{TTP}) can be calculated. Once this is known, the allowable time the "push" system can be down before interrupting the flow to the bottleneck process (DT_{ALLOW}), is represented by the following equation:

$$DT_{ALLOW} = T_{PBBUFF} - T_{TTP}$$

Obviously, for accuracy, the calculations should include provisions for carriers travelling through the decoupler points and stop stations if any are located between the decoupler and the trigger point on the "pull" side of the systems. Too many carriers on the system or particular running methods on the push side of the systems could affect the number that can actually queue after the process bottleneck. A permanent queue just before the push side could be created, thus reducing the available space after the bottleneck.

3.4.1.7 Safety Control Factors

Safety Control Factors for design of the power and free system include safe methods of control, mechanical design and operating methods for, all power and free mechanical devices, all interfacing equipment, and all people working and maintaining equipment in the area, considering carrier movement, procedures for stoppages, and normal operating rules. Specific safety considerations are unique to each individual and proprietary system, dependent on handling system technology and intended operations.

3.4.2 Outputs

During the design analysis process, outputs should consider all items necessary for Design Approval, both fundamentally, and internally for the Customers. Generally, these can include, a Functional Design Specification, a System Layout, an updated Potential Problem Analysis, the revised installation plan, and the revised simulation model to the appropriate level of detail. The Functional Design Specification (terminology will vary depending on the customer) should consist of all relevant items necessary to conduct the final step of the Design Process as well as begin the Manufacture/Build Stage. The revised version of the simulation model can be critical to the Design Approval activities, consequently, a generic model methodology has been defined for power and free systems and will be reviewed in the following chapter.

4. SIMULATION METHODOLOGY FOR POWER AND FREE SYSTEMS

Structuring the simulation activities of power and free systems into IDEF format provides consistency to the design approach, comparable to the analytical power and free systems design. It requires a focus on "what is happening" as is a requirement of Discrete Event Simulation and although identified, it steers away from the organisational structure of "who is doing it", necessary in practice, but not particularly relevant to the actual simulation steps.[13] Overall objectives for the project become the input for the actual model build process, however, they also influence the controls, used in determining the level of model detail required. As with design of the actual system, simulation can address both the physical (layout) and logical (material flow) aspects, as discussed by Massey (et al.).[75] Although discussing design in the context of hierarchical, top down identification using alternative methods, general success is based on a common, repeatable design methodology, which supports the use of an structured format, one that IDEF provides. The format is used to divide the system into manageable sections for simulation and analysis, to produce a more effective result for simulation projects. From the standard simulation steps identified previously, a methodology for simulating automated systems was created, and is illustrated in figure 30.

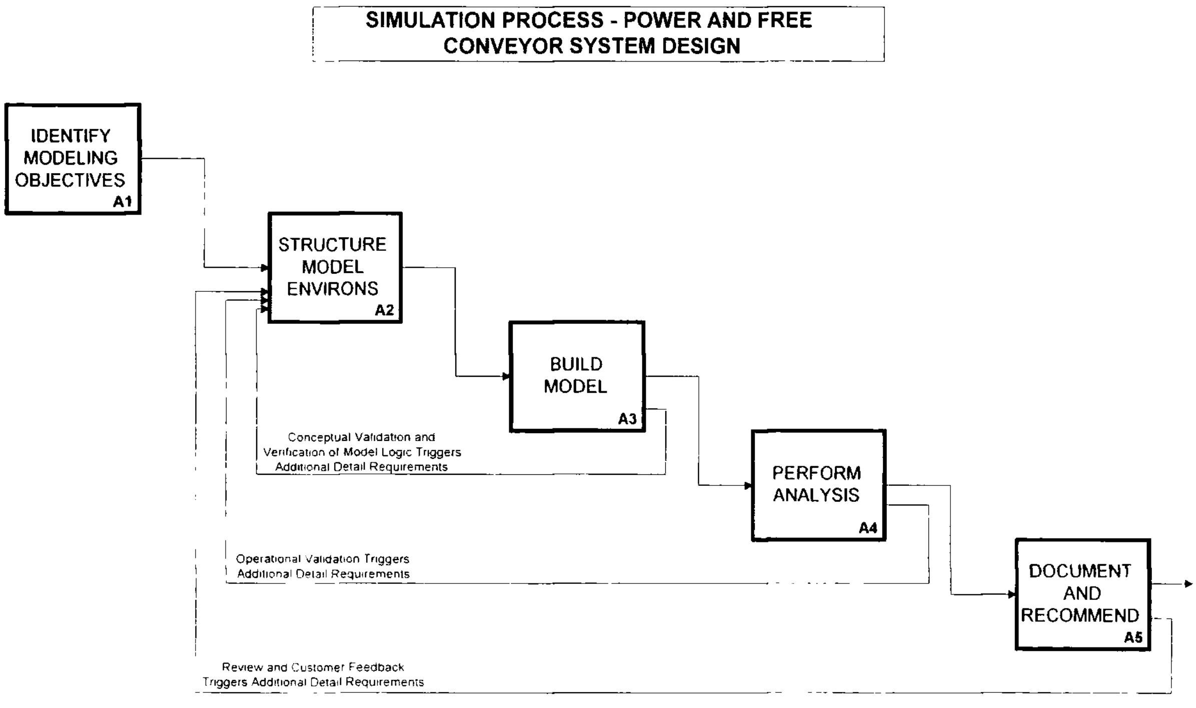


Figure 30. Simulation Methodology for Automated Systems.

The above methodology generally incorporates the four phased approach as recommended by Benjamin (e.g., Definition of the Scope, Modeling the System, Analysing the Results, Making Decisions), however, it expands from this method by including a primary step of Objective Definition. This is seen as critical for an effective, successful project. Further, "conceptual validation" (i.e., does the model behaviour appear correct), verification (i.e., logic coding accuracy checks) and "operational validation" (i.e., using established walk-through and statistical confidence/hypothesis testing techniques) are incorporated into the iterative process of structuring the model through analysis, to documenting and recommending next steps. This part of the approach is intended to illustrate the various types of validation/verification as they have been identified by Law (et al.)[76] and how they can fit into the structure of building power and free system models.

4.1 The Role of Validation and Verification

Validation and verification, an established necessary part of a simulation project, is embedded within each stage under this methodology. Support for this approach includes past investigations into the success of simulation projects, including studies performed by Carson, Benjamin (et al.), and Houshyar (et al.) [77 32 78] The above methodology with feedback loops resulting from validation and verification activities is an attempt to illustrate a level of approach to a simulation problem. In other words, the simulation definition should start at a relatively high level of model detail and only include further detail as is determined necessary through constant checking. To eliminate or reduce the possibility of wasting time and effort by producing inaccurate or misdirected models, a combination of customer reviews, observations to accepted standards, and statistical methods is recommended.

Banks and Carson suggest that verification consist of several techniques, including, direct check of the code by the programmer, comparison to a flow diagram (thus supporting the need for a systematic technique to capture event and process flow), observation for "reasonableness" given various input parameters using sensitivity analysis and other standard tools, checking for input data consistency throughout the model run, and documenting as effectively as possible.[3] The WITNESS package assists with the program debugging and model statistics by constantly verifying the lines of code input for element actions and rules, and automatically capturing a wide range of model statistics including, real-time and end run figures, measures which will be discussed in the case studies.

4.2 Identifying Model Objectives

Factors that were considered as inputs to the project objectives stage included the overall engineering project objectives, assumptions or background information on the new or existing system, and anticipated benefits from the simulation experiments. Controlling factors on the objectives for a simulation project included, available time and available resources, i.e., software type, money and personnel knowledgeable in simulation and statistical techniques. Further controlling factors which affected the formulation of simulation objectives, as illustrated in the case studies included, engineering project objective boundaries (i.e., what the engineering project was intended to accomplish), and simulation software capability (particularly for detailed device modelling).

Outputs from this stage included a specification of the project objectives in the form of a Simulation User (Customer) Requirement Specification. The requirement specification included, a direct summary of anticipated end goals (Objectives Summary), anticipated constraints such as timescale, a background summary of the engineering project activities/objectives, a system description, a scope of supply, project exclusions, a system schematic/layout, and brief process descriptions. All these items were used as inputs to structuring the model boundaries.

4.3 Structuring the Model Environs

Structuring the model environs, refers to creating boundaries both in scope (beginning and end points), depth (level of detail), and the user interface for the eventual model creation. Controlling factors for structuring the model environs included, evaluation of the end user's (customer) capabilities, and the engineering project objective boundaries. The required structure of the simulation software program, or that which the software needed to accurately capture the defined elements, was identified as a further control factor, due to its effects on the methods for data capture and identification for subsequent stages. Outputs at this stage were structured for providing guidance to the model building stage (i.e., where to effectively focus most effort), and included, identification of the physical elements, detailed depth for the model elements by process description, and the description of user interface required.

It has been shown that visually and graphically representing the conceptual design of the system can improve the overall design results and decrease the design time, as discussed by Alabastro (et al.).[79] This includes using process mapping techniques to complement the simulation build process, not simply building the graphic simulation model. Further, it was shown that by introducing these techniques early in the Design and Build Stages, ownership as well as communications improved, resulting in better execution of the overall design activities. Other standard tools, such as the data documents necessary for element definition, the System Schematic, and existing performance measures/reports create the model's physical boundaries and thus can be used as outputs from the Structure Process to initiate the Model Build Process. Identified boundaries should naturally identify the required inputs for the Build stage. Other standardised tools have been created to assist in analysis and model handover and will be discussed in subsequent chapters.

4.4 Building the Model

The model building process has been divided into two distinct areas: model elements, or the structure of the model required for interactive analysis and animation, and model reports, the structure required for evaluating model results.

4.4.1 Model Elements

Using the WITNESS simulation program, building activities are broken down in to three parts: define, display and detail. As inputs, the tools described above should give guidance to these activities. The relationship between the physical system and the simulation model are linked by their need for formal specification, as reviewed by Ma.[80] Properly specifying the high level requirements with the input from "domain specialists" should aid in the creation of lower level simulation models providing the following general aspects of the system are included:

- Assumptions (of flow, quantities, rates, etc.).
- System Structure.
- System Components.
- Initial and Steady System States.
- Indication and acceptance of differences in actual and modelled system behaviour.
- Change Requirements for System States.

These aspects, along with the simulation software structure, become the controlling factors affecting the model build process. As shown in the structured diagram, the building of the model is an iterative process potentially going from simple to complex, but in a focused way. For example, a manual inspection process may have three variables in the process for, when a reject occurs, how long it takes to process a good product, and how long it takes to process a reject product. Modelling this behaviour would probably start at a basic level, with the rejects occurring randomly, and a standard, theoretical distribution being used for the cycle times of the process. Then, as more information is known about the process, and it is tested for significance during the Analysis Stage, more sophisticated methods can be used, if required, such as "user-defined" distributions and creation of rejects occurring successively for a period of time as would probably be the case with in-line processes (due to process parameters drifting if not constantly checked and adjusted). Alternatively, it may be sufficient to keep the simpler representation. This depends on the integral verification and validation activities mentioned previously. Therefore, controls for the element detail process would be the standard distributions for goodness of fit for stochastic behaviour of elements. Note, however, that much of the design of power and free systems can be based on deterministic behaviour of elements, assuming a worse case for the analytical models.

Every simulation will contain different specific inputs, controls and outputs depending on the level of detail at the model build stage. Regarding engineering system simulation at PCL, three levels of system design related to the level of simulation model detail were identified:

1. Overall Manufacturing Design (plant to plant or general process to process).
2. Individual Overall System Control (e.g., the entire power and free system with its interfacing components).
3. Detailed Device Control (e.g., the individual device control on the power and free system).

It is important not to model with too much detail if it is not significant. Many times, "significance" is simply an educated guess, however, if the model is built on simpler principles and found not to be performing as expected or true to actual performance, then the decision of "significance" can be a more educated one using established statistical methods. A combination of the project objectives and the verification/validation activities such as, statistical confidence testing and observed element behaviour, define criteria that is used in making the decision to go to the next successive stage down in detail. This is similar to the approach used by McDonnel (et al.) for design of a manufacturing system using simulation to support the decisions on different levels.[81] A hierarchical model of the manufacturing system is created, with each level containing different control objectives, dictating the stages of detail for the simulation model. Using this approach, a breakdown of general simulation design considerations or control objectives at each level involving power and free handling systems was identified:

Level 1 - Overall Manufacturing Design Factors (Multiple Manufacturing Systems - Plant level):

- General Manufacturing Process Speed Requirements.
- Process Utilisation Requirements.
- Dynamic Buffering Requirements.
- Top level rules for the handling system, including descriptions of the necessary processing components (e.g., on-line Inspection).

Level 2 - Overall System Design Factors (Within one production area - System level):

- Constraints on intended operating rules of the system.
- System operational control parameters (e.g., reports, displays, special high level control, imaginary reservoirs).
- Equipment requirements, including carriers, reservoir sizes (number of carriers required in a reservoir at any particular time), stop stations and junction points.
- Potential problem area analysis and contingency planning, requiring special control logic (e.g., to prevent abnormal queuing, blockages, improve carrier utilisation, etc.).
- System capability (i.e., throughput behaviour).
- Average delivery rates between boundary processes (e.g., Black Matrix to Flowcoat).

Level 3 - Detailed Mechanical and Control Design Factors (within one system - Device level):

- Physical positioning of sensors or trigger points and devices or equipment in the system.
- Type of Control Method to use for each reservoir.
- Detailed control logic for Safeties and Release Logic.
- Device capability (e.g., minimum, maximum and average throughput capability).
- Robustness of device control logic through analysis of "what-if" scenarios (e.g., the effectiveness of device logic safety given the coding sequence and the emergency-stop locations/timing).

For simulation of detailed device control, a more temporally-based tool is required to conceptually capture the device operations and rules. Operational device control is a sequential activity, while overall system design is an evolutionary process, and the tools used in building the model can reflect this characteristic. For example, $IDEF_0$ is a more evolutionary tool, identifying the "how", "what" and "where" system characteristics, in contrast to $IDEF_3$ or other event mapping techniques which are more sequential in their construction, identifying the "when". Further, capturing rules for device control can benefit from the GT approach, in which standard blocks or lines of code are created for every common device. For example, carrier movement rules were created for each type of reservoir control method when controlling individual carriers, which is similar to the SSE6 simulator approach employed by Farrington (et al.).[40]

When building the model, it is important to remain as generic and simple as possible in order to facilitate future changes. For example, if a simulation requires revision due to layout changes, it can be quickly changed if buffers are used to model the conveyor reservoirs. Only the time element requires updating. If any other type of element is used, such as conveyors or additional machine elements, it is more difficult due to their method of definition within the simulation program. Consequently, it is important to survey the elements of the simulation package prior to building a model in order to identify the least number of potential parameter changes.

A goal of the research was to understand the power and free system components using the analytical models to a level such that common elements could be created, to facilitate simulation understanding. It has been proven that analytical methods, as the ones described previously, can be used to cut down the amount of simulation complexity (in logic and the number of design runs) and the overall design time for the system.[47] It was anticipated that the use of standard or pre-designed elements specifically for simulation would be a contributor to reducing both the design time and operational logic errors. Past research into verification techniques has shown that it could improve at all stages with the use of a common model base from which to choose (pre-existing model code).[41] The more established the methodology or model, the less there is required to check, therefore, if standard elements can be defined for simulating power and free systems, it should improve project effectiveness. The case studies were used to identify the generic parts of this design process, due to their wide differences for roughly the same type of material handling system.

4.4.2 Model Reports

The process of building reports within the simulation is controlled by the project objectives and existing reports and performance measures used for the actual system. All relevant reports should directly correlate to the system measures identified at the Project Objectives Stage and the boundaries at the Structuring Stage. Understanding of the internal reporting capabilities of WITNESS is required so that none are created that are already captured automatically by the interface, such as, machine utilisation, and average buffer capacity. The steady-state reporting functions or critical performance indicators used in numerically analysing power and free systems included:

- Stop station (or processing station) and junction point statistics for the number of operations, and the percentage of time idle, busy, and blocked or waiting. Statistics such as the percentage of time down, on set-up, or repair are usually input factors defined by the modeller and only change if the behaviour is dependent on a constrained resource. These factors were not extensively analysed due to the nature of the power and free systems or the design objectives, i.e., being either fully automatic or designed for infinite resource in the areas of set-up and downtime figures.
- Conveyor statistics for the percentage of time empty, free-moving, blocked or queued, and averages for the amount of processing time per part (i.e., the amount of time the part spent on the section) and the number of parts on a section at any point in time.

- Buffer statistics (which are coupled with conveyor statistics due to the model design for conveyor reservoirs) for average number of parts, time per part, time any part spent waiting and number of parts having to wait.
- Part or carrier statistics for the number entered (for evaluating carrier requirements), average work-in process (WIP) and average time per part spent in the system.
- Timeseries or variable plots for maximum, minimum and average throughput (with standard deviation for last recorded values) per unit of time, total number of products loaded per time interval, and total number of products not loaded (missed opportunities) per time interval. System variables for part rejects were not considered, as they were model inputs and dependent on the specified level. No histogram reporting was used.

These reports along with the graphical representation and animation of the model elements were then used as inputs to the Analysis process.

4.5 Analysing and Experimenting with the Model

Although model analysis in the form of verification and validation is an integral part of the overall simulation methodology, the activities at this stage should be focused on the end result or the recommendations for further activities. Ideally, there are two types of model analysis: visual observation of model behaviour, and statistical testing of the numerical reporting for identifying levels of confidence. An additional input includes the identification of experimental boundaries in terms of data input such as the production program, the length of each simulation run, the number of runs or replications to establish independence, the initial model state conditions, and the length of the warm-up period.

Controlling the Analysis Stage, are established methods for analysis of variance and statistical significance, such as, T-Tests (for determining validity of simulation data in comparison to known data), established methods for determining the number of required replications, and methods for obtaining a range for a measured output given a specific level of confidence or desired accuracy. As the power and free systems studied can be classified as non-terminating systems, methods were based on those identified for steady-state operations. All report analysis activities for the warm-up period of the systems studied were observational, such as the average time for certain areas of the system to fill or empty, particularly in push/pull type systems. These were subjective measurements and not categorised strictly under controlling factors due to their variability of use. The results of the experimental runs are identified as the Outputs from this stage.

4.6 Documenting and Recommending Next Steps

The use of standard tools throughout the simulation process was intended to simplify the process of reporting, and subsequent acceptance by the customer. These tools translate effectively to documentation necessary to illustrate simulation structure and results for recommending the course of action. Depending on the initial engineering project objectives, three courses of action usually exist. Either the model results are accepted and the model is shelved, the results are accepted and the model is used for ongoing problem analysis on production situations, or the results are not accepted due to a lack of confidence in any one of the previous process steps, which should, in a strict sense, require review of the process from its Structure Stage, assuming the project objectives have not changed.

5. CASE STUDY - 215 SYSTEM MODEL AND ANALYSIS

5.1 Operational Characteristics

The 215 Handling System, as it became known on completion, consists of a power and free conveyor system transporting mask and screen combinations between the Black Matrix and Flowcoat processing areas. Prior to detailing any equipment characteristics, it was necessary to identify the basic components of the process. As it is identified within the overall factory manufacturing process reviewed in the Background section, the Black Matrix process sits at the fifth step (counting handling between processes as a step). Therefore, the operational characteristics for handling combinations from Black Matrix to Flowcoat, the sixth step, are are illustrated in figure 31.

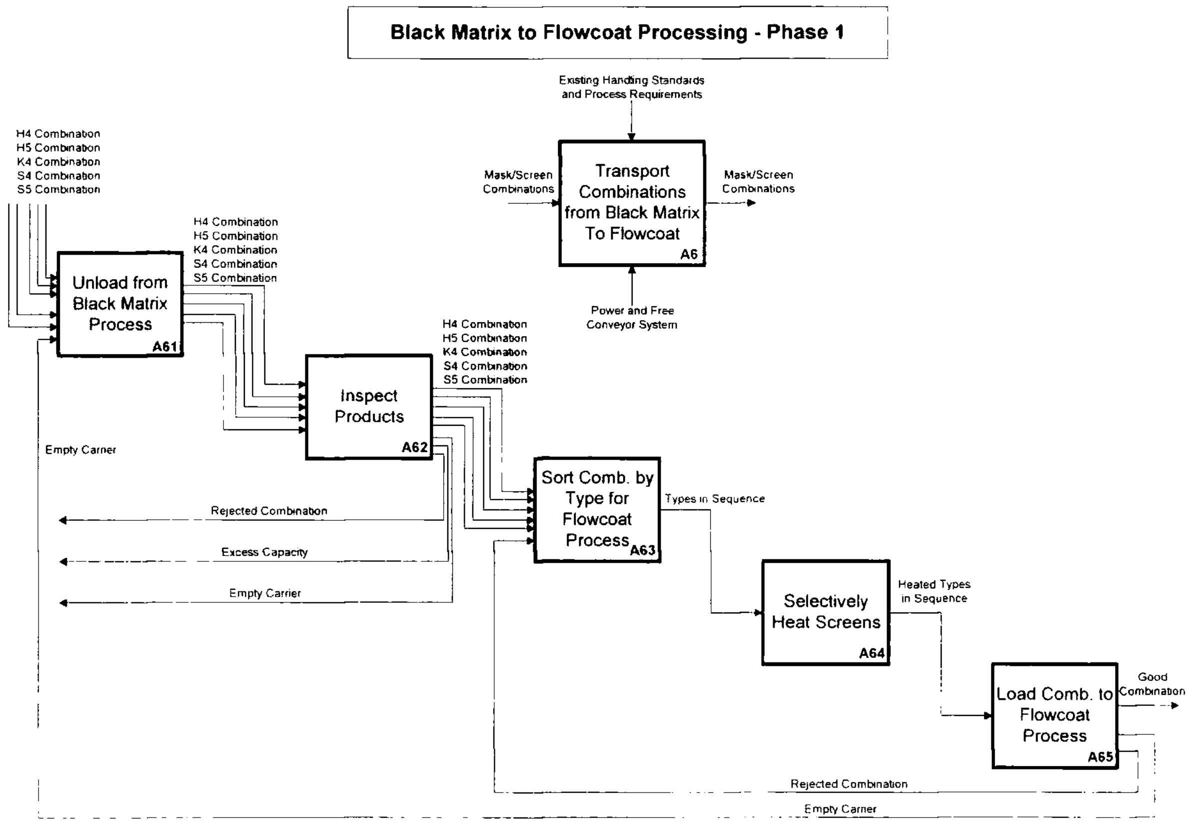


Figure 31. Process Map for Product Handling from Black Matrix to Flowcoat.

The "A" at each step denotes the IMT designation, e.g., A for IMT1, B for IMT2, etc. The process map can initiate layout design considerations, such as where to accommodate the type sequence requirement, and identification of the various buffers in the system.

5.1.1 Interfacing Equipment and Process Descriptions

In order to create the next level of detail, it is necessary to identify the interfacing equipment and specific routing requirements within the process map.

Matrix Line and Loading Equipment

Two independent Matrix Lines which process mask and screen combinations will be located at the start of the handling process. Each Matrix Line is an indexing process line (with finite positions) handling masks and screens that need to stay together as matched pairs throughout the entire manufacturing process. Each Line indexes on an internal clock signal which moves all combinations being processed on the line to the next position at the same time. Once combinations reach the end of the line, they are loaded as pairs by an anthropomorphic robot, located at the end of each line, to a waiting carrier and transported to the next processing point: Inspection. The index time for the line is 28.8 seconds or 125 combinations per hour, thus dictating the processing times for the robot.

Inspection

Once loaded, combinations will be transported to an on-line Inspection System, consisting of three process points where screens are unloaded from the handling systems, automatically and manually inspected for visual/surface defects, and loaded back to the original carrier. The Inspection System is a separate handling system located around the power and free system. Under normal operation, full carriers will advance to an unload point where the screen is unloaded to the Inspection System. The carrier, still containing the mask, is transported to holding point, awaiting confirmation of the screen. If the screen is rejected, both mask and screen are manually taken out of the system, resulting in an empty carrier. If the screen is accepted, a switch is made for verification, and both the mask (on the power and free system) and the screen (still on the Inspection System) travel to a load point, where the screen is loaded back to the carrier. Due to the sequential nature of the equipment, Inspection is always a first-in-first-out operation. Inspection cycle time must be able to accommodate two Matrix Lines' capacity or 250 per hour.

Routing After Inspection

Following Inspection, the carriers are transported to a junction point where their status is identified (empty or full and product type). Carriers are then routed to the next process or off the main flow line. Routing off the main line is required to accommodate a potential for excess capacity that Flowcoat cannot handle, or an error in product identification which could require manual assistance. Prior to being transported to Flowcoat, it is necessary to sort product types into a specific sequence. Flowcoat has limited equipment capacity for different types and as it is also a first-in-first-out process, combinations must arrive in sequence to fully utilise equipment and continue processing. As the sequence coming from the Matrix Lines cannot be guaranteed (due to random rejects), a re-patterning function must take place prior. Further, Flowcoat will eventually have the capacity to manufacture four different sub-types at one time in accordance to the factory master plan of four sub-types within a line, again using limited equipment to process the various types and requiring type sequencing. As a result of these requirements, combinations are sorted by type into one of four different lanes for routing to Flowcoat. The sorting lanes are not considered an interfacing process, as the power and free system can accommodate this function within the system.

Selective Heating

The Flowcoat process requires a screen surface temperature range of x +/- 1.5°C. Incoming screens will not be within the range required as they could be from stock or cooled in transport. Therefore, just prior to the Flowcoat process a series of on-line heating devices are required to heat the screens at fixed stop points. The cycle times through each of the stop positions are identical and correspond to the Flowcoat process speed.

Flowcoat Unload Point

Once screens are selectively heated, the combinations are transported to a manual unloading point. If the screens are within the temperature specification, the combination mask and screen is unloaded for Flowcoating. The resulting empty carrier is transported back to the Matrix process. If the screen is not within specification, the combination will be sent back on the handling system to begin the process of sorting and selectively heating again. The speed of Flowcoat in initial stages was 180 products per hour, which was increased to 225 products per hour in the a second phase of the engineering project.

5.1.2 Power and Free Conveyor System Schematic - Next Level of Detail

Based on the above model and interface descriptions, a more detailed schematic can be created, from which the conceptual or initial layout will be based. The schematic of the 215 System is illustrated in figure 32.

5.1.3 Schematic Description

The form of the above schematic for this level of detail was chosen over more detailed methods such as event-state mapping and $IDEF_3$[33], due to its user-friendliness, its ability to communicate system requirements to the Customer, and the need for a tool to assist in creation of the conceptual layout and simulation model. All relevant in-line and off-line processes are shown and described by name, activity, and process speed. All power and free conveyor routes are shown with direction lines in between specific process points. Process stops are defined as those points where carriers are required to stop for an interfacing process. Internal system stops, such as those required prior to junction points, and rise/fall sections are not shown. These will be dependent on the layout. Merges and diverts are shown as symbols for the relevant function between processes. All devices are shown for consideration of preliminary equipment considerations at this stage in the design process and points requiring priority rules for carrier routing, or design focus.

Empty carriers are transported to the end of the Matrix Lines on separate feeds, where they are loaded and transported to the Inspection System on a common feed. Inspection is as described previously, with carriers flowing through in sequential order. A side reservoir has been created to handle products either being unloaded from the system, checked for bar code condition, or to handle empty carriers for loading product back into the system from stock. A feedback reservoir has been added to accommodate empty carriers resulting from rejects at Inspection so that they can be returned to the process as soon as possible and not transported to Flowcoat. A feedback reservoir has been shown for full carriers (screens rejected for temperature) going back into the process after Matrix and Inspection to eliminate disruption to their carrier flow. In-line sorting harbours have been shown prior to heating and Flowcoat to buffer and re-pattern types for proper sequence routing.

Strategically, there is a requirement to buffer as Flowcoat is the bottleneck of the manufacturing area. Patterning into the Sorting Buffers needs to correspond to the potential production modes for a maximum of 25% type mix with four different types. Five unique patterns are identified in table 2.

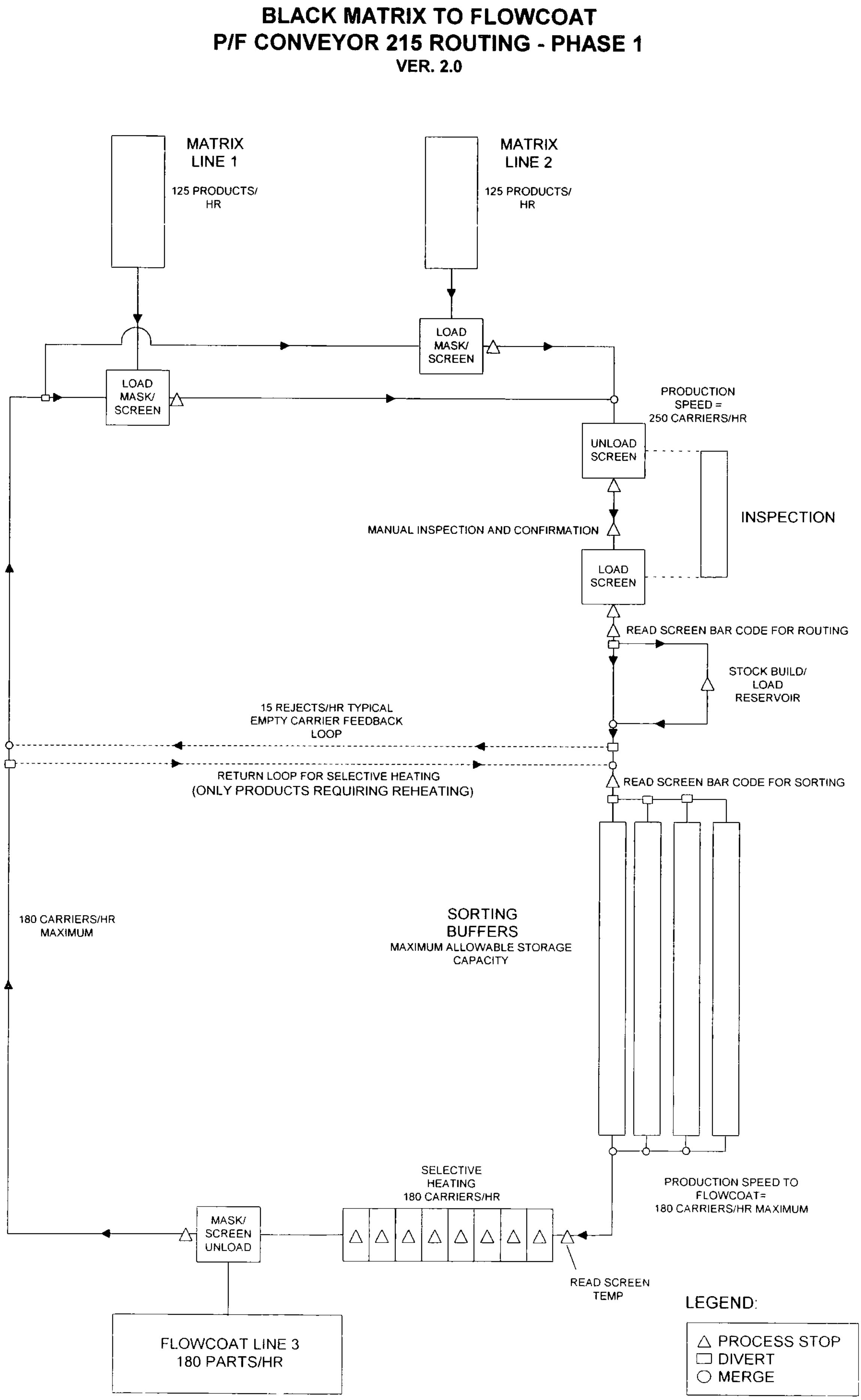


Figure 32. Schematic for the 215 System.

Table 2. Generic Sorting Patterns for Flowcoat.

Pattern No.	Sorting Lane 1	Sorting Lane 2	Sorting Lane 3	Sorting Lane 4
1	A	A	A	A
2	A	A	B	A
3	A	B	A	B
4	A	B	A	C
5	A	B	C	D

While products can be any type discussed previously, they are generically classified into four types (A, B, C, D) in accordance with the strategic Factory Master Plan restricting production to a maximum of four distinct types processed on the system at one time. Eight heating positions plus a pre-measuring position is shown to reflect the in-line selective heating requirements. The manual unloading to off-line Flowcoat is shown with a route for carriers returning to either the Matrix Lines or to the feedback loop to the Sorting Buffers.

5.1.4 Overall Engineering System Design Considerations

When designing the system at conceptual layout level, the following areas considered prior to any detailed engineering design included, temporary buffering, type sorting, potential problems with system logistics, given certain Production running situations or system states (based on operator functionality), general equipment requirements, such as the number of carriers required for operations, system capability from process to process, constraints for determining operating rules, layout restrictions, and identification of overall system control requirements such as routing logic and operator functions. These issues are in direct correspondence to the system level requirements reviewed in the previous chapter.

Dynamic/Temporary Buffering and Type Sorting

Dynamic buffering, or the buffering required for management of the bottleneck (Flowcoat) was defined at plant level to be approximately one hundred combinations or approximately one half hour of production capacity. This was determined using plant level simulations for strategic requirements from Matrix to Flowcoat by the Philips Corporate Design office and was not subject to the relevant research. It does, however, support the methodology previously discussed for level 1 simulations. As the power and free system contains the features of a sorting and buffering system, the following issues were considered, as discussed by Choi (et al.):[36]

- Avoidance or minimisation of carrier blocking either at process or junction points.
- Minimisation of the level of temporarily buffered (static) inventory. This was of particular concern due to the speed mismatch between Matrix and Flowcoat in the preliminary stages of production.
- Effective utilisation of the product patterning for production (i.e., ensuring that no types arrived to Flowcoat out of sequence).

A further objective of the handling system design was to leave ample WIP in front of Flowcoat in order to minimise the time needed to change over product type on the Matrix Lines, in accordance with standard bottleneck scheduling rules for manufacturing systems. This was accomplished by using a "transfer batch" or the number of products en route to Flowcoat to keep the amount of WIP to a minimum but still keep the bottleneck running efficiently.[6]

Potential Problems with System Logistics

Potential problems identified with the logistics or operating of the system were due to the fact that the layout and the system contained the following items:

- Feedback reservoirs (from Inspection and Flowcoat) that could cause problems for the main line flow.
- Synchronous Activities Coupled with Asynchronous - the system was combining both automatic processes (with little deviation in the cycle time) and manual processes (potentially a large amount of cycle time deviation).
- The Matrix Lines initially running at a much higher speed than Flowcoat would cause blocking of products coming from the Matrix Lines. Note, it was required that a Matrix Line run full and stop after it was empty, rather than running with gaps in the line, which is more costly. Therefore, the Matrix Lines required controlled stoppage when Flowcoat was well stocked.

General Equipment Requirements

Past experience with power and free systems had shown problems and/or confusion with the number of carriers required for a system, particularly for one combining automatic and manual processes. While the decision could be made to buy an excessive amount to cover design errors, identification of the optimum number was required, as too many carriers could also cause blocking problems.

System Capability, Layout Constraints and Control Requirements

Due to the amount of Production requirements for operating flexibility there would be certain constraints on the system or procedures governing system operation based on its capabilities. The capability and subsequent constraints required understanding and optimisation. The limited space and amount of interfacing equipment further placed limitations on the system (e.g., routing requiring high level approaches or decreases to certain reservoirs). These restrictions required identification and incorporation into the finished layout. Requirements for buffering, sorting, and handling rejects, placed operating logic rule constraints on the control system. Ideally, they required identification as early as possible to avoid changes at later stages under an uncontrolled environment.

5.1.5 Detailed System Design Considerations

Once the conceptual layout was created, detailed design parameters came under consideration, which included:

- Determination of the method of control from reservoir to reservoir (to improve equipment utilisation based on the observation that the less complicated the control method, the more reliable the system).
- Positioning of control equipment such as sensors.
- Determination of detailed control logic for safe operation and operational requirements.
- Review of Potential Problems with logic sequences.
- Determination of maximum device capability (i.e., speed and throughput).
- Creation of operator interface displays.
- Identification of equipment interface requirements (electrical and control).

5.2 Modelling Objectives

From the above design considerations, the following objectives were developed for the simulation project:

- Reduce project costs (initial design and future implementation stages).
- Reduce risk to the project by improving design confidence.
- Improve Customer ownership through use as a training aid.
- Justify the purchase of the WITNESS package.

Project Cost Reduction - Applications as a Problem Analysis and Control Design Tool

The areas addressed for reducing project costs included activities in both the design and implementation stages. Determination of the criteria for operating rules and system functions in the PLC program for reducing the design time (e.g., guidelines for priority at junction points, etc.) was considered. General control aspects included, carrier flow throughout the system and individual device control into reservoirs and junction points. Specifically, control design decisions included, identifying priority logic at junction points, logical and mechanical traffic control for junction points, such as sensors in the correct location or deadlock avoidance in the system. The goal was to identify zone control requirements to avoid too many carriers in various parts of the system creating blockages. Further, the simulation was intended to reduce time and effort needed for commissioning by using it as a tool for "live" troubleshooting.

Risk Reduction - Applications as a Potential Problem Analysis Tool

Previous implementation of power and free systems of a similar design had historically been designed with inherent problems, consequently, the aim was to use the simulation to explore design alternatives and confirm a recommended approach in the areas of:

1. **Equipment** - Confirming speeds and carrier requirements as recommended by the supplier and considering worse case scenarios.
2. **Layout** - Investigating and confirming minimum/maximum acceptable sizes of reservoirs and buffers, particularly where space was a premium in the building. Layout studies also included understanding the behaviour of the conveyor system prior to a bottleneck process, i.e., observing the "pipe-line" affect under specific production situations. Further, verification of how many products were required from Black Matrix to Flowcoat was a consideration. As the route (once carriers left the Matrix Cleanroom) involved travelling through a potentially "dirty" tunnel, the goal was to minimise the number of carriers en route, and maintain an uninterrupted flow to Flowcoat.
3. **System operations** - Testing lane priority and carrier routing to create scenarios for potential carrier deadlock and "traffic jams". Due to the requirements for simulating a system, it was anticipated that the design team could increase its understanding of power and free principles, and improve the in-house design knowledge base. The simulation model was also to be developed as a tool to test "what-if" scenarios to build up understanding of the particular system; e.g. identification of general rules for main flow and side flow reservoirs.

Improved Customer Ownership - Applications as a Training Tool

Due to the graphical nature of the WITNESS simulation package, it was anticipated to use it as a training tool for both Maintenance and Production personnel prior to the system being installed. The operation of the system did not require a detailed knowledge of power and free principles, however, it did require a good working knowledge of carrier flow and reaction to potential problems. Thus, it was anticipated that the simulation could facilitate the eventual ownership of these two groups.

Justification for Purchasing WITNESS

PCL Durham had historically used outside consultants to build and interpret the simulation models with limited success. Strategically, it was decided to use the 215 Conveyor System as a test case from which to prove the tangible and intangible benefits of simulation for a capital purchase. Using the tangible benefits from the project cost reduction and the intangible benefits from reducing project risk, it was anticipated that they would form the beginnings of a sound, systematic approach to simulation and its uses within the PCL factory, justification for its continued significance.

5.3 Modelling Project Methodologies Used

The design and subsequent modelling project objectives contained both detailed device considerations and general system considerations. As a result, it was decided to split the models into two types, in accordance with the two levels of system design considerations previously discussed: Detailed device level modelling (level 3), and system level modelling (level 2).

5.4 Device Level Model Specifications

Although the general system model (level 2) was considered first in the process of simulating, due to the lack of understanding and existing measures for power and free systems to validate simulation activities, it was decided to build the detailed level first, based on the understanding that building the detail could: 1. Be used for building the overall system model, 2. Have a greater impact for the designer on understanding power and free device principles, and 3. Give guidelines for the overall model and future models on the level of detail required for modelling accuracy. Using the general methodology for structuring, building and analysing, individual reservoir models were developed for the different types of reservoir control: Presence Carrier, Saturation and Counting.

5.4.1 Carrier Presence Control Model

Based on the devices used and design of this type of reservoir, the following elements to define in the model include, Carriers, Stop Stations, Conveyor Sections (level and rise/fall sections), Pusher Dogs, the Carrier Present Sensor, and the Pusher Dog Sensor. These items are illustrated in figure 33.

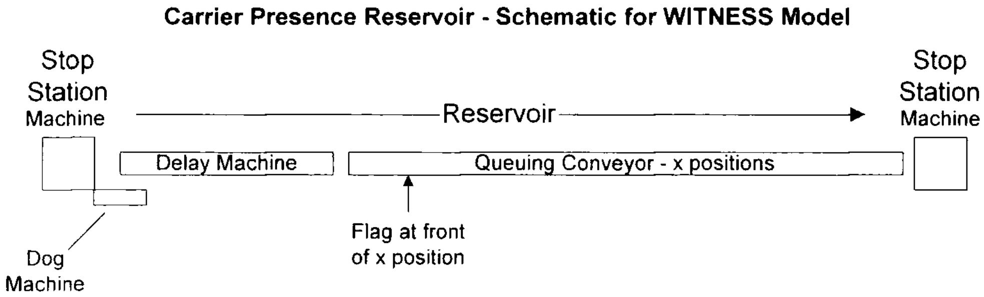


Figure 33. Simulation Schematic for Carrier Presence Reservoir Model.

A structured flow diagram similar to $IDEF_3$ was created to identify carrier release logic from the stop station, and is illustrated in figure 34.

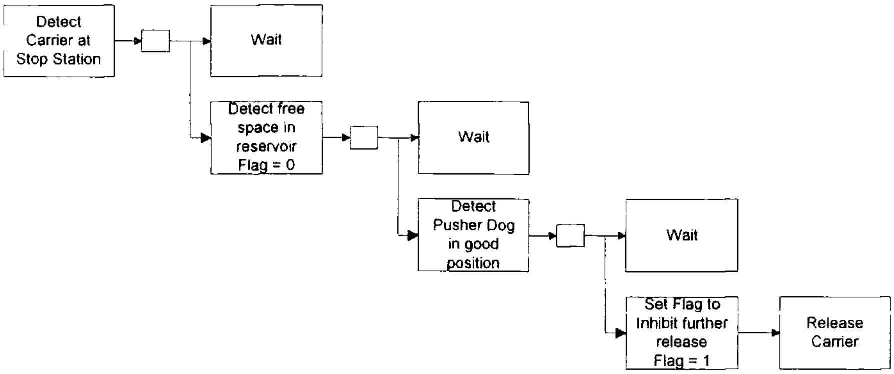


Figure 34. Detailed Process Map for Carrier Presence Control.

The flag would not be reset until the carrier travelled past the x position. The sequence is also used in the creation of the PLC code for the stop station device. The actual PLC sequence, however, includes detail about the system that is not used in the model, such as, safety checks to prevent the system from mechanically jamming or injuring someone, and checks for other devices such as solenoids for valve operation (stop station open and close). All these internal checks were not considered necessary to simulating at device level, as these are standard system monitoring functions that did not contribute to the simulation project objectives.

5.4.1.1 Model Elements

Carriers on the actual system are modelled as "parts" in the simulation model. In most cases of detailed analysis, the actual part type is not of concern, but rather the presence of a carrier (empty or full) to route. Stop Stations are defined as single machines with a cycle time equivalent to one carrier pitch length (queuing pitch) divided by the chain speed. If a carrier is available to pull in, it will do so. In the case of isolated reservoir analysis, as shown above, the first stop station pulls a carrier in from the "outside world". The last stop station pulls a carrier in from the previous conveyor reservoir, and pushes it out to "ship" when finished processing.

Conveyor sections are divided into two fundamental entities: a section just after the stop station (modelled as a single machine) where no carriers are allowed to queue containing only one carrier, and a queuing conveyor section which holds the capacity of the reservoir as specified in the layout, minus one position for the stop station. Cycle time of the first section is dependent upon the position of the last carrier in the reservoir, which will give the length of necessary travel. Note, WITNESS defines conveyor sizes based on a part quantity, not an actual length. This poses a problem for power and free systems, as often the design is not based on a unit pitch length, being dependent on interfacing process positions. Therefore, the first section incorporates the "slack" or excess conveyor amount in the reservoir to capture the travel time.

Several system devices pose problems for the WITNESS logic, of which pusher dogs are an example. Recall that carriers are picked up and transported from reservoir to reservoir by pusher dogs on the main chain, which are set at deterministic positions, but could be positioned with relative randomness to the carrier when it receives the signal to release. For carrier flow, this means that a carrier is not released when there is a space in the next reservoir, but also when a pusher dog is in position. Not all power and free systems work in this manner, (as will be illustrated in the AMS System Case Study) but in all systems, the positions of the pusher dogs create a delay from when the carrier is released to when it actually moves. In some systems, particularly the 215 system, the pusher dogs can cause a delay of as much as 2.4 seconds. If the interfacing processing time at the stop station is 280 per hour (as a typical example), this represents almost 20% of the overall stop station cycle time. Consequently, it was decided to investigate and model the pusher dog action, if possible.

For a Carrier Presence controlled reservoir, the effect of the time only element is required, as the trigger point for carrier release is not based on the pusher dogs, but a point in the reservoir. An alternative to modelling pusher dogs was to define them as active parts, created at time intervals equivalent to the dog pitch divided by the chain speed. As a carrier was ready to be released into the next reservoir, a flag variable was set to one. As the next pusher dog part was created it would reset the flag to zero. In the release criteria for the stop station, if the flag was equal to zero, it would release. Two problems were identified with this logic. It would only simulate the varied release if the reservoir was not full (i.e., as the reservoir was full, the flag would be set to zero before the carrier was ready to release). Creating a part every 2.4 seconds for every stop station was very computer intensive and slowed the model down to below real time viewing. A second alternative was therefore devised which modelled the time delay (or the flow characteristic) but not the pusher dogs. To model the carrier delay release, the stop station does not pull a second carrier in until the dog machine is "idle" or empty. This effectively models the pusher dog effects on carrier flow while reducing the computer processing time required.

The pusher dog sensor is inherently modelled within the cycle time logic of the dog machine described above. The carrier present sensor, or the sensor that signals an available space in the reservoir, highlights a second problem with WITNESS structure. Realistically, sensors could be placed on a conveyor track section at any point in the reservoir. In the simulation, sensors can be modelled as variable flags triggered when carriers pass through various beginning or end points in the model. However, to have a flag triggered on a conveyor position other then at the front or back, the conveyor needs to be internally "split" into individual positions. WITNESS does allow a conveyor to be defined by one name having N positions or quantity = N, albeit the method is cumbersome. This approach was used for modelling trigger sensors within reservoirs. For example, if a Carrier Presence reservoir can hold five carriers, a queuing conveyor with quantity equal to four is created. As the carrier moves to the front of position one, the first position reached in the reservoir, a flag variable (sensor) is set to one inhibiting any further release. If the carrier is the last in the reservoir it will sit at position one and the flag will remain set. As it moves to the back of position two, the flag is set to zero allowing release of another carrier. This is not strictly accurate due to sensor response, however, it does capture the relative position and general reaction of a sensor in a reservoir.

5.4.1.2 Model Variables

In order to make the detailed control as generic as possible for future design studies, the following characteristics of the control method and the power and free system were defined as variables, or common to most power and free systems:

CP	-	Carrier Pitch (in M).
CS	-	Chain Speed of the main driving chain (in M/min).
DPITCH	-	Pitch of the pusher dogs on the main driving chain (in M).
PDIST	-	Pitch between the pusher dog sensor and the c/l of the carrier (in M).
STORE	-	Length of storage in the reservoir (in M).
LBSS	-	Length between stop stations (in M).
RFLAG	-	Integer flag to inhibit carrier release from the stop station to the carrier present sensor in the following reservoir.

These variables are based on the general terminology used for describing general power and free systems as identified from analytical methods.

5.4.2 Counting Control Model

The same elements were required for definition as with the Carrier Presence Model, however, as the control logic is different, the schematic and logic sequence was altered accordingly, as illustrated in figures 35 and 36.

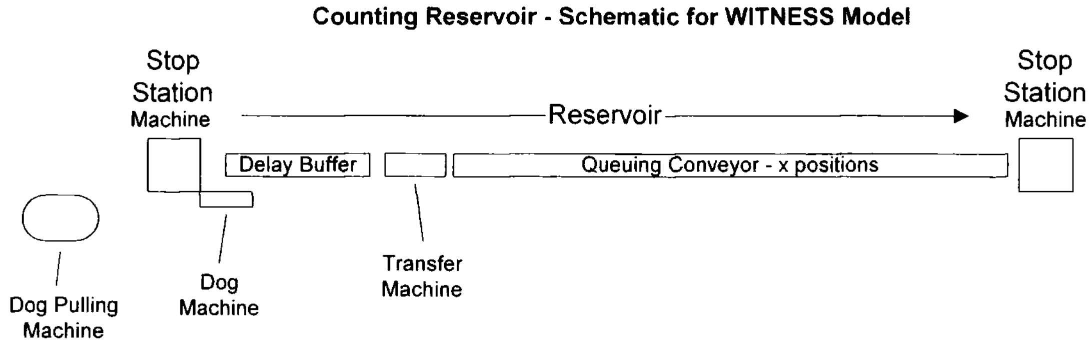


Figure 35. Simulation Schematic for Counting Reservoir Model.

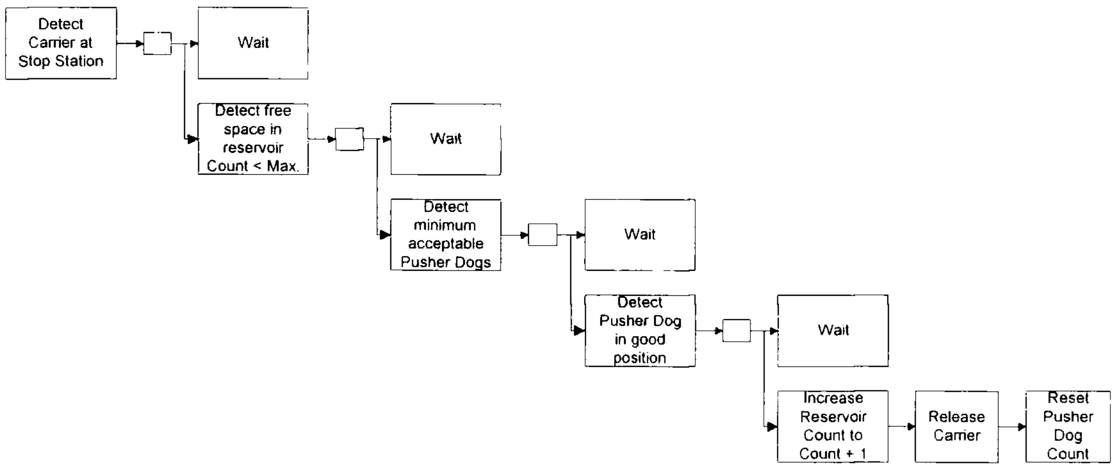


Figure 36. Detailed Process Map for Counting Control.

The Counting Model differs from the Carrier Presence Model in that the release of carriers if the following reservoir is empty, assuming a steady stream of carriers, is on a pitch of five pusher dogs; a deterministic pitch. Otherwise, it is dependent on the interfacing processing times and the position of the next available dog. Therefore, to accurately model this behaviour, the following additional elements are added:

- DOG - A part to simulate the arrival of pusher dogs past the stop station.
- DMACH - A machine to control the arrival of pusher dogs.
- SLACKBUF - A buffer to simulate the delay time of the carrier to the end of the reservoir.
- TFR - An internal machine required to pull carriers from the buffer and route to the queuing conveyor or main reservoir element; necessary due to WITNESS conventions for pulling with a queuing conveyor.
- DMACHCT - A variable to simulate the deterministic or stochastic cycle time for the carrier actually moving from the stop station with the value dependent on the dynamic situation.

- DOGCOUNT - A variable used to indicate the minimum number of dogs passing the stop station for safe release.
- RCOUNT - A variable indicating the total count in the following reservoir acting as the trigger to release from the stop station.

Under Counting control, carriers can be released on a deterministic pitch of N dogs or randomly depending on the interfacing process. The generic method identified to capture the deterministic behaviour was to model dogs as parts in the system. To reduce the amount of computer processing time, a machine was introduced to actively pull the minimum dogs required for a safe running pitch and stop when the number was reached. As the Counting control allowed more carriers between the stop station and the end of the reservoir, a multi-capacity buffer replaced a single capacity machine. No sensor flags were used in this model. On the actual system, they are only used for system safety, which was not under simulation consideration.

5.4.3 Saturation Control Model

For simulation, Saturation Control combines properties of both the Presence Carrier and Counting control methods. The schematic and logic sequence is shown in figures 37 and 38.

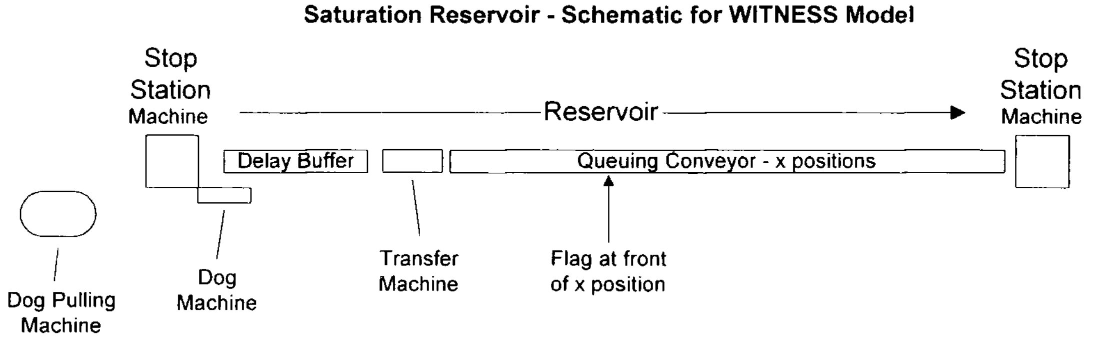


Figure 37. Simulation Schematic for Saturation Reservoir Model.

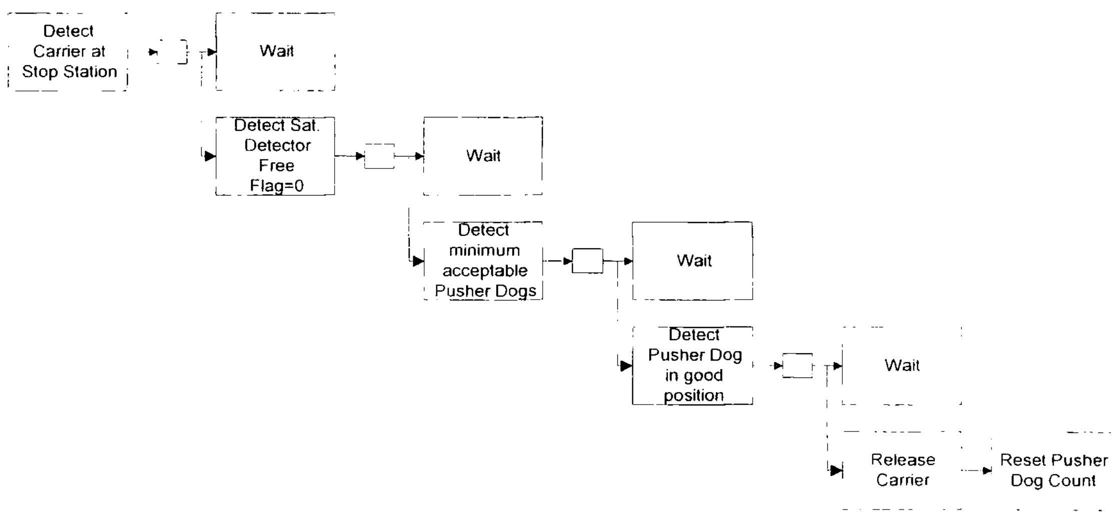


Figure 38. Detailed Process Map for Saturation Control.

Much of the logic was already created from the previous models, however, two additional variables were created, SATPSN, and RESCAP. SATPSN is used to generically define the saturation position for the reservoir, and is used to calculate the position of the flag for inhibiting release of any further carriers into the reservoir. RESCAP is used to define the capacity of the reservoir and also used in the equation to determine the position on the conveyor for setting or resetting the inhibit flag.

5.4.4 Measures, Validation and Verification

All the reservoirs were checked against the analytical models discussed in the previous chapter, and eventually, the actual working system. As the generic structured flow diagrams for the actual system's logic sequences were used to build the simulation models, verification was based on observation of the carriers within each simulation. Further measures included, average throughput, average running pitch between carriers, average carriers normally running within a reservoir in a non-queuing situation, and behaviour of the reservoir under static conditions.

Throughput was checked by creating a timeseries plot for carriers released from the initial stop station and comparing these figures to the analytical calculations. Average running pitch was recorded and also checked against expected running pitch. Using the length between stop stations, calculated running pitch, and an average cycle time for pusher dog availability, the expected number of carriers in a reservoir was validated against the average simulated. The Saturation Reservoir was of particular interest for validating it against static operations, as the logic for the location of the saturation sensor is critical if the model is to be used for positioning problems. For example, if the buffer used for slack at the end of the reservoir was ever blocked, this would simulate sensors being in the wrong locations, which could be checked against historical data. It should be noted that while the simulation measures were verified based on real system, observation, and calculated analytical averages, rigorous statistical methods for confidence were not conducted, as the simulation models were a mirror of the analytical models and would not have revealed or confirmed the simulation with any additional accuracy.

5.4.5 Preliminary Conclusions for Detailed Level Models

These base, generic models can be used to create specific, detailed reservoir models which incorporate other elements and interactions such as junction points and interfacing processing times. While they approach 100% accuracy of the actual power and free system detail, several flaws have been identified, particularly regarding the pusher dogs and reservoir detectors.

The pusher dog behaviour is not always stochastic. Due to the specific spacing of the pusher dogs on the main chain, there is a deterministic release of a carrier, relative to when the stop station receives the signal to release, which is based on the process time at the following stop station and (in some cases) the size of the reservoir. If that process time is fixed within a very small variance, such as a robot loading process, the release of the carrier will probably be on a repeating cycle, equivalent to "n" number of pusher dogs. For detailed timing investigations, inaccuracies could result. For stop times with a higher variance, however, such as manual cycle times, the stochastic release of the carrier is more accurate, due to the greater variability in the release criteria.

For models relying on the carrier release from the last position, or when the next carrier is allowed into the reservoir, there is a lack of accuracy. The last carrier in the proceeding reservoir is simulated as leaving the position as soon as the carrier in front moves, and so on. In reality, the carriers move on a running pitch greater than the queuing pitch, therefore, the last carrier leaves at a slightly later time than is simulated.

Sensors have a reaction time, usually from 0.5 to 2.0 seconds, defined in the PLC code to avoid sensor "blips" or stray signals. An example would be a delay time defined for the Saturation sensor, to verify that a carrier is actually contacting the sensor. While the behaviour can be modelled by introducing an active part, created at the required delay interval when the carrier reaches the "sensor" and triggering a flag to simulate the sensor "contact", it creates additional complexity, increasing computer processing time. However, if the unit time is brought down to seconds and not minutes, the detail might be effectively analysed. There is also a further complication of the size of the sensing "target" which does not give the free signal back to the controller until it is completely free of the sensor. The model assumes a point target with no delayed reaction. Again, this can be modelled with the addition of an active part with a processing time dependent on the size of the sensing area and the speed of the chain, again increasing the complexity.

Based on these apparent problems, and the time taken to build, replicate and explain the logic sequences, it was determined that using the analytical methods and designing for a worse case was a more cost effective method of designing the detail for power and free systems. However, the models can be valuable training aids for the novice system designer to understand how the various control methods operate. They can also be used for investigating a specific part of the system that might be causing current problems or potential areas for concentration of design efforts. For example, they proved helpful in re-designing the Saturation Control reservoirs that included a merge, divert or complicated combination of the two, when the initial placement of sensors was incorrect. Now created, they are justifiable for future detailed considerations, however, analytical tools are still recommended for the system detail for every reservoir. Simulation models for the detailed reservoir control methods should be used surgically to examine specific detailed areas, and no further, or they could ineffectively utilise precious design time.

5.5 System Level Model Specification

As with the detailed level, determination of the modelling approach and element detail was required for the system level. However, different from the detailed level, was the primary need for simplicity and efficiency, while still maintaining model accuracy and design confidence. A preliminary potential problem analysis was devised involving both the suppliers and the customers to determine the problems in the system those that would require additional operator functionality within the system control. Based on the results of the analysis and observations of the detailed simulations, a description of the modelled elements can be found below. Generally, the criteria used was that if it was seen to affect the flow, it was captured in the simulation requirements.

5.5.1 Conveyor System Devices and Equipment

Similar to the detailed level, stop stations were defined as machines. In most cases, they have been designed as single machines, with a fixed cycle time equivalent to the carrier travel (or a carrier pitch). The release from the stop station is then dependent on several conditions depending on its location within the system, including, the capacity status of the next reservoir, and the state of the interfacing process. Prior to releasing a carrier, the reservoir status and interfacing process criteria which has been configured as variable flags within the system are checked. An exception to the single machine configuration, was that used to model the stop station at Flowcoat. In this case, it was modelled as a multi-cycle machine with the first cycle being the carrier travel time into the stop station and a second cycle equivalent the cycle time for unloading the carrier or releasing it as a reject back to the Matrix area. As Flowcoat was the last process, the dynamics were not under investigation, therefore, the multi-cycle machine was a more efficient method.

Reservoir modelling was also based on the detailed structure, however, the intention was to eliminate as many additional elements as possible and design a generic configuration to reduce model build time. The resulting generic reservoir types are identified in figure 39.

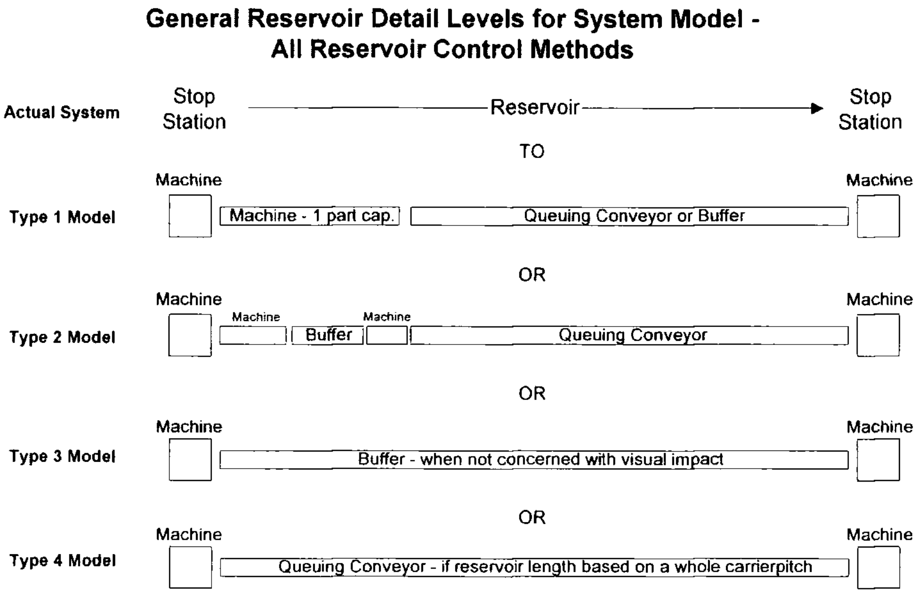


Figure 39. Generic Simulation Schematics for System Level.

The Type 1 configuration can be used for all Presence Carrier Control Reservoirs. The machine following the stop station would have a cycle time equivalent to the distance from the stop station to the last position in the reservoir, including the position. For Saturation and Counting, Type 1 can only be used in all cases if a buffer is incorporated. Further, the cycle time of the machine following the stop station should be equivalent to the minimum safe pitch between carriers. If the actual reservoir is not sized on a whole carrier pitch and evaluation of carrier flow is desired, Type 2 design is necessary, to capture accurate travel times and relative positions. The decision is dependent on visual analysis and animation requirements. Type 3 and 4 designs could be used if the reservoir is based on a whole carrier pitch, implying no slack, with Type 4 being used for added visual evaluation. Often, these can be used with an FMS, as the conveyor system is usually designed as compact as possible with carriers being stored as efficiently as possible.

It should be noted that the Dog Machine used at the detail level could be included if it was anticipated that an interfacing process would be waiting for the second carrier to get in position, the action thus causing a delay to the interfacing process. An example would be the manual Inspection station, in which the Inspector is always waiting to service the next carrier. However, this application is limited as most processes are designed so that the function is performed in other parts of the cycle not necessarily requiring the conveyor carrier, performing functions in parallel and reducing the throughput. An example would be the robot loading function at the end of the Matrix Lines.

The generic models are an effective representation of reservoirs at the system level due to the fact that for key processes, the analytical design normally accounts for a carrier waiting to get into position, therefore, the general position of that second carrier is sufficient. Further, pusher dog behaviour around manual interfaces such as Inspection and the Flowcoat unloading point could be modelled within the cycle time of the unloading process. This can be done due to the assumption that a person is always available to process the carrier. Although not entirely realistic, unlimited resource availability was seen as a valid assumption and a necessity for designing a relatively automatic system, therefore, pusher dogs were not directly modelled at the system level.

Merges and diverts, or junction points were modelled as single machines immediately following a stop station. The size or cycle time of the junction point was reflective of the controlled area, or the area in which only one carrier was allowed, naturally inhibiting the next carrier from being released and eliminating the need to have separate flag variables at various points. Carriers travelling through a divert all do so on an identical cycle time, as it is the following reservoir that could be of variable length. Travel time into the reservoir was addressed after the divert, therefore its time was fixed. Merges, however, had a variable cycle time due to the fact that the carrier could be from one of several routes containing varying distances. Depending on the destination, or its stop station origin, carriers were assigned a tag that, used by the junction point to either identify its destination for a divert or the appropriate merge cycle time.

Carriers were modelled as parts, being introduced at an appropriate position within the system that simulates an actual start-up situation, allowing them to queue opposite the Matrix Lines in anticipation for Production. An individual carrier assumed various characteristics depending upon its status, which could be empty, loaded with the four part types, or partially loaded with a Mask. A part "attribute" called CODE was used indicate the carrier status. As it is an enclosed system, there were only a finite number of carriers allowed into the model to investigate the optimum number given certain running situations.

Stock harbour and sorting buffer areas were modelled using standard elements as with the other conveyor reservoirs. Routing criteria, however, was based on the status of the operational settings. Standard conveyor sections were chosen over special configurations such as capacity buffers, in order to adhere as close to the actual system as possible and observe carrier flow. Consistent with the objective of using the simulation as a training tool, operator controls were modelled to illustrate their effects on the system. In actuality, operator controls took two forms, mechanical switches on a remote panel or station that directly or immediately affect carrier movement, and menu-driven controls/defaults configured on the PLC screen interface that indirectly affect carrier flow. Both types of operational settings were modelled as variables to identify status, identified in the system logic at the stop stations or interfacing processes. Modelling the controls was an iterative process, starting with the basic types first, and growing into what was perceived as significant. Generally, if it was anticipated operators would use the control to affect carrier flow during production, it was modelled. Otherwise, it was not necessary. An example of controls not modelled included maintenance type controls for devices and carrier flow used outside production or during a breakdown.

5.5.2 Interfacing Processes and Products

Screens and masks were not handled on the simulated power and free system. They were only created at various interfacing processing points within the system so that the interfacing process could hold or trigger the release of the carrier on the conveyor system. Products were, therefore, modelled as parts for an interfacing process, but as part "attributes" attached to a carrier with the description of "A", "B", "C", or "D" depending on the type.

The Matrix Lines were modelled using fixed, indexing conveyors. Two machines in front of the lines pulling screen types from the "outside world" and pushing them to the lines were used to model the fixed, synchronous, clock signal. Screen types and line speeds were defined for operator adjustment. Product loading to the power and free system was simulated with two machines per line. A robot pulls screens from the line and a dummy machine simulates loading to the carrier or triggers a stoppage if a carrier is not present. As the robot loading cycle times were not known, the simulated function was divided to investigate the process variability.

The Inspection function was modelled using a series of machines and buffers using the same approach as at the end of the Matrix Lines. However, screens being unloaded from, and loaded to carriers, was not modelled. Rather, the carrier was held at the stop station for the time taken for the loading/unloading operations, and its status was changed accordingly. The manual inspection process was modelled as a machine with a variable cycle time based on a theoretical statistical distribution. The variability in the inspection process could include, the affects of taking longer to process a reject than a good product due to the additional handling requirements, and the variations within the two types of activities. Handling rejects was simulated by a variable, randomly generated. While in some cases, rejects do not occur randomly, such as during a breakdown when a large number of successive rejects is generated, these instances were abnormal, and it was anticipated that a random generation was sufficient. Several statistical distributions were investigated for the variability within the inspection process, in particular, the Beta, Erlang K, Log Normal, and Triangle Distributions, as these are normally associated with service times or times that are lacking in a sufficient amount of real data.[82] It was concluded to simulate these times using a Truncated Normal distribution, with the processing of a reject having a slightly higher processing time than one for a good product. This distribution was used due to the fact that the Inspection process is very closely coupled to an automated system, or the robots loading product two reservoirs backs from Inspection. Therefore, if the inspection time increased, the trigger to "speed up", (queuing carriers with eventually no carrier for the robot to load at the Matrix Line) would be immediately visible, limiting variations. This behaviour was proven on the actual system.

Selective Heating was modelled as a series of stop station machines, their cycle time equivalent to the travel between stops. Additional criteria consistent with the actual system was not to release a carrier to the next position if there is not a carrier available to enter the heating system. This was modelled by checking the initial stop station machine's state for the output rule on the remaining machines. If the initial machine's state was blocked or waiting to index, the remaining stops could index. As mentioned previously, Flowcoat was modelled within the cycle time of the stop station machine at its unload point. Its variable cycle time was based on whether the product had been rejected due to unacceptable temperatures.

Although the actual system requires the controlled intervention by an operator, it can run automatically in the mode set, for a certain amount of time. The availability of labour was not a design issue, as an infinite resource capacity was estimated. Further, there were only three points in the system in which labour could be a factor on the actual system, but this was not considered in the objectives of the modelling project. For these reasons, labour was not modelled, only its behaviour as variations within the manual processes.

No breakdowns were captured in the simulation as the actual system was designed to be continuous. In actuality, if a breakdown occurs on the conveyor system, everything on the system stops, the result of which, is obvious. Interfacing processes were designed with contingencies in mind, such as flatbelts for the Matrix Line robots to prevent Line inhibits if a carrier was unavailable. Likewise, no set-ups were captured, as all set-up functions either occur off-line, in parallel with production, or in a production shutdown. Shift patterns were not required due to the continuous nature of production.

5.5.3 Simulation Modelling Structures

5.5.3.1 Attributes and Variables

Attributes attached to the carriers on the system divided into, standard (those preset by the WITNESS software) and user-defined types. Standard types included, PEN, DESC, ICON, and TYPE. All are related to the visual qualities of a carrier on the system, with the exception of TYPE. PEN was used to modify the colour. DESC was used when displaying the written form of the part. ICON was used typically to show animation and referenced the icon library created or pre-defined in the software. TYPE identified the original part characteristic, different from the DESC. For example, the TYPE could be a "Carrier", but its DESC may be "A" if it is loaded with a Type A product. User-defined attributes for the power and free system included the following:

- CODE - A string attribute (meaning it can be defined by any string of characters) to identify the status of a carrier, i.e., Empty, Mask only, or loaded with A, B, C, or D Types.
- CADEST - A string attribute to identify the destination of a carrier for the output rule of a divert.
- CAPAST - A string attribute to identify the past location of a carrier to calculate the cycle time of a merge.
- HFAIL - An integer attribute (meaning it is defined by an integer) to identify if a screen has failed the Selective Heating process.

Variables were created in the system in accordance with the GT approach, based on the requirement to quickly adjust parameters to be changed during experimentation for validation and verification purposes or those parameters generally common to all power and free systems that could be applied to a new model. Variables were be identified as one of four different types, including, real number, integer, string or name. The string or name variables were convenient when communicating their settings to a non-WITNESS user, as the actual setting state could be used; e.g., "on" or "off" rather than 1 or 0. Several variables were also identified with more than one quantity. This is a convenient and time-saving device when identifying variables of a similar type that assume different states at the same time, such as reservoir counts for individually numbered reservoirs. Variables identified in the system were created from the following basic categories:

1. Internal Production Settings or Measures (e.g., incoming type mix, failure rates, etc.).
2. Internal Equipment Settings (e.g., speeds, carrier pitch lengths, reservoir capacities, etc.).
3. Operational System Settings from the Panel Switches.
4. Operational System Settings or Displayed Measures from the On-screen Interface.
5. Loop variables used for patterning requirements at various areas within the system.
6. Internal variables for device operation triggered for each carrier.

Internal Production Settings and Measures were defined as integer or real variables and included:

PROGRAM	-	Variable for the type of product mix.
NCARRIER	-	Maximum no. of carriers allowed in the system.
M1SPEED	-	Matrix line 1 speed in products per hour.
M2SPEED	-	Matrix line 2 speed in products per hour.
TO_FC	-	Preset no. of carriers allowed to flowcoat
SHSPEED	-	Speed of Selective Heating in products per hour.
FAILINSP	-	% failure rate at Inspection.
FAILSHTG	-	% failure rate at Selective Heating.
TEMPTIME	-	Time required to read and register screen temperature.
STKBLD	-	Trigger to indicate that full carriers be unloaded in Stock Harbour.
STKLD	-	Trigger to indicate that empty carriers be loaded in Stock Harbour.
STKTOT	-	Total no. of products in off-line stock.

Internal Equipment Settings were defined as real variables and included:

LINSPCYC	-	Time to load/unload a screen from carrier at Inspection.
LOAD1	-	Speed of the loading cycle for line 1 robot.
LOAD2	-	Speed of the loading cycle for line 2 robot.
INSPSNO	-	No. of positions prior to manual Inspection.

FCUNLOAD	-	Unload time at Flowcoat in minutes.
DPITCH	-	Pitch between dogs on main driving chain in meters.
ADPTCH	-	Averaging the dog pitch availability (DPITCH / 2).
PDIST	-	Distance from the pusher dog sensor to the carrier pickup.
SFPITCH	-	The acceptable minimum dog number between carriers (DPITCH x 5).
CP	-	Carrier pitch in meters.
CS	-	Conveyor speed in meters/minute.
RESCAP (39)	-	Reservoir Capacity of appropriate reservoir.
LBSS (39)	-	Length between Stop Stations in meters for the appropriate stop station.
DLENGTH (7)	-	Pre-set length of a divert point (used for calculating cycle time of divert).
MLENGTH	-	Pre-set length for a standard merge point (0.622 + CP).
HTIME	-	Heating time based on line speed in minutes.

Operational System Settings from the Panel Switches were primarily defined as string variables to take advantage of switch states such as "on" or "off" for communication and training purposes and included:

LOADL1	-	Matrix line 1 loading ON/OFF.
LOADL2	-	Matrix line 2 loading ON/OFF.
FEEDL1	-	Feed carriers from S3 to Matrix Line 1 ON/OFF.
FEEDL2	-	Feed carriers from S3 to Matrix Line 2 ON/OFF.
REQEL1	-	Request empty carriers from Matrix Line 1 ON/OFF.
REQEL2	-	Request empty carriers from Matrix Line 2 ON/OFF.
OUTFEED (4)	-	Lane outfeed for Sorting Buffers ON/OFF.
RUNOUT	-	Selective Heating Operation ON/OFF.
S1INHIB	-	Inhibit the flow of carriers from S1.
S2INHIB	-	Inhibit the flow of carriers from S2.
STOCK	-	Switch in Stock Harbour to indicate operator function LOAD/BUILD/OFF.
STKBLDA	-	Send Type A products to Stock Harbour ON/OFF.
STKBLDB	-	Send Type B products to Stock Harbour ON/OFF.
STKBLDC	-	Send Type C products to Stock Harbour ON/OFF.
STKBLDD	-	Send Type D products to Stock Harbour ON/OFF.
STKBLDE	-	Send Type empty carriers to Stock Harbour ON/OFF.

Operational System Settings or Displayed Measures from the On-screen Menu Interface were defined as either real or integer variables and included:

SYNCTM	-	Synchronous timer for requesting empty carriers at lines in minutes.
MODE	-	Trigger used to set lane type for Sorting Buffers.
FCOUNT	-	Number of carriers enroute to Flowcoat.
UPTOSORT	-	Number of carriers between Inspection and Sorting Buffers.
SORTBUF(4)	-	Number of carriers in the Sorting Buffers.
LNCAP (4)	-	Carrier Capacity of Sorting Buffers (used for lane allocation).
RCOUNT (39)	-	Current Capacity of appropriate system reservoir.
FCDEL(4,2)	-	Array variable to display the types delivered to Flowcoat.

Loop variables were identified as integer type variables and included:

JJ1	-	Loop variable used for pattern mix change on Matrix Line 1.
JJ2	-	As above, for Matrix Line 2.
NN	-	Loop variable for allocating lane at Sorting Buffers.

Internal variables for device operation, cycle time or reject rate comparison were defined as either real, integer or name type variables and affected all stop stations with interfacing processes and patterning decisions and merge points in the system, including:

REL5	-	Trigger to release the carrier opposite Matrix Line 1.
S5INDEX	-	Index time for the stop station given certain system settings.
REL7	-	Trigger to release the carrier opposite Matrix Line 2.
S7INDEX	-	Index time for the stop station given certain system settings.
REL10	-	Trigger to release the carrier opposite Inspection unload.
S10INDEX	-	Variable index time for stop station based on carrier status.
REL11	-	Trigger to release carrier opposite the manual Inspection Station.
S11INDEX	-	Variable index time for stop station based on carrier status.
REL12	-	Trigger to release the carrier opposite Inspection load.
S12INDEX	-	Variable index time for stop station based on carrier status.
REL14	-	Trigger to release carrier at manual stock point in Stock Harbour.
S36INDEX	-	Variable index time for stop station based on product status.
TVAR	-	Variable to compare and trigger assignment of Sorting Buffer lane allocation.
LNALLOC(4)	-	Variable to indicate Sorting Buffer lane for assignment of CADEST attribute.
RELVAR	-	Variable used to control sequence release from Sorting Buffers.
X1	-	Variable used to generate a random no. for reject rate at Inspection.
X2	-	Variable used to generate a random no. for reject rate at Selective Heating.
MCYCTIME(7)	-	Variable cycle time assigned to a merge point depending on the CAPAST.
JAREACTL(7)	-	Variable used to indicate activation of an area control for complicated junction points to inhibit further carrier release until cleared (reset).
FLATBLT1	-	Counter used to identify the number of products loaded to the flatbelt due to lack of a carrier at Matrix Line 1.
FLATBLT2	-	Counter used to identify the number of products loaded to the flatbelt due to lack of a carrier at Matrix Line 2.

5.5.3.2 Logic Sequences and Operational Functions

As with the detailed level models, logic instructions used for the simulated devices followed a structured pattern similar to that used for the actual coding. By structuring the simulation logic in this format, the step sequences for the detailed ladder logic program were initiated. The final sequence maps were a supplier deliverable for the engineering project to be used for evaluating the system without the actual PLC program. The simulation logic initiated the PLC sequences, but did not complete them, as it did not include internal system checks such as device safety, interface equipment monitoring, system alarms, or any system construct not practical to model. Note that some of the alarms, such as loading a screen to the flatbelt, were incorporated into the simulation, however, the majority of system status alarms were not captured.

Using the "Run Immediate Actions" option within the WITNESS software, known variables corresponding to the real operator switches and running modes could be changed and evaluated accordingly. This was a relatively crude simulation of the operator interface and subject to certain limitations, particularly when communicating the simulation to a non-WITNESS user. Altering the variables required knowledge of the WITNESS software as well as the internal variable names and their parameter boundaries. This type of interface was observed to contribute to the problems encountered for training with the simulation and was subsequently addressed on models of the 225/226 and AMS Systems.

5.5.3.3 Measurements and Reports

The majority of standard measuring and reporting features resident within the software were sufficient for the model. Measures included, identification of carrier queue locations and sizes against designed parameters by identifying stop station and conveyor blockages, junction point states, carrier flow, location and capacity for various operating scenarios, average carrier travel time for the entire circuit, average buffer queue sizes, average conveyor queue sizes. and average times for the Sorting Buffers to fill, given various running scenarios.

Custom reports created within the model included, event messages to the interaction box of operational problems, and displays as they would have been designed for the actual system. An example of an operational problem was the occurrence of no carrier available to load at a Matrix Line, recording the line number and the time. This initiated analysis of potential problems in the control design, the number of carriers, or a problem upstream. An example of a display report was the number of products delivered to Flowcoat.

5.6 Analysis and Results

5.6.1 Validation and Experimentation

Logic verification was performed on two levels, and included, immediate checks of the correct structure automatically done by the software, and observed behaviour of device operation. Validation took place in several stages, and consisted of comparisons to the analytical model presented in previous sections, and to existing systems, when appropriate. As there were a limited amount of statistically variable processes, rigorous statistical testing using different random number streams and strict confidence limits were not implemented. When random number streams were used, as in the case for the Inspection and Flowcoat areas, several "runs", varying the streams were tested, with the number being dependent on heuristic methods, and the running situation. Given the amount of potential production modes, it was not viewed as practical, or necessary to introduce a large amount of rigorous testing, particularly due to the project objectives.

The objectives for building the simulation were interactive and observational ones, requiring analysis of carrier flow and system performance given specifically identified problems. Therefore, more traditional simulation experimental requirements such as length of run, number of independent runs for statistical confidence, and initial running conditions were not critical. To satisfy project objectives, the simulation was run for various scenarios at warm-up and steady-state. Warm-up was used to observe initial carrier flow around the entire circuit, significant for periods that involved start-up and shutdown procedures within the actual system. Steady-State conditions, or when carriers were "saturated" within the system, were used to analyse potential problems and various running modes, including, excessive processing times for Inspection, excessive reject rates at Inspection and Selective Heating, running with all five different type mixtures to determine system capability, observed carrier flow behaviour vs. expected behaviour, and device operation.

5.6.2 Modelling and Simulation Package Limitations Observed

Simulation activities were useful when understanding the carrier flow and potential production problems in the design process. However, it was observed that most of the problems encountered in the implementation stages of the system involved testing the logic sequences for interfacing devices, such as emergency stops and carrier release safeties. These items were not modelled for practical purposes, consequently the simulation had limited effectiveness at the installation and commissioning stages, due to the detailed device requirements. Further, it was found that many of the layout changes within the latter design stages could be handled effectively through the use of analytical methods, with the simulation only being used to verify carrier flow, afterwards. Two specific limitations were encountered with the WITNESS simulation package involving, the inability to automatically incorporate the physical layout, and the issues encountered for several components of power and free conveyor systems.

To illustrate the system graphically, it is necessary to "draw" a like replica of the system layout on the simulation screen palette, creating an added activity open to artistic licence with departs from standard Computer Aided Design (CAD) layout programs. Although three dimensional icons are available within the existing library, most simulations of the power and free system do not require this kind of visualisation, as could be the case for other types of automated handling systems such as Automatic Storage and Retrieval Systems that work in three co-ordinates. A recommended approach to cut model build time would be the ability to incorporate not only CAD created layouts, but the physical scaling and dimensions inherent within the CAD structure.

The inability to incorporate CAD-accurate data exposes a problem in the way queuing conveyors are defined within the software. Queuing conveyors are defined on their part capacity, not length, thus assuming that all conveyors are created on unit pitch lengths. An advantages of the power and free system noted previously is its flexibility in layout and the ability to be designed around existing or constrained processes, requiring that reservoirs not be based on a unit length. Consequently, to obtain true, discrete, travel times when displaying conveyors, it is necessary to incorporate additional simulation elements, further complicating the process. Two additional areas of limited capability involve the simulation of pusher dogs and the use of sensors, as discussed previously.

5.6.3 Modelling and Simulation Package Strengths

Practical strengths found with the WITNESS simulation package included, the ability to create "designer elements" while building the model, and its generic user interface for model and report configuration; both compliments to a GT simulation approach. Designer elements could be any standard simulation element with a unique name, display and operating logic to be used for cloning similar elements, thus decreasing the time to build a model. Generic and designer elements used for the power and free systems included:

- A standard queuing conveyor with a cycle time of CP/CS. Four types were created to correspond to four directions when moving on-screen (up, down, left, right).
- A standard delay buffer with a capacity of one and the cycle time of CP/CS.
- A standard stop station machine with a cycle time of CP/CS.
- A delay machine for a Presence Carrier control type reservoir with a cycle time of (LBSS (N) + PDIST + DPITCH - RESCAP (N) * CP + CP) / CS.
- A delay machine for a Counting or Saturation control type reservoir with a cycle time of SFPITCH / CS.
- A standard divert machine with a cycle time of DLENGTH (N) / CS.
- A standard merge machine with a cycle time of MCYCTIME (N).
- Integer and real variables with no definition (part of standard WITNESS designer elements).
- String and integer attributes with no initial definition as with the variables.

Using these designer elements substantially decreased the amount of time for model build, and could be applied to other power and free conveyor system models. The use of sub-models and modules was considered for this study, but not used. Sub-models are sections of models containing several elements that can be used as one element. Modules are elements that contain one or several sub-models. It was anticipated that these could be used for standard conveyor reservoir types, and further improve the time to build a model. However, due to the requirement to display carriers flowing in the correct directions based on the specific layout designed, it would have been necessary to create sub-models for all potential occurrences.

It was found, in practice, that a near equivalent amount of time was saved by simply using the basic designer elements created and not going to the next level of generic detail.

5.6.4 Objectives Achieved - Lessons Learned and Design Parameters Understood

Ideally, a power and free conveyor system of the type studied is designed to be continuously free-moving with carriers moving at all times. However, this is not practical, due to cycle time variations, unexpected reject rates, and variations in production schedules or modes. Therefore, the design can only accommodate as many variations as is optimally possible, given certain constraints, hence the restrictions on the number of carriers and where they are "placed" in steady-state running. It was decided to trade some of the system complexity for the maintainability of the system in the man/machine interface, designing manual switches to provide a great deal of functionality rather than creating automatic functions for all production scenarios. This was to prevent any occurrences in the system that the operators could not intuitively understand and quickly troubleshoot, if necessary.

From the initial simulation objectives of reducing project costs, increasing design confidence and improving customer ownership though the model's use as a training tool, the most effective were those achieved in the design confidence and ability to address potential problems. The modelling activities assisted in "fine-tuning" the initial design constraints and operator functions and identified new constraints immediately necessary or for potential improvements. For example, it was observed that if the empty carriers were allowed to circulate on synchronous mode past the Matrix Lines without product being loaded, for too long, carrier gridlock could occur, due to the fact that the logic rules did not allow empty carriers to be directed to Flowcoat. Empty carrier gridlock prevention was installed in the form of a switch to allow empties to Flowcoat as a "pressure valve" to relieve this occurrence. Detection was still reliant on operator awareness.

Junction traffic jams causing upstream problems were found in several areas. One example of this was the carriers sent up to the Sorting Buffers from Inspection. The initial design was intended to prevent the potential problem of empty carriers being blocked from Inspection due to a queue of full carriers prior to Sorting. The model showed that the original rule of counting carriers between the front of the Sorting Buffers and Inspection could not ensure free moving lanes for empty carriers back to the Matrix Lines. It was found that the combination of more than one type, random rejects from Inspection and rejects from Selective Heating being introduced into the count caused an unpredictable combination of carriers into the Sorting Buffers. Limiting the controlled count on full carriers destined for the Sorting Buffers to a point just prior to the Sorting Buffers and basing the number on the queuing capacity of the reservoirs after the junction split for full and empty carriers proved a more robust design.

Potential traffic problems were also observed at both of the "complex" junctions points that combined a merge and divert. The junction point shuttling full carriers back to the sorting lanes and also handling empty carriers back to the Matrix Lines created a requirement for a steady queue of carriers at the pre-Matrix Line reservoirs to account for a group of rejected components going into the sorting lanes. Further, the junction point following Inspection showed that a carrier at S13 could be incorrectly shuttled into the Stock Harbour because there was a carrier being sent from S15 and the carrier at S13 needed to be removed from the Inspection System area so as not to affect its flow. These examples illustrate a benefit to the designer using simulation in the ability to communicate potential problems or limitations of the system to Production personnel in advance.

Observations confirmed a requirement for sequence control on the outgoing lanes in the sorting system. The second carrier in the first lane could arrive at the stop station prior to the first carrier in the fourth lane. If no inhibit or sequence control was placed on the stop stations, part types could be sent to Flowcoat in the incorrect sequence. Further, the model also highlighted areas in the system where the recommended control method was not adequate. Although this could have been done analytically, and was on following systems, it identified the problem to engineers not familiar with this type of system. The sorting buffers were originally thought to be the most difficult to design, consequently, a great deal of design effort was placed on this area. However, when constructing the simulation, it was also observed that a great deal of effort was put into writing the code and operating rules for two complex junction points, which turned out to be the case in actuality. This illustrates an advantage of writing the simulation sequences as close to the PLC code as possible; to expose areas that could require additional design effort.

The number of carriers, analytically calculated from 235 to 279 with a weighted average of 250, was found to be adequate for the running conditions evaluated. Simulated system behaviour using the carrier number boundaries of 235 and 279, supported the design rule that the low and high limits are to be avoided due to potential problems caused by variations in running specific reservoirs full or empty. Using 235 carriers caused less traffic problems, but increased the potential for starving processes, while using 279 carriers caused contrary effects. The inability to simulate the carrier movement within the reservoir with 100% accuracy did not appear to significantly alter results. The simulation added the benefit of displaying the behaviour to system operators in order to communicate the affects of various changes on other parts of the system, such as the effect of running with a full reservoir prior to Inspection on optimum carrier quantities.

The simulations contributed to creating both the logic rules within the code and the production rules in handling products off-line, through analysing and illustrating specific "what-if" scenarios. Observations of the junction points under various running scenarios assisted in the acceptance that a rigorous priority ruling for some points was not necessary. Further, the production rules for running various sections of the system, such as the Stock Harbour, while not necessarily confirmed in the simulation, could be indirectly influenced by being able to observe their effects on carrier flow in the model. Other design parameters calculated analytically and confirmed by the simulation included, the minimum amount of carriers allowed to Flowcoat from the Sorting Buffers, conveyor chain speed, buffer sizes, and acceptable manual interface cycle time boundaries. Additionally, the "push" and "pull" areas of the system were understood from observation of the stop stations.

While the benefits are apparent and in a general sense, common to most simulation projects, it was found that the most beneficial way of designing and using the models for this type of large power and free system was on a general level previously described for the entire system to obtain an idea of the overall flow and operation, and only on a detailed level in certain, but limited areas. This was performed in successive stages of model analysis for the Flowcoat/Selective Heating Areas when a new design was installed. Further, it was found that the use of the model as a training aid was limited due to the time required to build the model to a level of detail to which the operator will need to be accustomed. Although initially accepted, it is anticipated that a more generic approach to reduce model build time further was the answer to improving its uses as a training aid.

6. CASE STUDY - 225/226 SYSTEM ANALYSIS

6.1 Operational Characteristics (in Comparison to the 215 System)

The 225/226 Conveyor System was a second phase installation of a power and free conveyor system similar to the 215 System. Consequently, all the system design and modelling characteristics used for the 215 were applicable. The primary engineering objectives for the installation were to increase plant capacity and reduce the per unit costs for handling and production from the previous installation. These objectives, coupled with the differences in equipment and process design made it necessary to challenge and put into practice that which was learned from the 215 System.

The process map for transporting matricised screens to Flowcoat was virtually identical to the one presented for the 215 System in the last chapter. While there was a different range of product types to process, the general rule of four-type flexibility remains, therefore, the methods used for the simulation model remained consistent. An engineering consideration for product size was required, being different from the previous installation, thus placing constraints on the layout. Differences in equipment and the handling speeds, further affected system and simulation design. The system level schematic is illustrated in figure 40.

The equipment was virtually identical to that used in the 215 System, with the exception of internal design and specific technology improvements. There was, however, a greater capacity, with three Matrix Lines feeding two Flowcoat Lines. The third Matrix Line (Line 5) was installed for added capacity and flexibility, used as supplement in case of problems on the other lines. For two Matrix Lines to feed two Flowcoat Lines, the process speeds needed to be increased by approximately 24%. This meant increased handling speed and additional conveyor system equipment, such as, devices, routes, and carriers.

Due to the increase in product size, interfacing process equipment, building constraints, and the requirement to maintain all operational aspects of the previous power and free conveyor system, it was necessary to design a single feed to two Matrix Lines rather than individual feeds per line. With both lines running at a combined 280 products per hour, this area was a focus of the design effort. The fundamental processes of Inspection, Stock Harbouring, Sorting, and Buffering were all designed as per the 215 System, with the only exceptions being in processing speed and layout. Selective Heating was split into two distinct lines to feed Flowcoat Lines 1 and 2. Once processed at Flowcoat, carriers were sent back to the Matrix Lines.

6.2 Engineering Design Considerations

Although the design was similar to the 215 System, there were several design challenges which made this system unique. It was intended to use the general knowledge gained on power and free system design and simulation with Phase 1 to improve the overall 225/226 operation.

6.2.1 Layout

Based on lessons learned from previous installations, the layout was designed as "simply" as possible. For example, complex junction points of merges and diverts were replaced with single junction points containing buffering reservoirs between the merges and diverts. Generic blocks including stop stations and reservoirs were created and used throughout the system, to reduce the amount of proprietary control logic design and placement of control devices such as sensors.

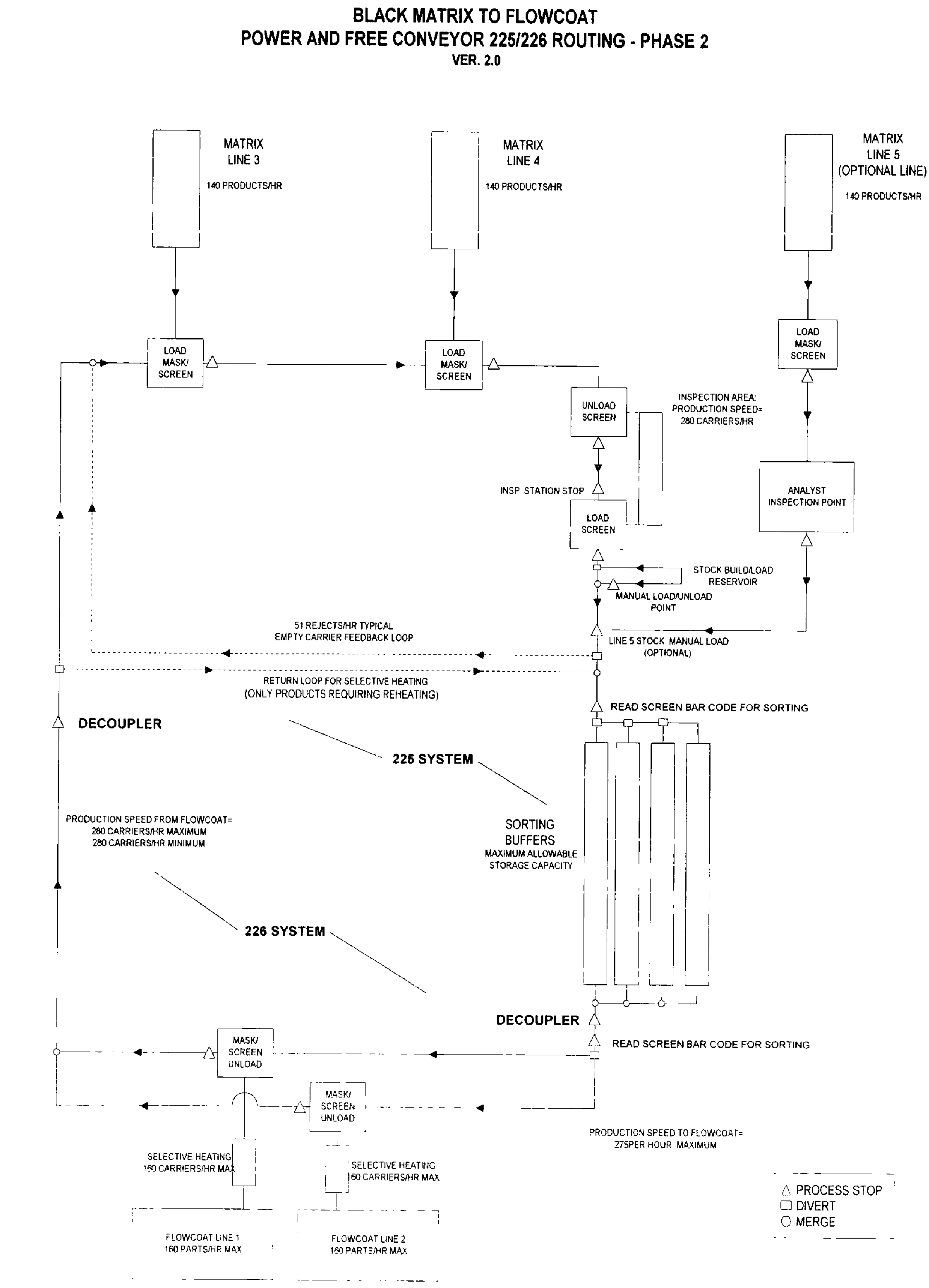


Figure 40. Schematic for the 225/226 System.

6.2.2 Operational Controls

The increase in processing speeds had implications on the running pitch requirements for the carriers and the speed of response to potential problems due to reduced reaction times. Consequently, the user interface had to be improved to decrease the response time for operator troubleshooting. More flexibility was given to Production personnel in the form of controls to override certain stop stations should they become blocked. Adding flexibility to the operator controls, saved design time by reducing the need to comprehensively address all potential traffic problems. A Supervisory Control and Data Acquisition (SCADA) System was installed to provide, in effect, real-time, graphical simulation of the running system for both Operations and Maintenance personnel.

6.2.3 Sorting and Buffering

The fundamental requirement for approximately one half hours stock for the handling process between Matrix and Flowcoat was still valid. However, due to the increased handling speeds, and reduced available space, the Sorting Buffers were actually reduced in size. To compensate, more products were routed to the queue just prior to Flowcoat. As the system was relatively large, communication between Matrix and Flowcoat was critical, thus the design needed to consider improving the DBR approach.

6.2.4 Non-Synchronous Matrix Activities Coupled Together

Additional to the change of the single feed for both Matrix Lines 3 and 4, was the fact that they did not load simultaneously, which meant a potential for a conflict of priorities in the conveyor control logic for product handling between the two Lines. There was a requirement to release two carriers, one full and one empty, past the first line so that the second line had a carrier available for loading its products. A potential problem existed in the running the line without carrier interruption, given the amount of production options, potential line inhibits, and non-synchronous loading cycle times between the Matrix Lines. These activities also had an effect on the minimum carrier running pitch requirements for this area of the system.

6.2.5 Increased Amount of Equipment Dependency

With approximately 30% more equipment as compared to the 215 System, there was a concern about the system utilisation and the potential problem of communication and troubleshooting, due to its potential complexity. Communication problems existed on the 215 System because there were two distinct processes that had different running characteristics coupled by a common handling system, spanning two buildings. The lack of effective communication further caused problems in management of the flow of products to the bottleneck, Flowcoat, if production speed was altered or problems arose that caused the feed to be temporarily halted.

Use of "decouplers" was not a new concept for relatively unmanned handling systems.[25] Black had previously introduced specific design "corollaries", two of which included, "Decoupling of a Coupled Design", and "Uncoupled Design with Less Information". Basing the 225/226 product handling design on these principles, it was decided that a method, internal and automatic to the system, would provide an optimum method of improving both the communication and utilisation of the system. A mechanical decoupler, similar to a standard stop station was designed for this function to effectively divide the large system into two semi-independent systems. Hence the 225 and 226 conveyor designations on the System schematic.

The decoupler reduced the interdependency of Matrix and Flowcoat by allowing one of the systems to operate for a determinant period of time if the other developed a fault, thus improving the utilisation. The introduction of a decoupler effectively changed the power and free system from a predominantly "push" system to Flowcoat to a "push/pull" system with Flowcoat requesting additional carriers when the stocks fell below a certain level; a form of "automatic production control". Due to the nature of the Matrix process and the random reject rates, a combination Sorting/Buffering System was still required for that area. Placement of the decoupler became a new design consideration with a goal to improve the management and utilisation of both areas, particularly the bottleneck. Controls on the design included available space, effective access, and a desire to average the complexity between the two areas.

6.3 Modelling Objectives

Although the analytical tools were well established, the use of simulation retained its observed benefits and it was applied to the design of the 225/226 System with similar objectives, albeit, more finely-tuned. These included, risk reduction through the increase in design confidence and its use as a potential problem analysis tool, verification of usual system parameters substantiated by analytical methods, improved customer ownership through its use as a training tool, and implementation as an on-going problem analysis tool.

Due to the reduced design time, and the lessons learned with the 215 simulation, the potential benefits for use as a system control design tool were seen as limited. Existing models created for the 215 system were used for any detailed modelling requirements. Further, the benefit of simulation as a training tool, not fully realised on the 215 simulation, was still seen as a potential benefit and the simulation structure was changed to improve the result. It was anticipated that the user interface, if designed well, could be used to design the actual interface as well, by testing users ability to use it on the simulation. To effectively implement the simulation and its objectives, an expert modeller from AT&T was employed to write the base model with assistance from internal personnel.

6.4 Base Model Characteristics

6.4.1 Model Elements

Many of the simulation components remained as per the 215 simulation. Due to the concern for simulation run time, conveyors were replaced more extensively with buffers. Additional simulation design changes made in an effort to improve the process and further the use of generic tools for future simulation models included, the use of functions to simulate complex handling areas, the use of external spreadsheets to import/export data, and an improved user-interface through the use of the OLE-linking structures and Visual Basic program capability. The goal was to design an interface that virtually mimicked the actual touch-screen and switch interface for the new system.

Although effective, the model device logic of the first case study was lengthy and inefficient in some areas, such as the Sorting Buffers. To improve the efficiency of the model logic and potentially increase computer processing speed, the user-defined functions or generic sets of code were introduced. General functions for this type of system included:

- Identifying the release pattern to the Matrix Lines.
- Assigning a Sorting Buffer Lane code number depending on mode and screen type.
- Monitoring and releasing carriers by sequence into and out of the Sorting Buffers.
- Assigning the destination of a carrier prior to processing it through a divert.
- Initialising reporting files, such as a file that contains list of screens loaded to the flatbelt.

Design data for reservoir sizes and storage capacities from the system supplier was in tabular form. The table was replicated on a computer spreadsheet with other standard information, including, carrier pitch and chain speed. In this form, a non-WITNESS user could call up the spreadsheet and alter the information without requiring an understanding of the simulation software, which provided a more user-friendly method of data manipulation and creation. Further, as most of the intended users of the model were unfamiliar with the simulation software, a link with Visual Basic was implemented and menus designed to act as the user interface; a true representation of the actual interface design. An operator console displaying the menu parameters and "switches" that could be changed by using the computer mouse, was introduced. This was in contrast to using the "Initialise Actions" and the "Run Immediate Actions" interface as on the previous simulation. The menus effectively created a non-WITNESS interface, a step closer to simulating the actual system and its operations. Examples of the menus can be found in the appendices.

6.4.2 Measurements and Reports

Measurements and reports were in much the same way as the 215 simulation. Internal reporting on devices such as blockages and utilisation were observed and recorded under various production modes. A change was made to the custom reporting of loading to the flatbelt to include an external file for use in other packages.

6.5 Analysis and Results

Activities were consistent with the methodology of ongoing verification and validation. Experimentation was focused on those design considerations that were of initial concern, including:

- The single carrier feed past the two Matrix Lines.
- The effect of the decoupler and calculation of buffer sizes to maintain optimum utilisation.
- The effect of the layout changes from the 215 installation.
- Potential problems involving production operations or operational mistakes.

The use of statistical confidence runs was limited and final validation consisted of comparisons to the actual system, which proved accurate against anticipated carrier flow and behaviour.

6.5.1 Simulation Project Performance and Preliminary Conclusions

While some of the problems encountered with the 215 simulation were avoided, such as an excessive amount of time dedicated to creating detailed level simulations of limited benefit, there still remained some basic concerns with simulating this type of power and free system. These included, the inhibiting amount of time required to build such a comprehensive model, and the lack of efficient links to actual system controls and equipment. Even with an expert modeller writing the simulation code, assisted by a second experienced modeller and systems designer, the time to build the model was prohibitively long. The design stage for this type of system was approximately three months, well within the boundaries of time required to build a basic model, however, becoming difficult, due to the time required to verify, validate and experiment. The amount of information requested and user-friendly format by which the model was structured further inhibited the process.

Use of the spreadsheet was effective in translating conveyor data to the model without requiring the internal WITNESS tools, however, data still needed to be input in some form. Whether this was done on a common spreadsheet program or in the Initialise Actions Menu within the simulation software appeared to be a minor point, particularly as there were expert users on site. With the objectives being interactive ones, for this type of simulation project, unless the spreadsheet program is used to perform calculations on input data to substantially improve process time or used to manipulate results from the simulation model, use of the spreadsheet involves unnecessary duplication. The use of functions to replace lengthy and repetitive sections of code was successful in terms of capturing the generic logic for those specific handling activities simulated. However, there was no improvement in the time required to run the model, although, the extra detail of the menu interface and the modelling of carriers as icons rather than word descriptions, methods not used in the 215 simulation, might have caused an increase in processing power required.

While the menu interface was an effective facsimile of the actual operator station, there was also a negative side to its creation, aside from the additional time required. It was intended to eliminate the need for commands on Initialising Actions. However, if this was to be the case, it meant the user had to set up the entire menu interface prior to any run, consequently, default actions were still needed for initialisation. The menu interfaces did, however, improve the model operation in that one did not need to know the actual variables used for the parameter changes, an improvement on the 215 simulation. Regarding its use as a functional tool for structurally designing the operator interface, more traditional tools such as CAD were found to be just as effective, i.e., the link from the interface to the act of changing the simulated system parameters was not as beneficial as anticipated. Upon observation, it is anticipated that a potential benefit would exist if the simulation model interface created in the design stages could be incorporated into the menu interface for the actual system.

6.5.2 Objectives Achieved and System Design Parameters Understood

In review of the project, the simulation did achieve some of the objectives identified at the beginning and provided insight into objectives for future projects of similar type. Although analytical methods were initially used in identifying the standard design parameters such as the number of carriers necessary under varying production conditions, the simulation was able to confirm these as well as provide visualisation to potential problems. While the use of the spreadsheet, Visual Basic linking and detailed operator interfaces were of limited value in the short term, they provided a basic criteria for future models to use these tools more effectively.

A more measurable success was achieved through other design activities, such as the introduction of a decoupler, a simplified layout approach, improved operator control over all junction points in the handling system, and the installation of a SCADA System. By focusing on the requirements for effective implementation of the DBR methodology, system utilisation, communication channels between Matrix and Flowcoating processes, and customer ownership all benefited from the installed improvements.

7. CASE STUDY - AMS TESTING CIRCUIT MODEL AND ANALYSIS

7.1 Operational Characteristics

The Automatic Magnetising System (AMS) consists of a closed-loop power and free handling system transporting television tubes through a series of testing and magnetising processing stations directly connected to the conveyor system. It is effectively a flexible manufacturing system, and although it currently only processes two general tube types, it has the capability of processing as many type variants as required. The operational characteristics of the system are shown in figure 41, in IDEF$_0$ format, with the AMS function located at the second stage in the overall manufacturing process within IMT3:

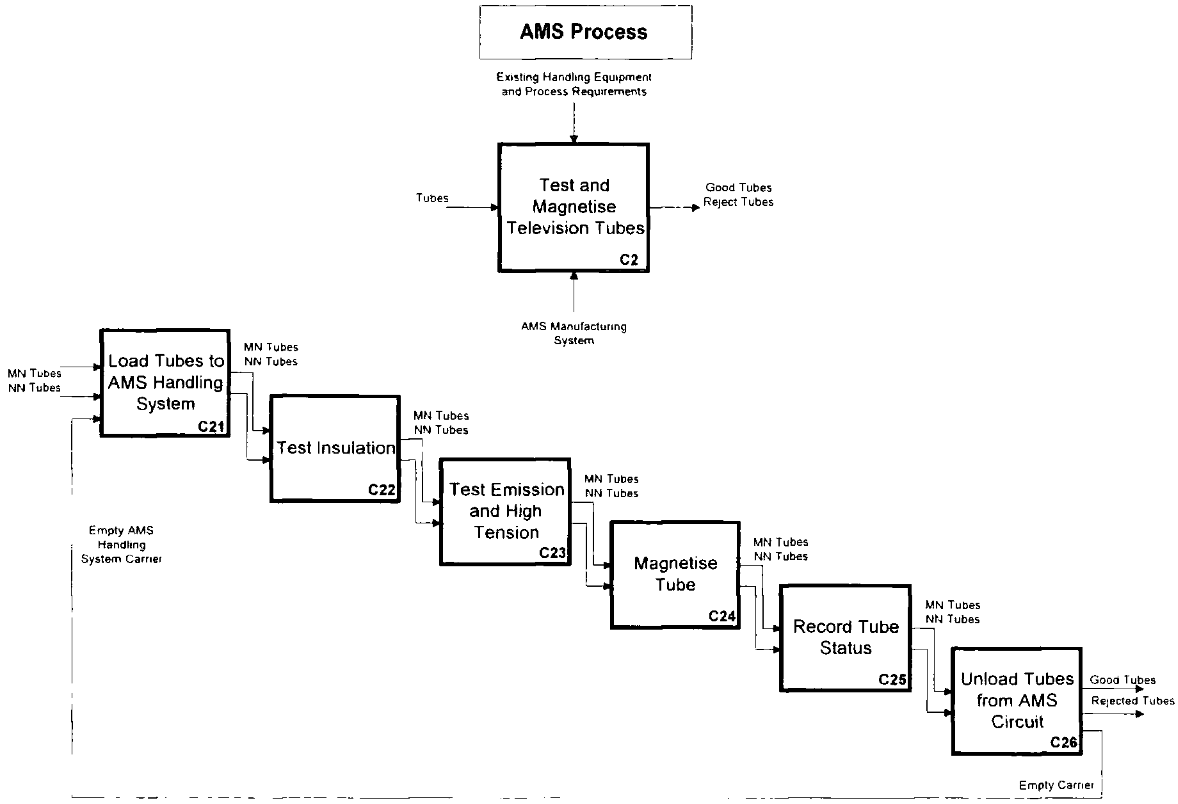


Figure 41. Process Map for the AMS Circuit.

At the time of the design study, the AMS was an installed system, in contrast to the previous systems reviewed. Further, the system is virtually an automatic one, with an operator present only to unload tubes from the circuit. The independent flows for each tube type implies no sorting of types through the manufacturing process. Each type has an independent route through the system depending on the shortest path through the conveyor layout. Sorting only occurs when organising empty carriers to match the incoming type pattern.

7.1.1 Equipment and Layout

Although different from the previous systems in functionality and design, conceptually (particularly for simulation purposes), the systems were identical. These included, a power and free conveyor system installed within the manufacturing process transporting carriers at various pitches depending on station availability, handling units to load products onto the carriers, process points which utilise standard conveyor stop stations, junction points for traffic management, and a sorting and buffering system internally designed within the power and free system.

Being a self-contained FMS circuit, the power and free system was designed on unit pitches, which means there is virtually no slack in queuing reservoirs following a stop station or junction point. Regarding simulation, this means that models of reservoirs do not require extra elements to accurately capture travel times. While the principle of pusher dogs to transport carriers around the system still exists, the dogs are of a resistance type, and the carrier is never delatched from the system, eliminating the need to control the release of a carrier after processing. Further, the pusher dogs are pitched at a closer distance, at approximately 333 mm corresponding to a unit of the carrier pitch which is 1000 mm. When the first carrier in a queue is released, the second and other preceding carriers are picked up immediately, onto the next position. The flow behaviour is more closely related to the standard queuing conveyor in the simulation package. In general, the power and free system is designed as a closed loop, which means unit lengths and pitches have been used extensively and the manufacturing processes are designed to fit within the handling system. This is in contrast to the previous power and free systems which are designed to fit around processes.

7.1.2 Processes

Based on the existing layout, the system schematic is illustrated in figure 42.

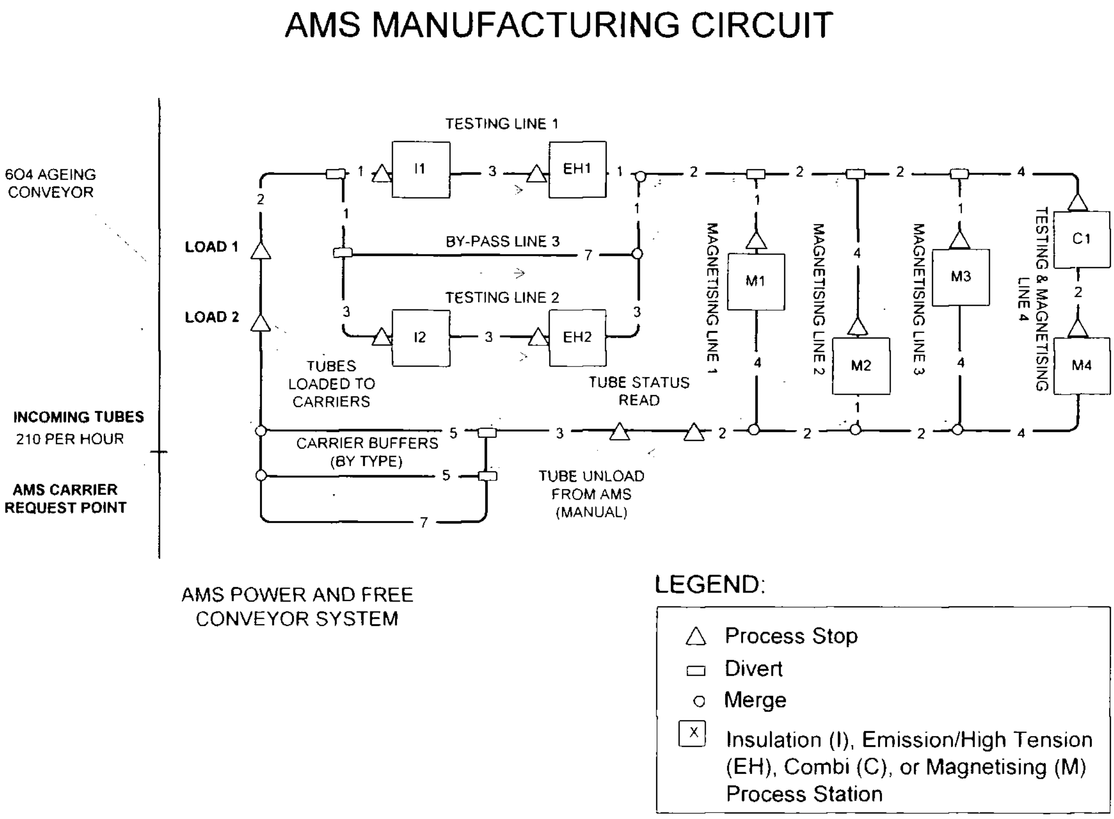


Figure 42. Schematic for the AMS Circuit.

The schematic contains additional equipment detail as compared to the previous schematics, but essentially it is of the same format. The schematic is virtually the actual conveyor layout with buffer capacities shown for each reservoir. Once the internal carriers have been configured for the incoming product mix, all routing decisions are made automatically with running modes being fixed until the product mix is changed. Routing is done on the carrier identification, not the product type.

Load Points 1 and 2

MN and NN Tubes are transported from the previous manufacturing operation on a standard, indexing conveyor system (604 Conveyor) to loading points 1 and 2. While they are being transported to these points, empty carriers on the AMS System, located in the three buffer storage lanes are also transported to the load points. In correspondence to the tube types, there are two general types of carrier. Only MN tubes could be transported in MN carriers and NN tubes in NN carriers. Typically, production runs favour one tube type and these majority carrier types are assigned to the two nearest sorting buffer reservoirs. Empty carriers are requested in the following manner: A particular pattern mix is assigned to the incoming conveyor. While on this conveyor, prior to loading, the type is identified at the "AMS Carrier Request Point" and the appropriate carrier is released from the sorting buffers. The request usually happens in pairs for dual loading, although single loading capability is available. Once the carriers are in position, two robotic transfer arms remove the products from the 604 Conveyor and load them to the AMS System. The dual transfer is synchronous with both units having identical cycle times. If a carrier is not available on the AMS System, the tube will remain on the 604 Conveyor and be loaded at another time.

Testing and Magnetising

Once loaded, carriers are transported to a junction point where routing priority is based on the shortest route through the system. Testing Lines 1 and 2 are identical with carriers transported through a series of on-line tests for Insulation, Emission and High Tension. Tests are performed with two separate machines, the tube remaining within the AMS carrier. Testing Line 3 is a bypass route for those carriers not able to be routed to Lines 1 and 2. Carriers being transported through this lane are routed to Line 4, containing a combination testing machine in which all the testing processes are contained within one machine.

Once the tubes have been tested, they are transported to one of four Magnetising machines. Carrier routing is again based on the quickest route through the system, dictating which line has priority. Normally products tested on Lines 1 and 2 are routed to Magnetising Lines 1, 2, or 3. However, if these lines are full, the carrier will be routed to Line 4, with testing being duplicated on the combination machine. Magnetising cycle time is variable, depending on the uniqueness of the product. If the product has previously failed testing, it is checked and passed on, not completing the full magnetising cycle.

Tube Status Read, Tube Unload, and Routing into the Sorting Buffers

Once carriers are on a common line, they are transported to an on-line status reading station. At this point, data about the tube which has been stored within the carrier from previous operations is collected and sent to a Factory Production Monitoring System. Carriers are then transported to an unload point. Based on the status of the tube (reject or good), it is manually loaded onto one of two conveyors. Good tubes are sent on to the next process on the 702 Conveyor, and rejected products are loaded back to the 604 Conveyor for reprocessing. This is the only point in the AMS System where operations are performed manually, with exception of miscellaneous peripheral activities, including, program changeovers, machine set-ups, and machine resets. As this is the only manual station in the system, all equipment breakdowns (resets) are first addressed by the operator, leaving the station unattended for a certain amount of time. Resulting empty carriers are transported to the storage buffer lanes, and routed depending on their carrier type. Each lane can be programmed to hold either MN or NN types, however, during a production "run", one lane is dedicated for one type. Runs are dependent on the production program and can be changed at any time in the process.

7.2 Engineering Project Objectives and Design Considerations

The AMS System was understood to be one of the primary bottlenecks for the factory and certainly one within the IMT. The engineering project involved modifications to an existing system, consequently project objectives were different, although the design considerations were similar to the previous new installations. The primary objective was to increase the throughput for the AMS System and eliminate the bottleneck by introducing two changes. First, the individual pieces of testing equipment for the two dedicated testing lines were to be replaced by three, single combination testing units, similar to the unit on Line 4, to improve equipment utilisation. Then, these three combination testing machines would be incorporated with the existing equipment into a redesigned layout to provide an increase in throughput and carrier routing flexibility.

Due to the original system design, new equipment specifications, and existing building items, such as, support columns and available floor space, practical options for the new layout were constrained. These constraints resulted in three feasible variations. Schematics of the options can be found in the appendices. The first option included only upgrades to the equipment, with the location being as per the existing lines. Therefore, no changes to the layout would be necessary. The second option involved upgrades to the equipment and minor changes to the layout, utilising as many existing routes as possible. The third option included equipment upgrades and a relatively large amount of layout modifications to the system, still remaining within its existing outer boundaries. The recommended option had to address as many of the existing problems and potential problems with the system, including:

- **Type mixing problems**. If the incoming type pattern did not correspond to the carrier type mix, there could be an excessive amount of mismatches when a carrier was requested, and the product would not be loaded to the system, causing it to "ride-by" for a second attempt.
- **Carrier quantity problems**. There was limited understanding of the threshold amount of carriers allowed in the system before blocking and traffic problems would arise.
- **Under-utilised processing lanes**. It was found by experience that the first three Magnetising Lanes would be utilised close to 100% and carriers were not being routed to the fourth lane. As all the equipment is on a revolving maintenance schedule, the recommended running philosophy is to run all lines as evenly as possible, known as distributed equipment utilisation. Again, there was limited understanding as to the effects of varying the routing logic. An interim remedy was to place reflectors on carriers to "force" routing to the fourth lane.

Analytical design methods, successful in designing a system from the beginning were not as applicable to this system. Many of the processing and handling equipment parameters had already been practically tested and validated with the existing system. Further, given the constraints placed on the layout, an infinite amount of design options did not exist, in comparison to the previous "green-field" installations. The detailed level was not the concern, but rather the lack of understanding of process interactions at system level. Due to the available routing options and variability of product mix, there was an incomplete understanding of the significant factors contributing to throughput problems within the system, aside from obvious parameters, such as product yield. An effective tool was therefore required to verify that the recommended changes in layout and equipment utilisation would significantly contribute to achieving the objective of increased throughput with minimum cost. Given the amount of variability within the process for carrier routing, product mix, and equipment breakdowns, analytical methods were limited and time-consuming, leading to the conclusion that simulation would be a necessary design tool.

7.3 Modelling Objectives and Modelling Project Approach

The simulation project was organised according to the main engineering project objectives. The simulation would, therefore, be used as a Decision Analysis Tool to give direction to Engineering activities. In this respect, objectives were focused and limited to the following:

- Evaluate the effects on product throughput, given specific changes to processing and handling equipment layout , providing a recommendation based on highest throughput.
- Evaluate the effects on product throughput given specific changes to testing and magnetising cycle times, number of carriers, incoming product speeds, incoming product type mix, and AMS System carrier type mix.
- Provide a tool that could be used by production engineering personnel with limited simulation experience, on a daily basis, to test the above mentioned parameter changes. The model was not intended to become a full-blown Production Scheduling Tool, but one that would assist Engineering personnel on the general issues and potential problems.
- Provide a tool that, having tested the specific design changes, could be used in the future by design engineering personnel with or without simulation experience, but with experimental design knowledge, for the identification of all significant factors contributing to throughput. These results of the experimental design and sensitivity analysis would eventually be used for the optimisation of System Resources, Routing Logic, and Engineering Equipment Strategy.

Cost and time were both factors in the project approach and options were favoured that maximised the intended objectives while minimising the costs. As a result, it was decided that a collaboration with AT&T personnel for the initial model build would provide the best results. The simulation specialist would begin with the project team by writing a base model, of which the simulation logic would be jointly verified. All subsequent simulation activities would be undertaken by the in-house design team which included, base model validation, and creation of any subsequent models to test layout design, using the base model as a reference point.

7.4 Base Model

7.4.1 Model Boundaries

Based on the established objectives, the model boundaries were defined. This involved structuring them on three levels: the physical element boundaries, the depth of the element details captured, and the scope of user interface required. The physical element boundaries included the activities of the incoming conveyor to introduce parts to the AMS System and the activities surrounding the two outgoing conveyors for good and reject products. The level of model detail was considered based on the primary objectives and past experience with the model results for power and free systems using the WITNESS package. In order to maintain the objectives for retaining the model as a Production Tool and as a tool to quickly evaluate specific changes, a large degree of modularity was required which favoured creating the model on the basic system level, with limited or no direct modelling of system control devices such as sensors or pusher dogs.

Further, given the mechanical and control design of the power and free system, much of the detail required for simulating the power and free systems previously reviewed was not required. For example, the system design contained no rise/fall sections and based the reservoir size on unit pitches, placing the processing stations around the system, creating no slack or excess travel time for carrier movement from reservoir to reservoir. Due to the size of the junction points, and the processing speed requirements for individual reservoirs, the control was based entirely on the Presence Carrier method. Given the measurements for evaluating design performance and model validation, such as throughput and system utilisation, they could be observed after a run, therefore, the need for a great deal of visible interaction was not required. All these factors contributed to a much simpler model build approach.

When identifying the level of user interface, again the objectives were evaluated. Those items that were in direct control of Production Engineering personnel were placed on a front-end menu interface. As there was no defined control panel as with the previous simulation, the interface was a simple selection menu for the following options:

- Carrier Type Mix on the AMS System.
- Process Station Cycle Times.
- System Yield.
- Incoming Product Speed (by way of conveyor speed setting)
- Incoming Product Type Mix.

The type of interface was intended for non-WITNESS personnel to quickly change parameters requiring limited knowledge of the simulation package.

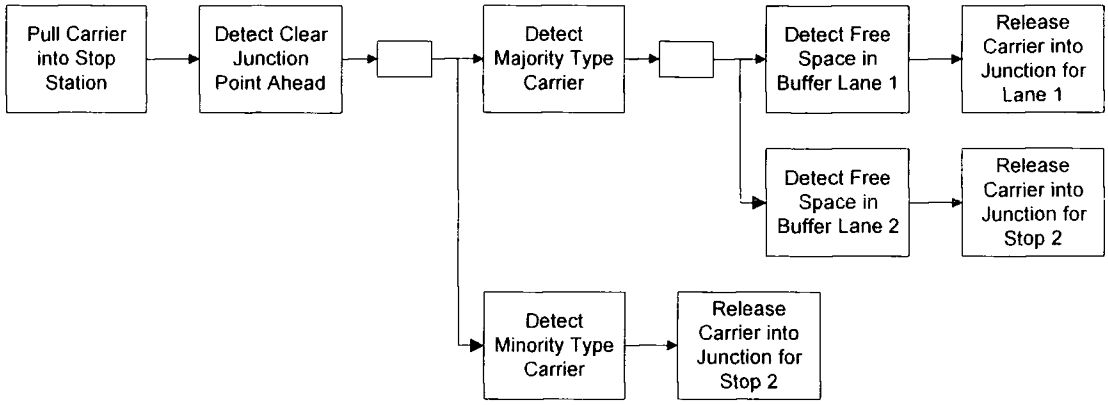
7.4.2 Model Build

Once the boundaries had been defined, the build process was initiated. To provide a common means of communication between the customer and the model builder, and improve the level of resulting simulation documentation, standard tools were used, which included the system schematic, a data collection table for all system elements, decision logic for all elements structured in the form of process/event flow charts as previously described, and existing performance measure reports. The system schematic, shown previously, focused on element definition and relative process locations. The data table was structured as per the simulation package element definition/detail requirements and included characteristics of the elements, such as, name, function, quantity, labour relationship, cycle time, reject rate, and breakdown information. Additional information on the data table included incoming production type mix options, initialising data, and labour activities by priority. An example of the Data Table can be found in the appendices. Examples of the structured flow diagrams are shown in figure 43.

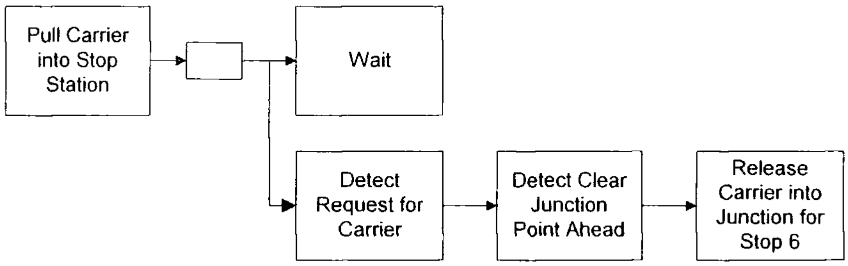
7.4.2.1 Model Elements

The 604 Conveyor System, the function of identifying the incoming product type, and remotely requesting the appropriate carrier from the AMS System was contained within a single machine element. The entire identification and handling function is a complex interaction, one that needed simplification for the simulation. Consequently, it does not follow actual operations. The programmer from AT&T devised a method by which carriers that are identified as the ones to be loaded are, in effect, "loaded" with the part type attribute at the end of the Sorting Buffers. When they arrive at the robot load station, the carrier description is changed appropriately to illustrate a "load". It was thought this might be a source of inaccuracy as it did not actually model the operation, however, the method proved conceptually correct. The handling units are modelled, but only to record the amount of ride-bys and tubes "loaded", and model breakdowns. Consequently, they had no cycle time, the loading cycle time being placed on the appropriate AMS System stop station. Breakdowns were modelled using a Poisson distribution based on limited collected data.

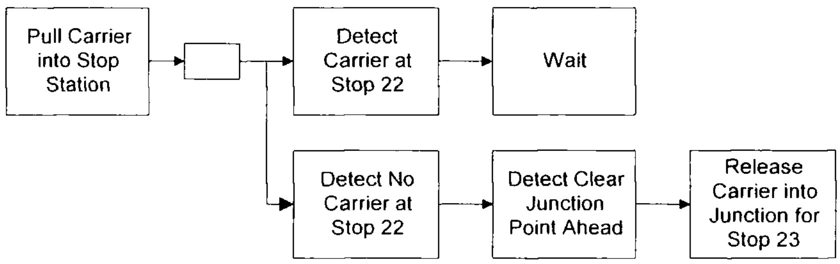
Stop Station 1 - Stop prior to all Sorting Buffer Lanes



Stop Station 4 - Stop at the end of Sorting Buffer Lane 3



Stop Station 21 - Stop after Testing Line and By-pass Lane, prior to Main Line



Stop Station 23 - Stop prior to all Magnetising Lanes

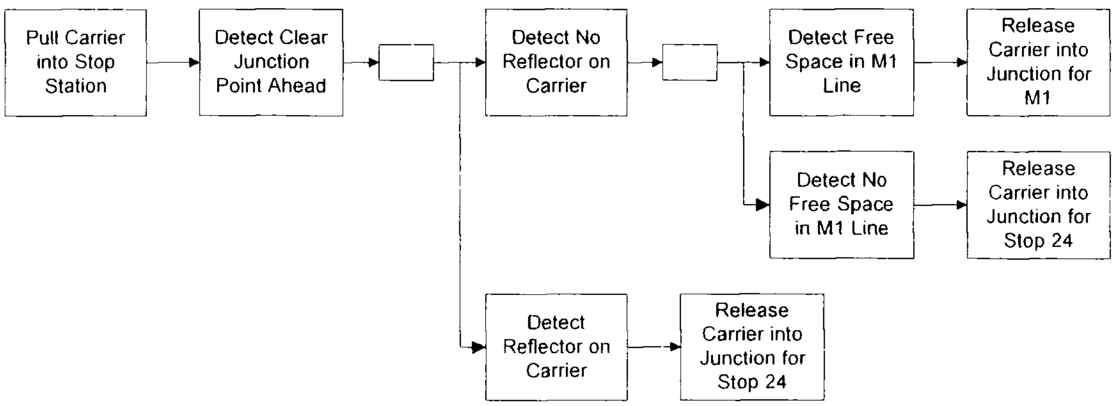


Figure 43. Example Structured Flow Diagrams for the AMS Handling System.

The AMS System is modelled with similar structure to the power and free models previously discussed. Standard components, such as stop stations, reservoirs and "controlled areas" were still required, however, due to their unitary design, reservoirs could be modelled as simple buffers with junction points being modelled by travel time only within the appropriate reservoir. Further, due to the design of carrier release to the drive chain and tighter spacing, modelling the detail of the pusher dogs was not significant, therefore, not modelled. The only conveyor elements used were located at the sorting buffer area and were purely for visual verification and validation.

Insulation, Emission and High Tension testing for each line all have cycle times that vary only slightly, thus an average was used. The operation of testing is coupled within the stop station machine cycle time, including travel time into the processing station. Tubes that fail at this point are tagged with a reject attribute which will affect Magnetising cycle time. Magnetising is similar to testing in that its cycle time is modelled with the stop station operation. However, it can have three types of cycle time, including, a specific one for reject tubes, a cycle time for 84.5% of the tubes that varies depending on the number of magnetising "shots" required, and a cycle time that is twice the normal average for the remaining 15.5% of tubes. Samples were recorded for the cycle time which was modelled as a Truncated NORMAL distribution with the calculated mean. The Truncated NORMAL was necessary in place of a NORMAL distribution, as the NORMAL could occasionally display negative cycle times. All breakdowns were estimated on a Negative Exponential Distribution based on collected data.

The tube status read machine cycle time was modelled within the appropriate stop station. The cycle time for unloading from the AMS System was modelled, similar to the Flowcoat unload, as a two-stage machine with the first being the carrier travel time and the second, the unload time, requiring the presence of the operator. Statistics were updated at this point, and carriers were cleared of the tube description attributes in preparation for the sorting buffers.

Parts were created for the part types and carriers as per previous methodology. However, as the testing and Magnetising stations all required set-up operations, "dummy", active parts were created to trigger the set-up, the frequency of arrival dependent upon the time between set-ups for the appropriate machine. The only labour modelled was the primary operator unloading tubes from the AMS System. The decision to do this was based on the fact that the system operator does not simply unload parts, but also resets equipment, such as the handling units or the Testing/Magnetising stations when they go down. Once away from the unload station, there is no one to take over, consequently, the carriers eventually queue. This relationship was considered significant to require modelling.

7.4.2.2 Model Logic

As with previous models, variables were employed for all aspects of element operation and model logic that might have required future modifications. These included, machine cycle times, breakdown and repairs times, "manual" unloading times, equipment speeds such as chain speed, yield and reject variables, counting statistics such as hourly throughput, set-up triggers, and operational variables identified as Production Engineering changes at the start of the project. Model attributes included, carrier identification for determining routing for carriers with reflectors, carriers identified for loading at the handling units, and those for determining part statistics and cycle times for carriers holding rejected tubes. No attributes were used to identify part types, as with previous models.

As discussed previously, an internal menu interface was created to enable personnel not fully familiar with the WITNESS package to make specific operational changes. A parent function, entitled "menu" was created to display the information on an interact box. The interact box was then used to call on the other functions or items changed through the interface, including, Carrier Mix in the AMS System, Testing and Magnetising Cycle Times, System Yield, Incoming Product Speed, and Incoming Pattern Mix. Data files were created of the twenty standard incoming product mixes, and were called upon as required. Existing functions for standard distributions were used to model machine cycle times, where appropriate, rather than creating unique functions, consistent with the methodology of keeping the logic as generic as possible.

7.4.2.3 Reports

Reports took two forms, the internal standard reporting on element statistics within the WITNESS package, and external reporting in the form of tables and a Timeseries graph of hourly throughput, a sample of which can be found in the appendices. These reports were structured according to existing Production reporting relevant to the intended project objectives.

7.4.3 Model Analysis - Verification and Validation

The simulation model created for the AMS System was intended to test specific production runs for throughput and equipment utilisation. As with most model verification and validation, the techniques used consisted of subjective comparisons to system behaviour based on observed actions versus anticipated actions, and statistical comparisons to the measured output for equipment utilisation and hourly throughput. Subjective comparisons took advantage of existing knowledge resident with system Operators, Production, Operations and Maintenance Engineers.

Verification was carried out by first checking the model logic against existing data for all equipment items, parts, system devices, labour functions, breakdowns, calibrations or set-ups, and equipment reject rates, which involved direct comparison to the actual data and flow diagrams. The sequence logic was then verified using observational walk-through of the individual elements, using displays and in some cases, temporary variable measures for breakdowns and scrap to ensure basic behaviour and system inputs were being adequately captured. Problems were encountered in the initial stages which required further programming changes, however, these tended to be errors in the placement of variable checks, such as a "scrap" attribute being placed on a carrier and not removed when appropriate, causing cycle time problems.

Banks and Carson have shown that for specific types of queuing systems, the measures for operation and performance are "interrelated", thus if one measure, such as line utilisation, is found to be predicted successfully, it can follow that other measures will be adequately predicted as well.[3] Operational and input data modelling assumptions with this type of system were limited due to the wealth of data already collected and used for the simulation. In order to avoid the potential problem of having the model "fit" one particular set of data points, three scenarios with varying inputs and common run lengths were used for the model validation, shown in Table 3.

Table 3. Scenario Data forAMS Base Model Validation.

Scenario No.	Carrier Mix		No. of Reflectors	Incoming Type Mix (MN:NN)	604 Conveyor Speed (products/hr)	System Yield (%)
	MN	NN				
1	40	2	5	19:1	210	87.1
2	33	8	5	16:4	210	84.5
3	22	20	5	10:10	210	87.2

Machine cycle times were consistent for all scenarios. Mean time to failure and meantime to repair for system equipment were based on specific data for each scenario. Mean time to repair for the testing and magnetising stations remained consistent, in accordance with the average time required for an operator to address a problem, before a Maintenance operator was requested. It was chosen not to simulate minor occurrences at this stage, such as when an operator notices a failed test in lines 1 and 2 and places a reflector on the carrier to route it to Testing/Magnetising Line 4. Only if the model proved statistically insignificant in comparison to actual measurements, would these details be addressed.

Although the actual AMS System is a non-terminating type of system, with production running 24 hours, it was identified that steady-state is reached quite early in the run from cold, approximately 60 minutes, or the amount of time to completely saturate the Magnetising Lines. The length of run for each simulation was, therefore, dependent on the occurrences of the statistically distributed operations, such as equipment breakdowns, and Magnetising cycle times. The scenarios identified above were chosen from actual production data, using the following criteria:

- The production run contained a relatively consistent carrier type mix and incoming product type mix.
- The sample duration allowed for the random number streams from those anticipated significant contributors in the simulation to be used more than 10-15 times.[7] While the breakdown occurrence of a junction point was the most infrequent, according to the previous rule, it would make the run length approximately 30 weeks. This is not practical due to the frequently changing production mix and excessive due to its steady-state nature. Consequently, the distribution for the breakdown of the magnetising units was the limiting factor and the simulated run was no less than the days necessary to obtain 10 breakdowns on the best machine.
- Between scenarios, a representative spread of incoming product and type mix was apparent.
- A representative variation in system yield was present.
- Actual equipment breakdown and set-up occurrences were not outside normal expectations and consistent with the average input data, although specific breakdowns for each scenario were identified and used.
- The scenarios could eventually be used to test the new models for significance of changes to process cycle times and system layout.

Based on these criteria, it was anticipated that the least number of model changes would have to be carried out to validate the model. The most challenging part of the validation stages was adequately convincing the customers that a simulation was never fully representative of the system under study, but adequate for the engineering objectives. Clear definition of the objectives in this case was imperative. There was a target for simulated throughput discrepancy at 5.0% from actual measures if the input values were comparative. Although 5.0% could mean as much as 10 tubes per hour, the goal of this stage in model development was to obtain a relatively accurate model which served as a decision tool for relative layout options. Therefore, at this stage accuracy greater than 5.0% was not seen as cost-effective. The model was then validated with the above described experimental runs, according to the following criteria:

- Statistical significance of the simulated hourly throughput versus the actual hourly throughput for the three sets of production data.
- Measured utilisation of the four Magnetising Lines versus observed general utilisation.
- Measured percentage of carrier "ride-bys" versus observed percentage.
- Measured equipment behaviour versus observed behaviour (e.g., carrier flow in buffer lanes).

7.4.4 Preliminary Results and Conclusions

Input data and output statistics for the experimentation can be found in the appropriate appendices. Initial statistics showed that there were some flaws in the model logic, namely the inaccurate identification of rejects within the system, and the cycle time associated with the robotic handling units. These errors were rectified and measurements were taken on the three scenarios. Using the standard two-sided t-test with a level of significance of $\alpha = 0.05$, given the number of runs or replications for each data set at $n = 6$, corresponding to six replications of a run length equal to ten days of production simulated per scenario, the results are noted in Table 4.

Table 4. Results from AMS Base Model Experimentation.

Scenario No.	Actual Average Hourly Throughput (μ)	Replication No.	Simulated Average Hourly Throughput (x)	Simulated sample mean (X) and standard deviation (S)	$t_{\alpha/2, n-1}$ [83]	Calculated t_0
1	153.0					
		1	151.59			
		2	153.40			
		3	152.47	X = 153.23	2.571	0.466
		4	153.10	S = 1.210		
		5	152.59			
		6	155.26			
2	142.4					
		1	141.88			
		2	143.68			
		3	143.80	X = 142.80	2.571	0.663
		4	140.35	S = 1.477		
		5	142.79			
		6	144.31			
3	146.5					
		1	143.94			
		2	148.43			
		3	148.36	X = 145.98	2.571	-0.563
		4	144.32	S = 2.262		
		5	147.18			
		6	143.62			

All absolute values for t_0 were well within the range of $t_{\alpha/2, n-1}$, therefore, it was concluded that the simulation model was adequate in its prediction for average hourly throughput. There was some concern that the number of replications might be low and could be giving an incorrect result, however, each scenario was tested using accepted principles for the number of replications, given a 5.0% specified accuracy and a 95% confidence interval, and found to be within the calculated recommended number of replications. Further, upon analysis of the variance of individual days readings, and the comparison of the sample Timeseries for hourly throughput to actual plots, it was shown that the simulated behaviour was a good approximate.

It should be noted, however, that this was not an entirely exhaustive study of the AMS System for all known production mixes and potential occurrences, but rather a comparison of the system under relatively stable conditions. There was a risk that certain significant occurrences happening under the actual system in less than ideal conditions had not been adequately modelled, however, in regards to the initial objectives, the model was considered adequate. Other recorded results compared to observed behaviour, but not rigorously tested are shown in Table 5.

Table 5. Other Measured Results from AMS Base Model Experimentation.

Scenario No.	M1 Utilisation (%)	M2 Utilisation (%)	M3 Utilisation (%)	M4 Utilisation (%)	"Ride-Bys" (%)	Average Sorting Buffer Size
1	97.7	96.2	90.1	97.3	16.7	1.7
2	94.9	92.5	89.1	93.9	19.9	2.2
3	94.1	92.4	88.7	93.2	20.3	2.7

Utilisation of the Magnetising Stations showed a marked difference with M3 from the others. This was consistent with observed operations, and while this would not happen continuously, it is due to the effect of the reflectors on the carriers for increased utilisation of Magnetising Line 4. It was probably also indicative of the fact that priority was given to the Magnetising Lines 1 and 2 for carrier discharge, thus blocking M3 more than those other stations. Actual observed ride-bys ranged from 15-20%, depending on type mix and handling equipment utilisation, which is reflected in the simulation results. Average buffer size indicated that the three sorting lanes prior to product loading were generally running at a minimum level with no queuing, which reflects actual system operations. Based on the above results, the model was considered validated and ready for layout/process experimentation.

7.5 Experimentation - Changes to Layout and Manufacturing Processes

From the initial engineering project objectives, two primary changes were to be implemented: refurbishment of the Testing and Magnetising stations resulting in an increase in throughput and yield, and a redesign of the AMS conveyor layout and process positions to improve the throughput. It was thought at that time that system layout was a significant contributing factor in the currently reduced output. These proposed changes resulted in the formulation of three separate simulation models.

7.5.1 AMS System Layout Design Options and Their Relation to Simulation Logic

As mentioned previously, due to the limited space and unitary design of power and free system, there were very few options in modifying the layout that were both technically and cost-effectively feasible. The design process conducted by an internal Production Design team resulted in three layouts, utilising as much existing handling equipment as possible. The routing logic for all layout alternatives was based on the original system with priority on the shortest route. As a result, the structured flow diagrams were manually updated for each alternative when appropriate.

The first design scenario included only upgraded Testing and Magnetising equipment, and did not include modifications to the actual power and free handling system. The Insulation stations were removed which created an additional buffer position for each existing testing lane. The new Combination Testing stations were placed in the original positions of the Emission/High Tension stations, also the case with the upgraded Magnetising stations. The third Combination Testing station was placed in the original "by-pass" lane to create three Testing Lines, leaving a fourth Combination unit not used. Creating a layout without the fourth Testing station would result in excess capacity. Three Testing machines processing at a combined capacity of approximately 250 products per hour should be capable of handling all requirements up to 210 per hour.

The production rate of 210 per hour was virtually a limit due to the design of the robotic handling units, not considered in the project.

The second design scenario included both upgraded process equipment and changes to the handling system, albeit, the changes were limited, to reduce the amount of installation costs. The layout took advantage of as many existing junction points and reservoir sections as possible. From loading to the system carriers would be routed to one of two secondary lines. Each secondary line would split into two distinct Testing and Magnetising Lines. Once processed, carriers would then be routed in a similar manner to the main line for unloading. While utilising four lines for testing and magnetising, it is not a distinct four lane system. While three Combination Testing stations were well within capacity at 250 products per hour, the Magnetising stations produced at 65 products per hour, requiring four stations to maintain the minimum capacity of 210 per hour. Therefore, in any four-line scenario, a fourth Combination unit would be required.

The third design was a distinct four-line layout with carriers routed from the main line to one of four testing and magnetising lines. Once processed, carriers would be routed back to the main line for unloading. It was originally intended that a distinct four-line design could have advantages over other alternatives, due to its ability to facilitate equipment set-ups. If a set-up was required on a particular Magnetising station, carriers could be routed to other lines with a minimal loss in throughput as compared to the existing design. Further, the four-line design increased flexibility for product routing if additional product types are introduced. Each processing station has a limited amount of product range, therefore, different types could be routed to specific lanes with minimal affects on routing around junction points due to the isolation.

7.5.2 Process and Equipment Changes and Their Relation to Model Elements

Changes to the equipment were consistent for all layout variations. The three sets of Testing equipment were replaced by upgraded combination units with an improved utilisation and combined cycle time, and a fourth was added in anticipation for a fourth, distinct testing/magnetising line. The four Magnetising stations were upgraded to improve utilisation, cycle time and yield. All other internal operational data, such as handling unit load times and breakdowns, AMS conveyor speed, and equipment set-ups, remained as per the base model. Testing and Magnetising station breakdowns were improved, but identical amongst the three models. The commonality eliminated any significant variation that could have caused error in experimental comparison.

Further, while the AMS System was currently handling any range of product type mix variants for MN and NN type tubes in steps of 5%, it was recognised that this type mix resulted in lower total output for the factory. Due to these observations, changes in product options offered, and a combined drop in MN demand, an alternative method was devised by which MN tubes could be processed on a different system. Therefore, during the simulation project, experimenting with varying type mixes was no longer a priority. Experimentation, therefore, focused on running one type mix (NN) only. These events, coupled with the limited changes to layout and equipment meant a much more simplified experimentation process, supporting the methodology of constantly verifying and validating project objects as discussed in previous chapters.

7.5.3 Experimental Scenario Data

The experimental models were structured with the input shown in Table 6.

Table 6. Scenario Data for AMS Experimentation.

Carrier Mix		No. of Reflectors	Incoming Type Mix (MN:NN)	604 Conveyor Speed (products/hr)	System Yield (%)
NN	MN				
42	0	0	20:0	210	91.0

Reflectors on carriers for forcing particular routing decisions were removed to observe ideal Magnetising utilisation. System yield at 91.0% was indicative of the anticipated increase in yield resulting from the equipment improvements. When using the simulation results for initial decision analysis, it was decided not to use a nominated confidence interval *with a specific accuracy*, as this could add an excessive amount of time to the experimentation, by requiring a relatively large amount of model replications. Rather, the initial replications were made and analysed for variability within each model. If the variability was similar amongst the models, no further replications would be made. Therefore, a specified confidence interval of 98% was used as the criteria, with the accuracy dependent on the number of replications, set at n = 6.

7.5.4 Experimental Results and Conclusions

Simulation logic verification and validation was addressed prior to any experimentation. Changes in all three models were focused around the reservoir and junction logic for the handling system, and the Testing/Magnetising stations. Therefore, verification was limited to these areas. Initial validation involved observing these areas with short runs used to check element operation, decision criteria for carrier flow, and carrier blocking. Sample timeseries plots for hourly throughput between the three variants can be found in the appropriate appendices.

When calculating the average hourly throughput for each model, accepted methods for estimation of a confidence interval for a fixed number of model replications were used[3], the results of which are shown in Table 7. Basing the probability on 98%, for this analysis, $\alpha = 0.02$, $t_{\alpha/2,\, n\text{-}1} = 3.365$, and n = 6.

Table 7. Results of AMS Experimental Runs.

Model No.	Run No.	Run Length (hrs)	Simulated Average Hourly Throughput (X)	Simulated sample mean (X) and standard deviation (S)	Calculated Variance $\sigma^2(X)$	Calculated Range for Average Hourly Throughput (X)
1		240				
	1		182.85			
	2		185.41			
	3		182.95	X = 184.59	$(0.559)^2$	184.59 +/- 1.881
	4		185.09	S = 1.369		
	5		186.17			
	6		185.08			
2		240				
	1		181.65			
	2		183.88			
	3		182.24	X = 183.57	$(0.559)^2$	183.57 +/- 1.881
	4		184.33	S = 1.368		
	5		185.32			
	6		183.98			
3		240				
	1		182.47			
	2		184.96			
	3		182.38	X = 183.95	$(0.527)^2$	183.95 +/- 1.773
	4		184.60	S = 1.290		
	5		185.44			
	6		183.86			

The results showed that there is relatively no significant difference between the three layouts. In fact, the design that utilises the existing layout is marginally superior, although with the range calculated, all designs were comparative. Standard deviations were also similar. Thus, it was concluded that for a 100% product mix, changes in layout were not significant in affecting average hourly throughput. Further analysis was performed on other model statistics, shown in Table 8.

Table 8. Other Significant Measures of the AMS Experimentation.

Model No.		M1 Utilisation (%)	M2 Utilisation (%)	M3 Utilisation (%)	M4 Utilisation (%)	"Ride-Bys" (%)	Average Sorting Buffer Size
1	X	96.94	95.44	90.21	73.98	4.15	6.85
	S	0.565	0.695	1.087	0.683	0.674	0.065
2	X	96.78	97.18	94.76	65.94	4.52	4.49
	S	0.581	1.011	0.623	0.787	0.641	0.033
3	X	98.39	95.81	94.48	66.55	4.42	5.57
	S	0.434	0.599	1.137	0.700	0.610	0.077

As anticipated, utilisation spread of the Magnetising stations reflected the routing logic for the particular design scenario. The drop in utilisation of Magnetising Station No. 4 is indicative of spare capacity, following the simulated "removal" of the carrier reflectors, although Model No. 1 provided a more even distribution for equipment usage. All scenarios greatly reduced the percentage of incoming product "ride-bys". Model No. 1, on average, used more empty carriers in its Sorting Buffer area implying less product being processed at any one time, however, this probably accounts for the lower percentage of "ride-bys", representing an acceptable design trade-off. As a result of the analytical and simulation studies, the decision was made to only upgrade the equipment and make no changes to the layout.

7.6 Simulation Project Results and Preliminary Conclusions

7.6.1 Validation and Designing Experiments for Future Analysis

Identifying specific layout changes and product type mix kept the amount of validation and initial experimentation activities to a minimum. Even with the minimum experimentation requirements, the amount of data and statistical analysis required was lengthy, consequently, measured steps with clearly defined boundaries and end goals resulted in a manageable process. Clearly, the limited number of design options in the experimental stage provided both. It might be concluded that not enough analysis was done on the initial model to ensure operational accuracy, in testing changes to statistical distributions used or the breakdown behaviour to ensure capture of the correct point estimation for simulation measurements, however, this should be taken in context to the objectives and cost constraints within the simulation study.

Although process equipment cycle times were proven to be very significant , the next step in improving the production process would be to undertake a formal experimental approach to determine the remaining significant factors. The design factors to consider should include: variations in the product loading speed, variations in the number of carriers in the system, effects of process equipment breakdowns, and variations in labour rules. Heuristically, some of the variants can be eliminated from experimentation, such as labour rule changes, as the operator can unload at a rate of approximately 240 products per hour, quickly eliminating resulting queues which affect throughput. For more complicated interactions, it is recommended that established design of experiments and optimisation techniques such as Variables Search, Factorial Experimentation, or Taguchi methods would be appropriate.

7.6.2 Objectives Achieved

The simulation project fulfilled its intended objectives of evaluating the effects on production throughput and system behaviour, given specific changes to process times and system layout. Certainly, the results saved a considerable amount of time, effort and capital for the project by identifying the significant and insignificant factors contributing to system capability, albeit, those factors were limited to the recommended design changes. Further, an expert modeller writing the initial simulation was an important factor in establishing a model base from which to quickly build options. Although a relatively expensive alternative, and one that requires an effective methodology and design to ensure modular simulation build for experimentation, these costs must be weighed against the anticipated benefits, which in this case, were achieved.

The user interface was generally accepted and served its initial purpose of introducing the Production Engineering customers to simulation techniques as well as providing them with a tool to evaluate current production problems. Currently, it is recognised that the benefits of using the simulation for on-line production problem solving purposes has not been achieved extensively, however, this could be more a problem of user access to the WITNESS program, rather than lack of need. The simulation model based on the scenario implemented has not been completely validated against current data, however, with minimal effort, it can be validated and used for evaluating current production problems and recommendations on a more frequent basis. This process is currently underway.

7.6.3 Standards in Communication Through the Use of Standard Documents

A benefit identified from the AMS Case Study was the use of common, comprehensive documentation for the initial simulation project definition and model build stages in facilitating all stages in the simulation process. The documentation provided a "bridge" between the model builder and the simulation project customers, facilitating their acceptance. Specific documents used during this project included:

- User (Customer) Requirement Specification - Identified background, purpose, objectives and deliverables for the project.
- System Schematic - Provided the bridge between the actual and the conceptual for functional design.
- Model Input Data Document - Identified all model elements (not necessarily those that will be directly incorporated into the simulation model) for beginning the model build process.
- Structured Flow Diagrams - Provided the modeller with the appropriate operational logic.
- Validation Release Checklist - Identified standard components and items unique to the project, used as a common handover tool.
- Preliminary and Final Results Documents - Communicated simulation study results and gave direction to subsequent activities.

8. DISCUSSION AND COMPARISONS BETWEEN THE THREE CASES

8.1 Engineering Project Objectives Affecting Design and Simulation

The Black Matrix simulations were based on engineering projects of new systems installations. Consequently, design activities were focused on potential problem analysis with little or no existing data. The limited knowledge of the type of power and free system, created uncertainty when reviewing and approving operational designs and layouts. As a result, there was a desire to understand the engineering principles to a detailed level using simulation and analytical methods. Further, the project was concerned with effective commissioning of a new system which involved a great deal of training activities with Production Engineers and System Operators, to improve system handover. These factors contributed to simulation objectives that incorporated "soft" or potentially complex issues with large boundaries, making it difficult to establish well-defined criteria. This caused the simulation project objectives to be more broad, and less defined, requiring a great deal of observational interaction with the models. Large, detailed boundaries caused the simulations to be very large, and thus, difficult to manage and communicate to the users.

In contrast, the AMS project was one carried out on an existing system with the operation well understood. The primary engineering objective for this project was optimisation of the known options, containing a limited amount of design changes, which translated to very specific simulation project objectives. Further the performance measures used for the project such as average hourly throughput, facilitated the use of statistical tools, providing a more structured approach to identify and communicate recommendations.

In all engineering projects, there exists a balance between the three factors of time, cost and quality. While all factors were a consideration at some point in the projects, with the green-field installation of the 215, 225/226 systems, quality of the end product was predominant. Thus, the engineering objectives focused on a broad range of details, resulting in a less focused simulation study. The AMS project, however, had cost or more precisely, cost reduction, as its driving factor, with quality an existing given and time although important, not as relevant. The targeted cost reduction activities resulted in simulation objectives that were more focused.

8.2 Engineering System Differences and Their Affect on Model Build

The 215 and 225/226 power and free systems, while based on similar carrier handling principles, were slightly different from the AMS power and free technology. The AMS Carriers worked on resistance which meant that carriers queuing behind one another were not "delatched" physically from the system, reducing some of the safety issues. Consequently, the control design for a minimum running pitch other than the carrier length was not necessary. Pusher dogs on the AMS System were spaced on a tighter pitch, which meant reaction time from control release to actual carrier movement was reduced. Further, the AMS System was designed without any rise or fall areas, which again contributed to the lack of need for a minimum running pitch. These differences in power and free system technology and track design resulted in a less complex control design and thus, a less complex simulation design.

The AMS System, being an FMS was designed as a relatively self-contained, closed-loop system, which meant all conveyor reservoirs could be optimised for simplicity; they were designed for a whole number of conveyor carriers. The product or carrier flow through the system had a singular goal, with carriers being routed through the shortest path possible, making priority logic at junction points obvious. In contrast, the 215 and 225/226 Systems, being linking systems handling as many production occurrences as possible between the two main processes, were subject to additional design factors. Process stop points were optimised according to outside factors such as building size, operator visibility and mating system size restrictions.

These systems did rely on physically "delatching" the carrier and did contain rise/fall sections, and thus were subject to controlled minimum pitch requirements.

Further, while the product flow in this type of system was relatively unidirectional the carrier flow was not, consequently, the system contained both by-pass and feedback loops to accommodate normal and abnormal production operations, complicating the layout design. These manufacturing design factors contributed to more complicated simulation models. The greater the significant factors in design input, the greater the detail required for simulation. The number of control options devised for the 215 and 225/226 power and free systems created additional "generic" model types, making a GT approach to subsequent simulation activities more complicated.

8.3 Significant System Design Factors and Their Effect on Model Build

The level of design analysis activities affected the model build and analysis stages by affecting the level of depth required in the simulation. The 215 and 225/226 systems required detailed analysis of all aspects of the handling systems including mechanical and control design, requiring these models to be more interactive, less reliant on statistical analysis methods. Provided that the model was used for visualisation and observing the affects of different interactions, rigorous experimental design was not a requirement, supporting conclusions made by Keller.[30] Analysing the effects of cycle time increases and specific layout changes constituted the design activities for the AMS redesign, mechanical and control design of the handling system not being necessary as it was limited to the existing assumptions. Analytical models did not, therefore, effectively apply to the performance measurements for this design. These differences resulted in more detailed build and interactive validating activities for the 215 and 225/226 models and more detailed reporting and statistical analysis activities for the AMS models.

The type of design analysis had an effect on the visual effects built into the models. The 215 and 225/226 models were more visually interactive due to the requirements for animated potential problem analysis and the model's use as a training aid. Consequently, animation such as queuing carriers, machine movement, or stocks being built for various types were seen as significant, and thus captured. In comparison, the AMS models were focused on the resulting output and statistical machine behaviour, with the animation activities being secondary. As a result, there was less animation built into the model, allowing time to design more efficient, user-friendly means of data capture and reporting.

8.4 The User Group and Its Affect on the Model Build Stage

The user group or the end customer differed between the Matrix and AMS simulations, influencing the simulation user interface, and the amount of information graphically displayed and animated on the screen. The 215 model was built with the systems designer, familar with the simulation software package, as the primary user. The designer did not require special facilities for data entry, thus emphasis was not placed on the menu interface and more detail was placed into accurately capturing the principles and potential problems for the type of system. The type of model exhibited characteristics of a "throwaway" type that once used, is no longer needed. The 225/226 model was intended for the designer as well as the system operators and production engineers. It therefore needed facilities that allowed non-WITNESS users access to the simulation functions without training in the software package. Though increasing the requirements for the build stage, it reduced the amount of time required for problem analysis, as the system parameters could be quickly changed with the menu interface being a reproduction of the actual interface.

The AMS simulation models were structured with a limited user interface for production engineers, under their area of concern for production design parameters. Therefore, the model interface required a level of detail less elaborate than the 225/226 models and a simple menu interface consisting of only those design parameters was sufficient. Like the 225/226 model, it was not seen as a throwaway model, therefore, the interface required the minimum level of detail that allowed its effective use after the initial study.

8.5 Simulation Project and Model Success - Critical Factors

From the case studies carried out on power and free systems and general simulation within PCL Durham, significant factors for success of a simulation project are identified below.

- Comprehensively identify simulation project objectives.
- Do not change the objectives unless it is to simplify them.
- Limit those objectives to well-defined measurables if possible. If not possible, limit the boundaries (either physically or in depth). In other words, do not start too large. A failure identified in the 215 simulation project was that the detailed level was created first, which did not allow sufficient time to build and analyse other system level detail.
- Use the objectives to structure the model boundaries, prior to initiating the model building process. The 215 model build was initiated prior to adequately understanding the actual system and how the objectives could be met by simulation, thus causing an excessive amount of build time. In contrast, the AMS model build did not begin until objectives were firmly established, therefore, the environs were structured appropriately.
- Identify and incorporate the appropriate level of detail. This is dependent on adequate analytical knowledge of the system being simulated. For example, the 215 and 225/226 handling systems assumed certain behaviour that was not necessarily discrete, however, analytical knowledge of the system identified an adequate approximation.
- Use standard simulation elements wherever possible. Although this may be limiting depending on the capability of the simulation software, most manufacturing design functions can be handled by the simulator packages. If designer elements are used, make them generic enough to become part of the normal repertoire.
- Use analytical models as much as possible to reduce the level of detail required and the subsequent design time.
- Keep the customer involved at all stages of the project.
- Keep verification and validation an integral part of all stages in the process. System design experts should be involved as much as possible.
- Use standard tools to implement the model build and analysis stages. This will reduce the amount of documentation efforts required in the latter stages of the project.
- Do not consider simulation the end all and be all of analysis. In other words, simulation is only as good as the information put into it. Use as many design tools as the project allows.
- Use simple distributions to represent stochastic behaviour before using more complex distributions. This could save a great deal of analysis time if they validate.

8.6 General Benefits Observed and Measured from Simulation

The simulation studies carried out at PCL Durham resulted in both awareness of the uses of simulation and a level of confidence in simulation results to ensure its continued use for manufacturing systems design. Recognised benefits for utilising simulation during the engineering design process included:

- Improved awareness and understanding of system design parameters for implementation of power and free handling systems by requiring the identification of significant factors for the simulation.

- A more robust engineering design resulting from the ability to quickly and cost-effectively evaluate alternatives and potential problem areas.
- Reduced implementation costs through effective evaluation of alternatives to eliminate non-significant factors, such as the layout designs for the AMS System.
- Improved communications to end-users for system analysis, utilising graphics and animation capabilities to illustrate design alternatives.
- Increased potential for future design effectiveness, using a common tool that can be quickly understood. Increasing the saturation of simulation within the plant, improves the awareness and effectiveness of its implementation.
- A complement to analytical models that can be used to "fine-tune" certain operations in which the analytical methods prove inefficient.

8.7 Future Use of Simulation at PCL Durham

Simulation was proven an effective tool for systems design at PCL and has been accepted as part of their design process. Applying a GT approach to its development will ensure its effective integration into the manufacturing systems design strategy. Future simulation projects at PCL should investigate several areas, including:

- Optimisation of the existing AMS System using the simulation model with the application of Design of Experiment techniques to identify significant system factors controlling throughput and system utilisation.
- Application of simulation to other areas of the facility on a system level.
- Application of simulation at the plant level. It is anticipated that this type of simulation would best fit the WITNESS capabilities, particularly for a plant redesign.

9. CONCLUSIONS

9.1 Design Considerations for the Industrial Environment

When designing a system, it is necessary to identify the significant factors that contribute to its success or failure. To design successfully, and thus simulate effectively, significant factors must be accurately captured, however, often times, significant factors are not known without simulating them and evaluating their effects. The lack of analytical and dynamic understanding of new systems can account for why observations made during the study showed that existing systems were less complicated to simulate. When undertaking new system design, therefore, it is necessary to fully understand the established analytical models to give guidance for simulation activities. This also supports the recommendation for initiating simulations with simple detail and introducing more complexity if validation supports its requirement; the methodology discussed previously.

For the simulation studies at PCL, those that were of relatively large boundaries, physically, were more effective if kept to either the plant or system levels. These types of simulations had relatively large bounds, but minimised depth and subsequent element detail. Only if the initial objectives were not met by the higher level simulations would a detailed model, focused to a specific area of the system, be required. Thus, the detailed simulations were only effective if the boundaries were kept to a minimum, limiting the amount of complex interactions and coding requirements. There was an observed inverse proportion of model boundary to model depth for successful modelling, resulting in reduced model build time and run time for illustration to others and conducting experiments. It was noted that regardless of the model structure, all simulation projects required specific objectives to be ultimately successful.

9.2 Using Discrete Event Simulators

Discrete event simulators proved effective for modelling and analysing power and free conveyor systems on the plant and system levels due to their use of common manufacturing elements and interfaces to build models quickly. However, their ease of use is compromised by having limited applications for detailed level analysis of power and free systems. WITNESS, in particular, could benefit from a more user-friendly method of identifying conveyor detail, such as track lengths, control sensors, and pusher dogs. Presently, to effectively simulate detailed devices of a power and free system, it is necessary to utilise a simulation language, which has the disadvantage of requiring further expertise in proprietary computer languages. The question is one of significance. For the system design activities at PCL, it was shown that effective use of the analytical methods for detailed design and use of the simulator for dynamic design and potential problem analysis could provide an effective alternative to the use of a simulation language.

9.3 Significant Factors in Designing and Simulating Power and Free Handling Systems

The analytical methods used in identifying significant factors for design were reviewed in depth previously. Two primary goals of the power and free design process should be, to ensure that the physical design is correct, such as layout and internal device placements, relative to interfacing equipment, and to ensure that the control of carrier flow and traffic management is acceptable under all anticipated production scenarios. For systems that link together two or more distinctly different processes, the use of push/pull methodologies when designing the layout and control of the system has been proven superior to the conventional designs. Implementation of push/pull techniques requires adequate knowledge of the use of buffers in the conveyor systems and desired equipment utilisation. Further, any control design or interface devices that can improve upon existing production control strategies such as the Drum, Buffer, Rope method discussed previously should be pursued when undertaking design of power and free systems.

Simulation was used in assisting the design functions for both goals mentioned above. Practically, it was concluded that simulation is effective for the first goal only if the boundaries were localised, while it was more effective in assisting the second goal when evaluating transient and steady states. If the objective was to examine the transient states then it was successfully done on a limited boundary level, whereas, if the emphasis was on steady-state analysis, the system was usually relatively large for simulation, favouring less detail. The less complicated the simulation, the more effective the results.

To bring less complication to the simulation, the use of generic or user-defined elements should be used to capture common items in the actual system. Using a simulator to create generic designer elements or standards for the various general power and free systems had several advantages which included:

- Minimal required knowledge of simulation elements.
- Model changes were quickly performed.
- Sensitivity analysis was carried out quickly, provided the parameters for performance were accurately identified and captured.
- If the sub-model had to be reconfigured, it was done very quickly with someone relatively familiar with the WITNESS package.

As experienced with other studies, a negative effect in using generic models is that they could take a very long time to develop from the beginning which could be cost-prohibitive in practical situations.[40]

9.4 Using Simulation for the Design Process and Production Operations

While using simulation for the layout design of the AMS System was successful, it did not prove as useful when designing the layout for the 215 and 225/226 power and free systems. In those cases, the analytical models, structured towards a worse-case operating scenario, provided the most effective tool during the design stage. Similar results were encountered for designing handling and process requirements. When determining carrier requirements for the 215 and 225/226 systems, for example, analytical methods for carrier estimation were sufficient. The simulation was capable, however, of illustrating the effects of carrier numbers on the system or a reservoir that was under capacity more effectively than static models. It was concluded that the analytical methods, if used correctly, could be a more effective tool for calculating the maximum levels, and simulation was effective if "fine-tuning" those requirements, when required. Practically, however, the worse case is usually chosen for design strategy as a contingency to address unknown potential occurrences in the system.

The systems evaluated in the case studies contained several areas where stochastic interactions created complexity that could not be easily addressed with the analytical models. System models provided the opportunity to effectively evaluate operating decisions and potential problems previously identified. Detailed models created for the 215 and 225/226 systems further assisted the control design by identifying potential areas requiring additional design consideration. If it was complex to simulate there was a strong possibility that the actual design would be difficult.

The simulations created had limited effectiveness in the area of system operator training. Although, it was concluded that this was due to the length of model build time and detail thought to be required to provide the system's operators with a "true" picture. Availability of the system's operators was also a factor. Creating the operator controls to the level of detail for the 225/226 simulation was useful for changing system parameters in comparison to past simulation interfaces, however, it was not effective in assisting the interface design. More appropriate tools, such as Computer-Aided Design (CAD) packages were more effective. If the time to build the model could be reduced, and the amount of interface detail limited, this area might be properly exploited. Having an expert modeller with the appropriate time, there is no need for a complicated or user-friendly interface as created for the 225/226 and AMS simulations. If an expert was not available, the menu interface was required for the system level. It then required efficient management of project activities to be effective. It was observed that the level of the model interface should directly correlate to the level of user knowledge. The less familiar the user was with the modelling language, the more detailed the interface assistance, and the more outside influence required.

Continuous improvement and ongoing problem analysis using the simulation models created were two areas that remained effectively under-utilised. Once the initial project was completed, there was a loss in visibility, subsequently, the model was not used. Further, restricted access to the model also contributed to its lack of use after the initial experimentation. The observations supported the use of "hit and run" models that have limited detail and were treated as throwaway models. Currently, efforts are underway to reintroduce the AMS simulation model for production optimisation and classification of significant factors for immediate throughput improvements.

9.5 Future Simulation Capability in an Industrial Environment

The objectives of manufacturing simulation should continue to be aimed towards the most effective use of the tool to improve system design and operation in the production arena. From the activities carried out with simulation at PCL, two areas in which future research could prove effective include, the use of simulation coupled with optimisation tools, and the integration of simulation to on-line monitoring and control packages, such as, SCADA packages.

The use of simulation in conjunction with other optimisation tools to quickly capture best production parameters for a system or design is, in a sense, approaching automation of the design process. It is aimed generally at the design area of manufacturing systems, its objective being the effective optimisation of a system based on changing production requirements. A system cannot be optimised for all production scenarios, therefore, utilising a tool to quickly evaluate the effects of changes and recommend a solution would greatly facilitate the activities of the designer and production engineer. Further, existing systems that are to be optimised are concerned with day-to-day scheduling, provided that the layout and other design factors are fixed. Simulation models for this type of system that bridge the gap between the actual schedule and a simulated schedule are applicable here.

When SCADA packages are introduced they need to implement graphics and devices that are similar to those used in a simulated environment. If the two packages could be combined, the design effort could be substantially reduced with the end result a real-time simulation and control system. Systems that are to be designed from the beginning are always concerned with the potential reduction in development time. Integration could improve the one-off design activities for a manufacturing system by combining the simulation and control design efforts into a single product that can be used throughout the life of the system. This could further improve the anticipated benefits of effectively training operational personnel prior to system installation. A connection between a simulation system and a SCADA system could improve the design time and the operator ownership.

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APPENDICES

Appendix 1 - System Illustrations

The following are pictures of the three systems used for the design studies at Philips Components Ltd, Durham. All the systems studied are currently in use within the facility for product handling and manufacturing processes.

A. 215 Power and Free Handling System

The 215 System is an overhead, hanging carrier, power and free system, manufactured by Matflex, France. Figure A1. shows the four sorting harbours used to buffer and sequence product by type prior to Flowcoat. The harbours are located on an overhead platform remote from the other production operations, illustrating the flexibility of such systems, with complicated handling functions being performed away from busy areas. Mask and screen combinations can be seen on the hanging carriers.

Figure A1. 215 System Sorting Harbours With Return Leg

Figure A2. illustrates a stop station for this type of system. The relevant mechanical elements are identified, appropriately.

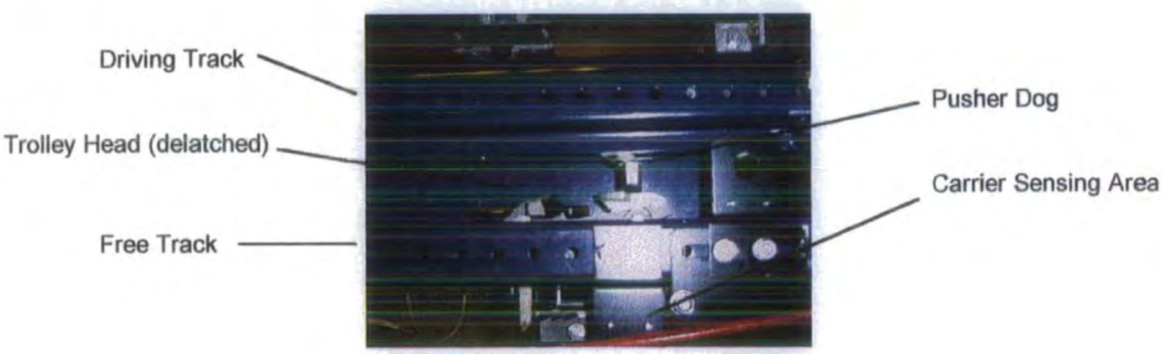


Figure A2. Stop Station With Trolley Arrangement

Figure A3. illustrates the route for empty carriers prior to Matrix Line 1. Carriers are transported from high level to the front of the Matrix Line robot at low level. There, they are loaded with mask and screen combinations. The single track shown on the incline above the main double track is for chain return, noting that a single driving chain is used for this type of system.

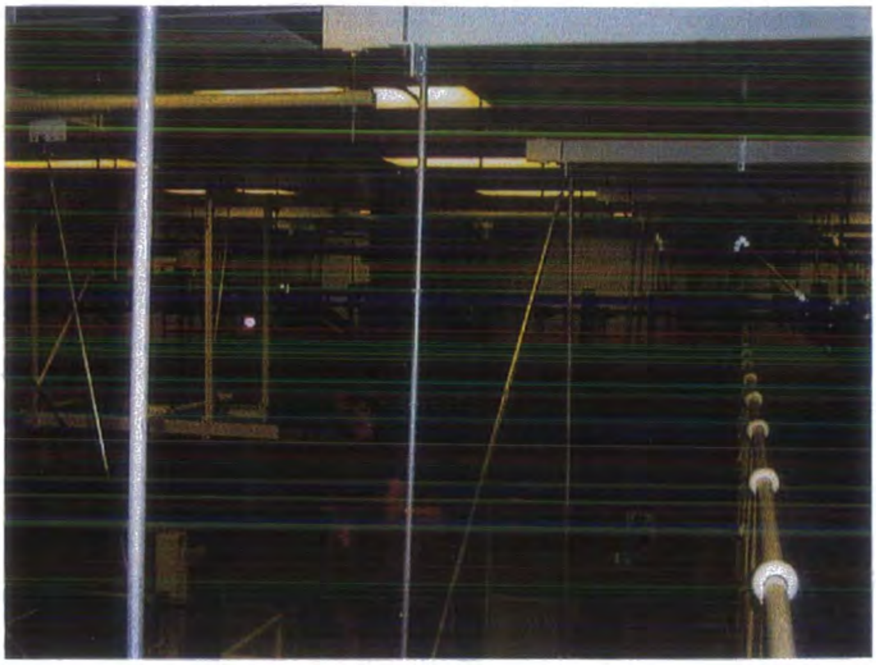


Figure A3. Route From High Level to Matrix Line 1.

Figure A4. illustrates the Selective Heating area of the system, in which combinations, kept on carriers, are transported through an on-line heating tunnel to attain the required temperature for Flowcoating. Many of the manufacturing processes can be performed on-line with power and free systems.

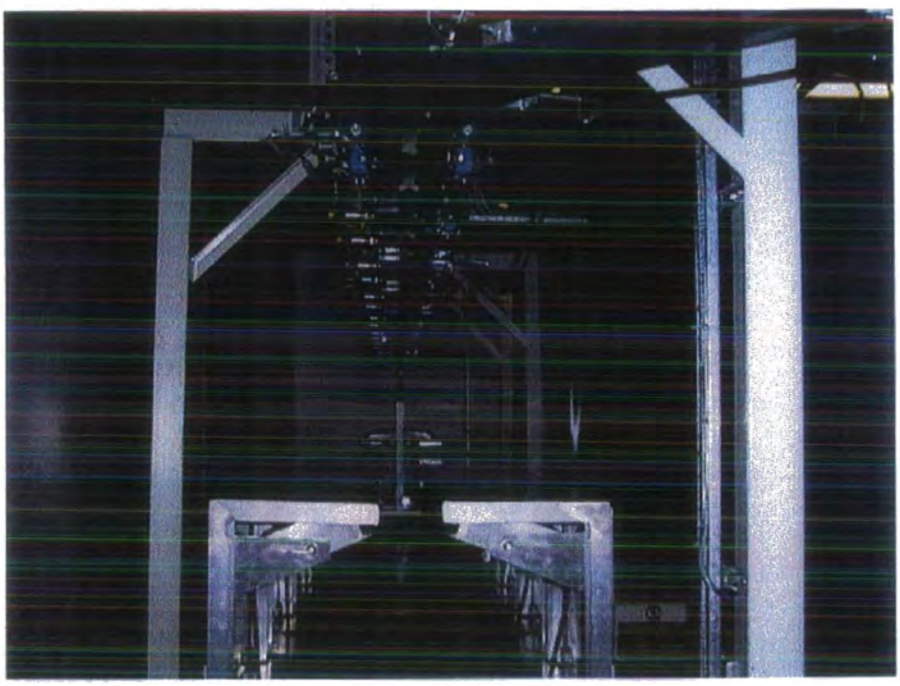


Figure A4. Selective Heating System With Carrier.

B. 225/226 Power and Free Handling System

Virtually identical to the 215 System in mechanical component design and manufacturer, the 225/226 System differs in its layout and production speed. Figure A5. illustrates the main operator station for the system. The Man/Machine Interface (MMI) and the SCADA System can be seen in the lower right corner of the picture. Also shown is the stock harbour, used to load or unload product from the system.

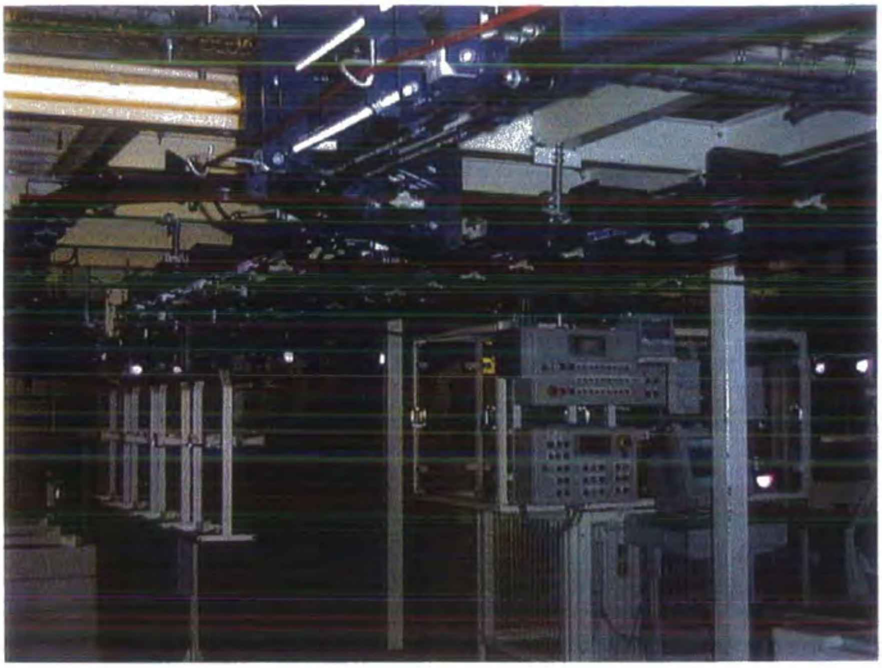


Figure A5. 225/226 Operator Station and Stock Harbour.

Figure A6. illustrates a carrier in a stop station opposite Matrix Line 4. It has been centralised and is awaiting the robot to load a mask and screen combination. Note the carriers queuing behind the first one. This was a design requirement, as the second carrier must be released empty, and in sequence with the first carrier, for loading a combination at Matrix Line 3.

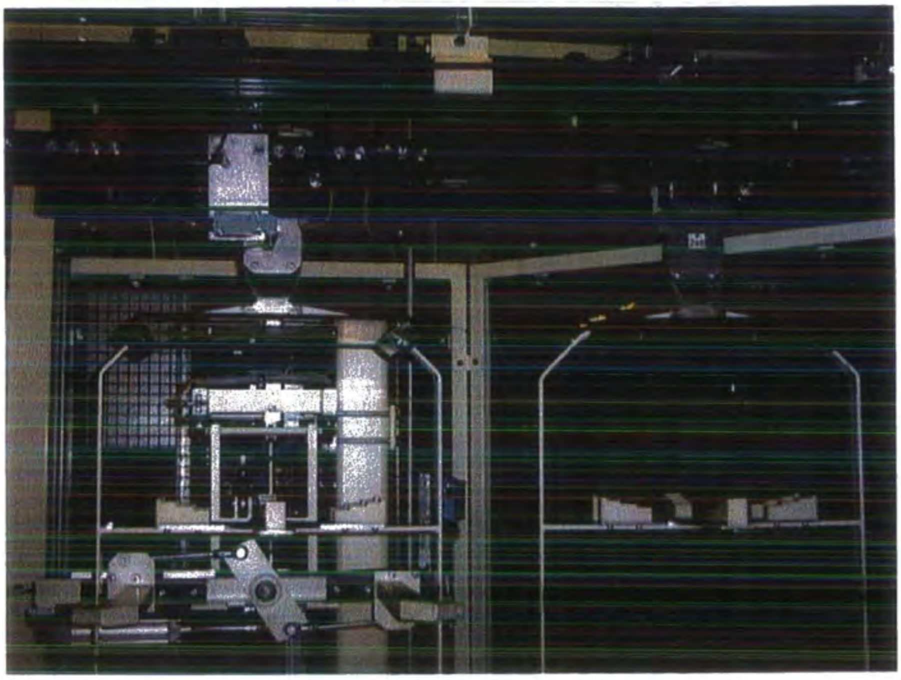


Figure A6. Centralised Carrier at Matrix Line 4.

Figure A7. illustrates the decoupler mechanisms installed for the 225/226 System. Full carriers can be seen at the bottom of the picture awaiting transfer to the 226 side and eventually Flowcoat. Empty, returning carriers are shown awaiting transfer from the 226 side to the 225 side and eventually back to the Matrix Lines. This improves the effective overall system utilisation by creating two, semi-independent systems from a larger, more complicated one.

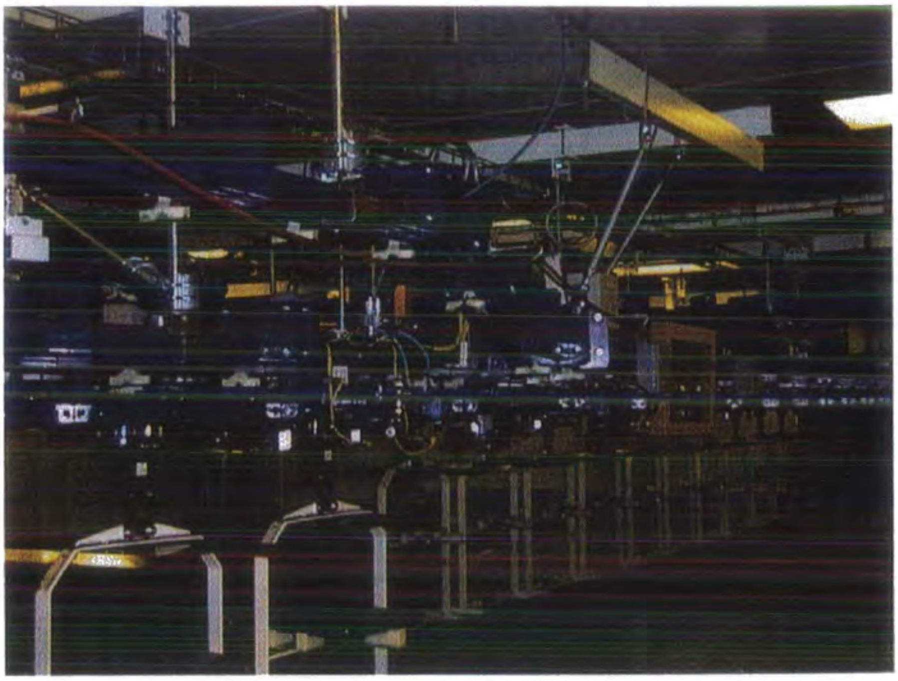


Figure A7. Decoupler Mechanism for 225/226 System.

C. AMS Circuit Handling System

While the power and free handling system used for the AMS Circuit is a hanging carrier system similar to the ones reviewed previously, it differs, both in track technology and carrier design. Figure A8. is a profile section of the power and free system stop station (track shown in yellow). The pusher dogs are resistance type dogs, designed to pull a front bar attached to the carrier (shown at the bottom of the picture in black). Being resistance type, the carriers are not mechanically delatched from the system.

Figure A8. AMS Circuit Handling System Stop Station.

Figure A9. illustrates the sorting harbours for the circuit. Empty carriers await their release into the circuit from three holding bays, depending on the availability of the MN or NN Tubes. Carriers are dedicated to one of the two general tube types.

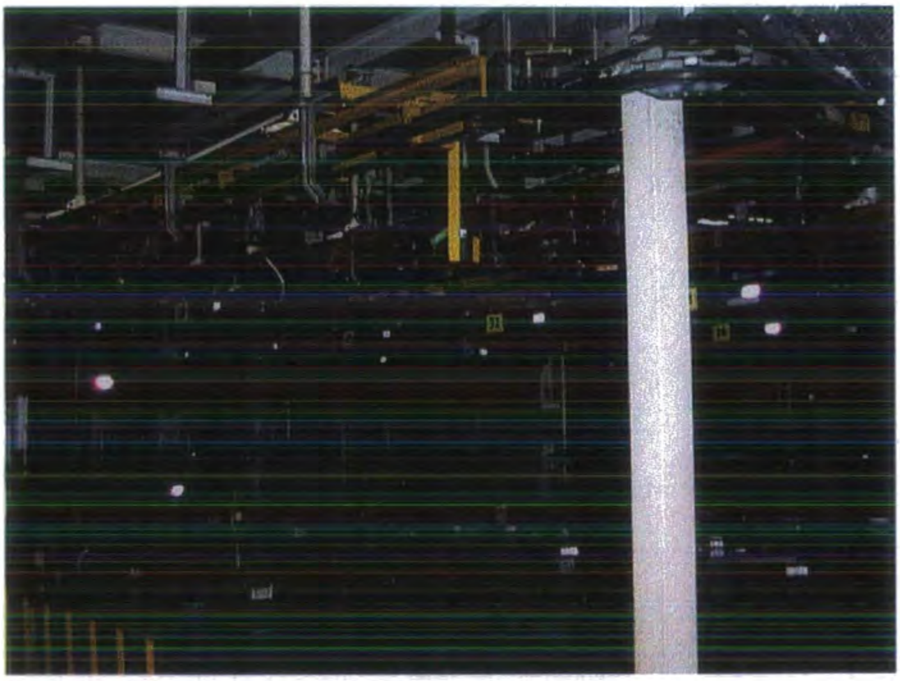


Figure A9. Sorting Harbours on the AMS Circuit.

Figure A10. illustrates the configuration of a Combination Testing Unit. Similar to the selective heating process on the previous systems, testing is performed on-line, with the tube remaining in the overhead carrier. On the far line shown, carriers are transported to the testing cabinet (its halves shown in white on either side of the handling system). The two halves then close on the carrier, shielding it from any outside elements. A centralising unit, internal to the testing station adjusts the carrier prior to the Insulation, Emission and High Tension tests.

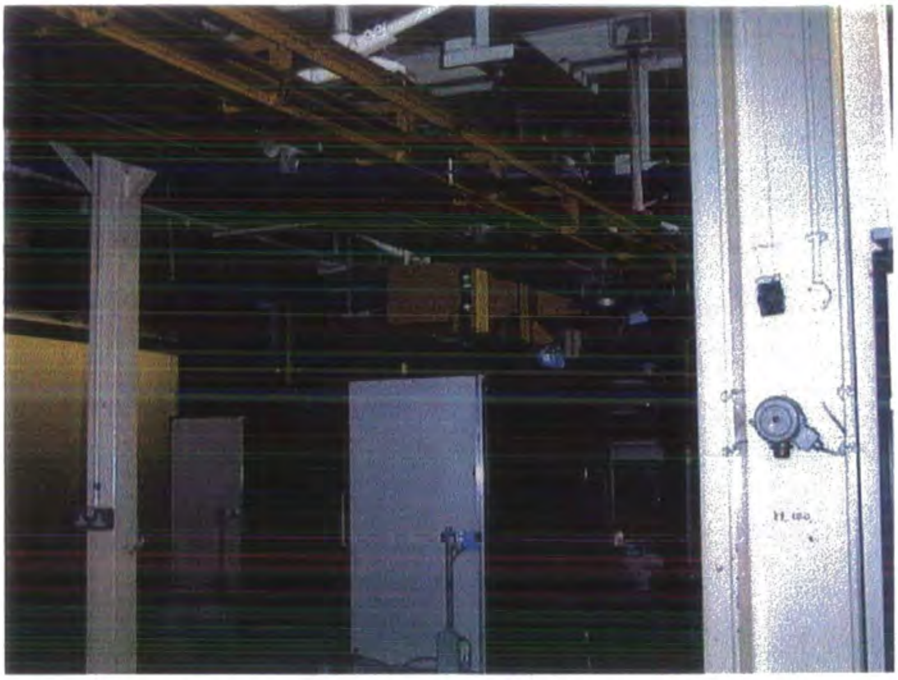


Figure A10. Combination Testing Unit on the AMS Circuit.

Appendix 2 - Handling System Layouts and Schematics

The following pages include layouts and schematics of the systems used for the research at PCL, Durham.

Figure A11. is a layout of the 215 Power and Free Conveyor System, handling mask and screen combinations between Matrix Lines 1 and 2 and Flowcoat Line 3. All processing points and surrounding equipment items are noted. Stop stations, merges, and diverts are numbered sequentially, e.g., stop station 1 is “S1”, merge 1 is “M1”, and divert 1 is “D1”. As this drawing is also used by Maintenance personnel, “inspection gates”, or sections of track used to inspect conveyor chain and carriers, are shown in yellow. The floor level equipment, while actually installed directly under the top level in the Matrix Area, is shown separately, for clarity. The system spans two buildings in the facility and its entire length is approximately 0.850 km.

Figure A12. is a layout of the 225/226 Power and Free Conveyor System, handling mask and screen combinations between Matrix Lines 3, 4, and 5 and Flowcoat Lines 1 and 2. Processing points, surrounding equipment, and system components, are marked as per the previous designation. Inspection gates have not been expressly identified. Floor level equipment has been separated from top level for clarity. The 225 side of the system has been shown in blue, to distinguish it from the 226 side of the system, shown in green. Similar to the 215 System, the 225/226 System spans two buildings and its entire combined length is approximately 0.800 km.

Figures A13., A14., and A15., are the schematics used to illustrate the three layout design scenarios for the AMS Circuit design project. All terminology is identical to the schematic of the original AMS Circuit, shown in figure 42., previously.

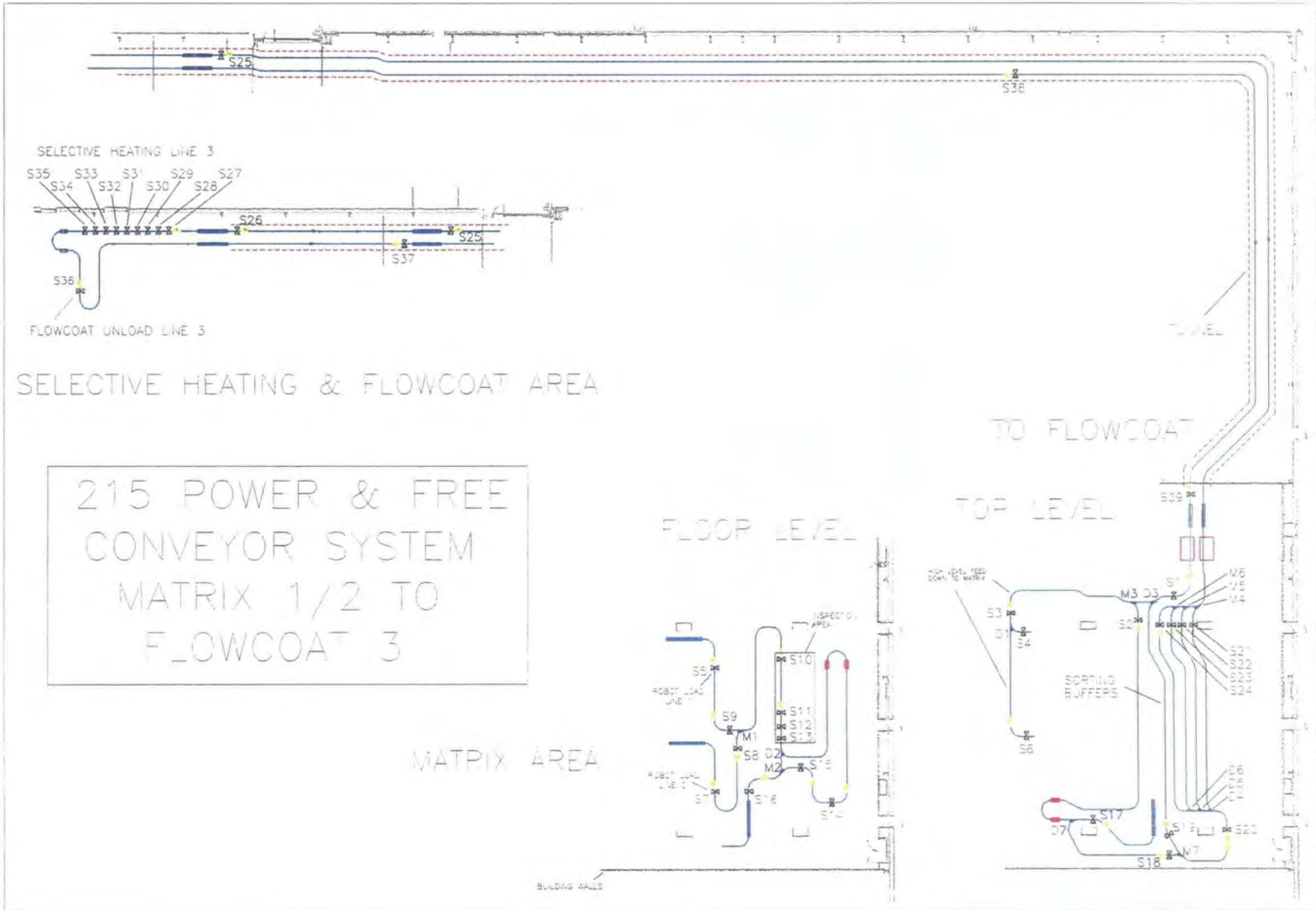


FIGURE A11. 215 System Layout

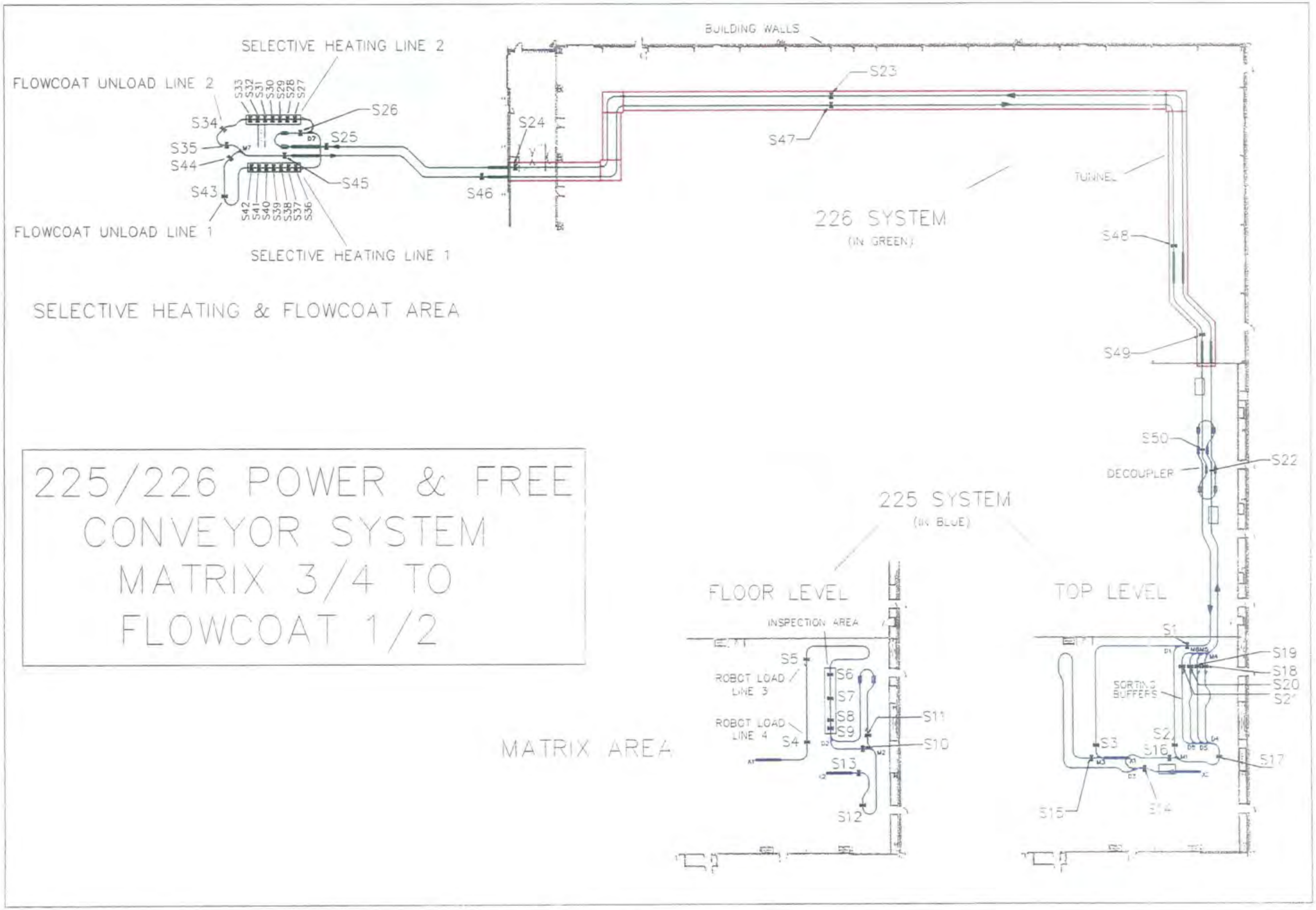


FIGURE A12. 225/226 System Layout

AMS Circuit - Design Scenario 1

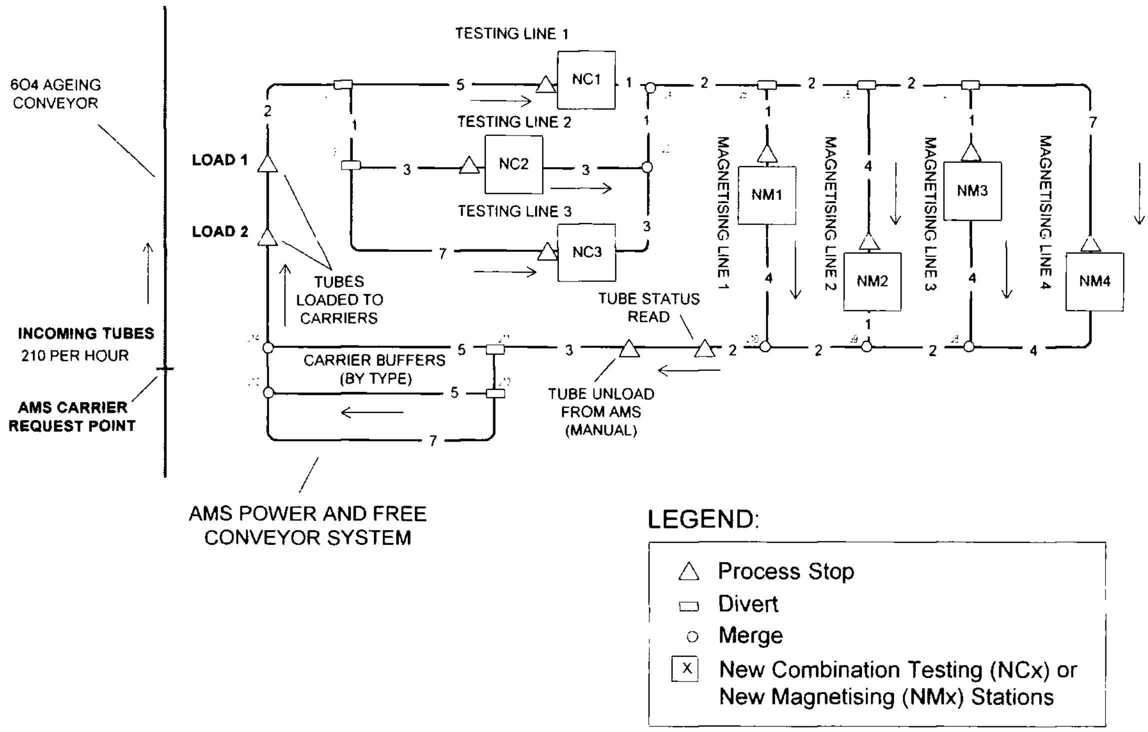


Figure A13. Schematic of Design Scenario 1 for AMS Circuit Layout.

AMS Circuit - Design Scenario 2

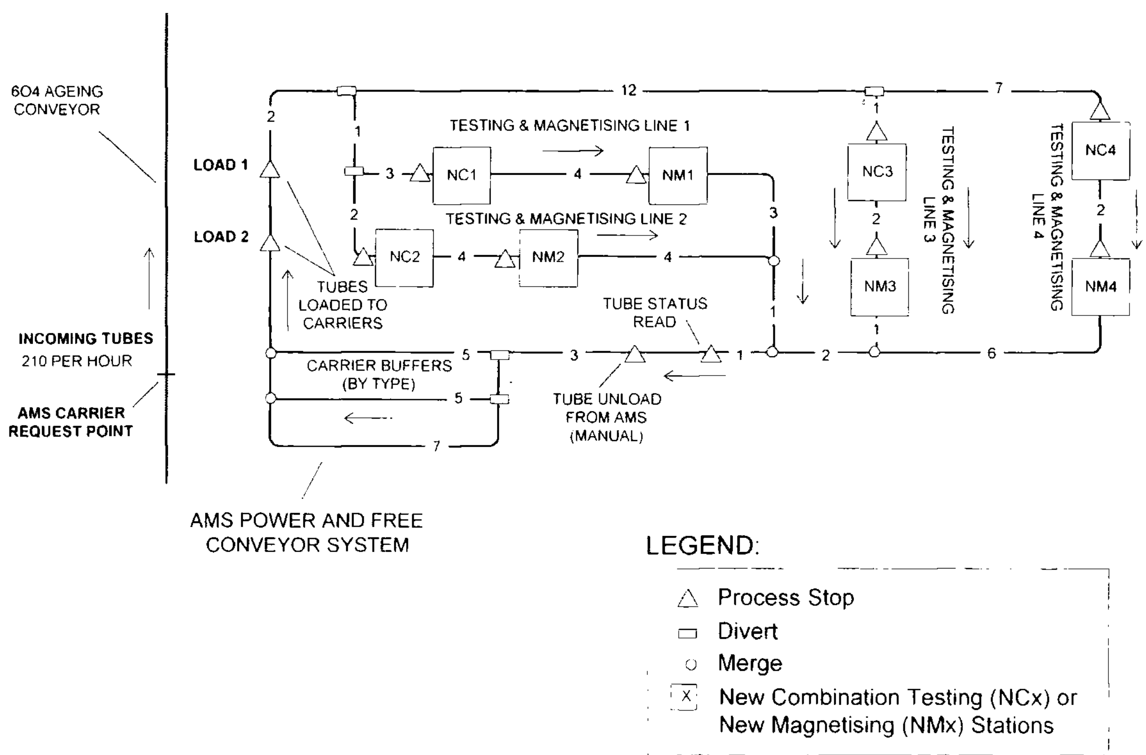


Figure A14. Schematic of Design Scenario 2 for AMS Circuit Layout.

AMS Circuit - Design Scenario 3

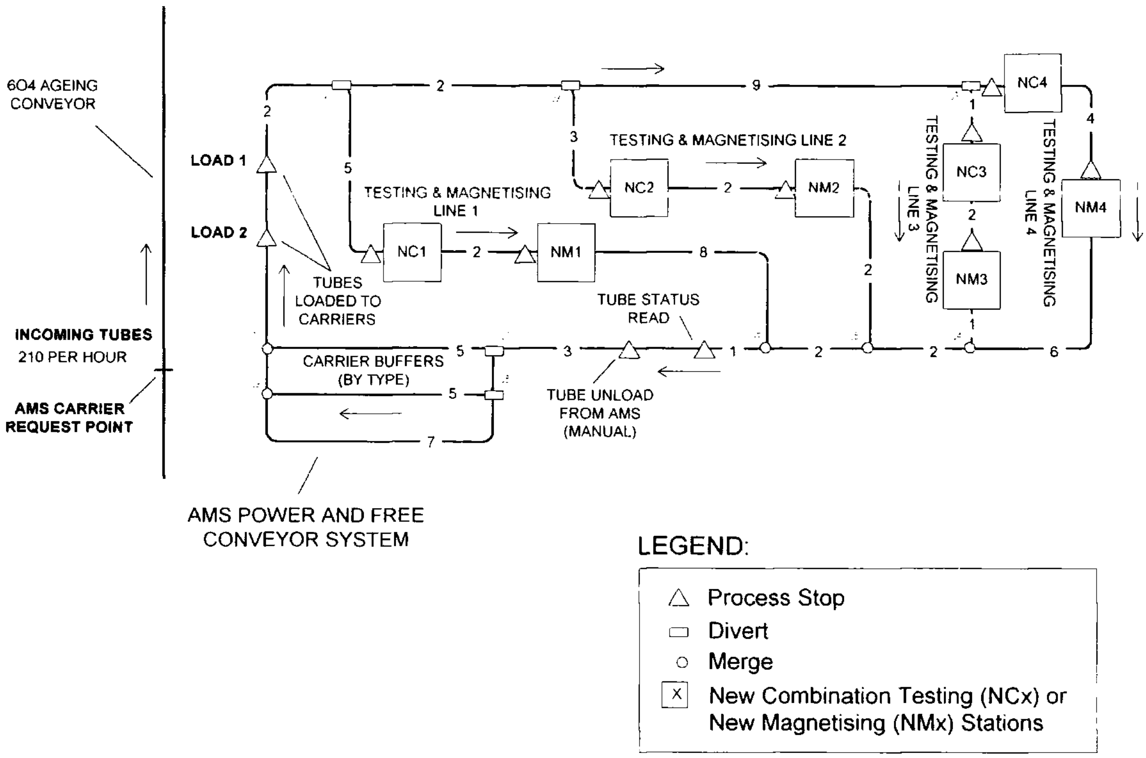


Figure A15. Schematic of Design Scenario 3 for AMS Circuit Layout.

Appendix 3 - WITNESS Simulation Model Displays

The following pages include illustrations of the WITNESS models created for the systems studied at PCL, Durham.

A. 215 System Simulation Displays

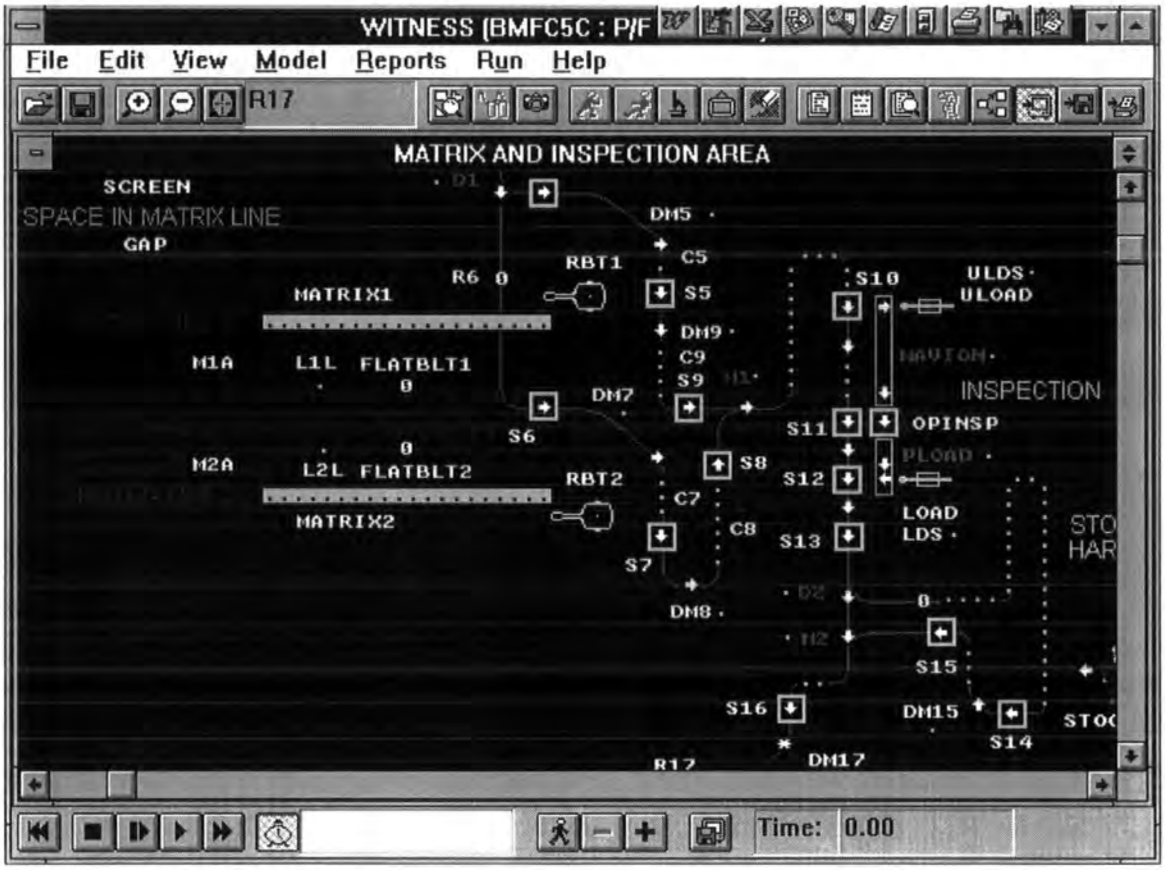


Figure A16. Simulation Display of the Matrix and Inspection Area - 215 System.

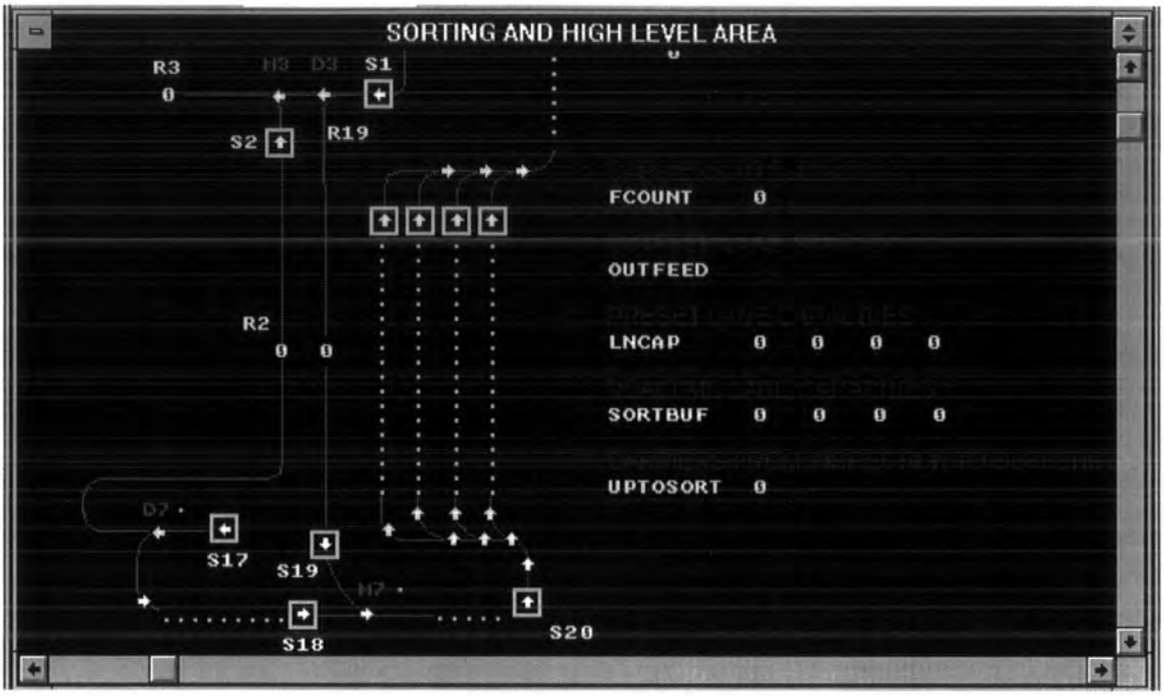


Figure A17. Simulation Display of the Sorting Buffers - 215 System.

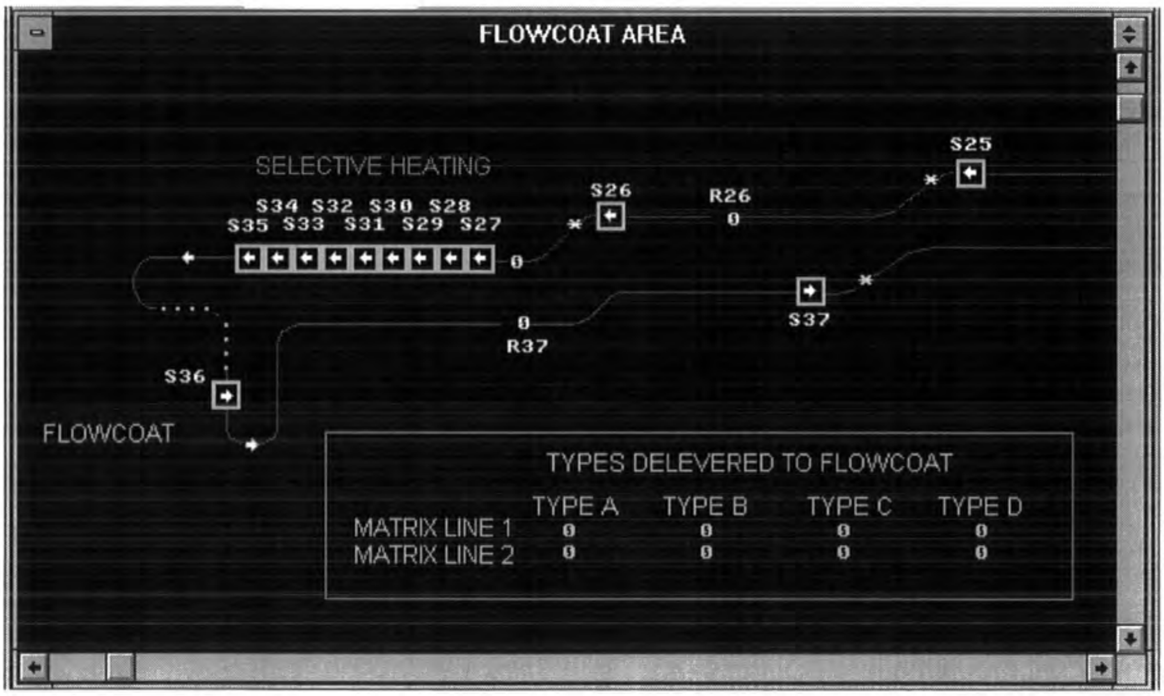


Figure A18. Simulation Display of the Selective Heating and Flowcoat Areas - 215 System.

B. 225/226 System Simulation Interface Displays

The following displays illustrate the user interfaces created for the 225/226 simulation. They were designed to either mimic the actual operator control panels, as shown in figure A19., or facilitate "production" schedule changes, as shown in figures A20., and A21. During the simulation run, the "switches" shown on the displays could be toggled using a computer mouse. The designs are alternatives to the traditional methods for entering data into a simulation model, intended to assist a person unfamiliar with the WITNESS program. They were also used to test the layout and user-friendliness of the control panel layout.

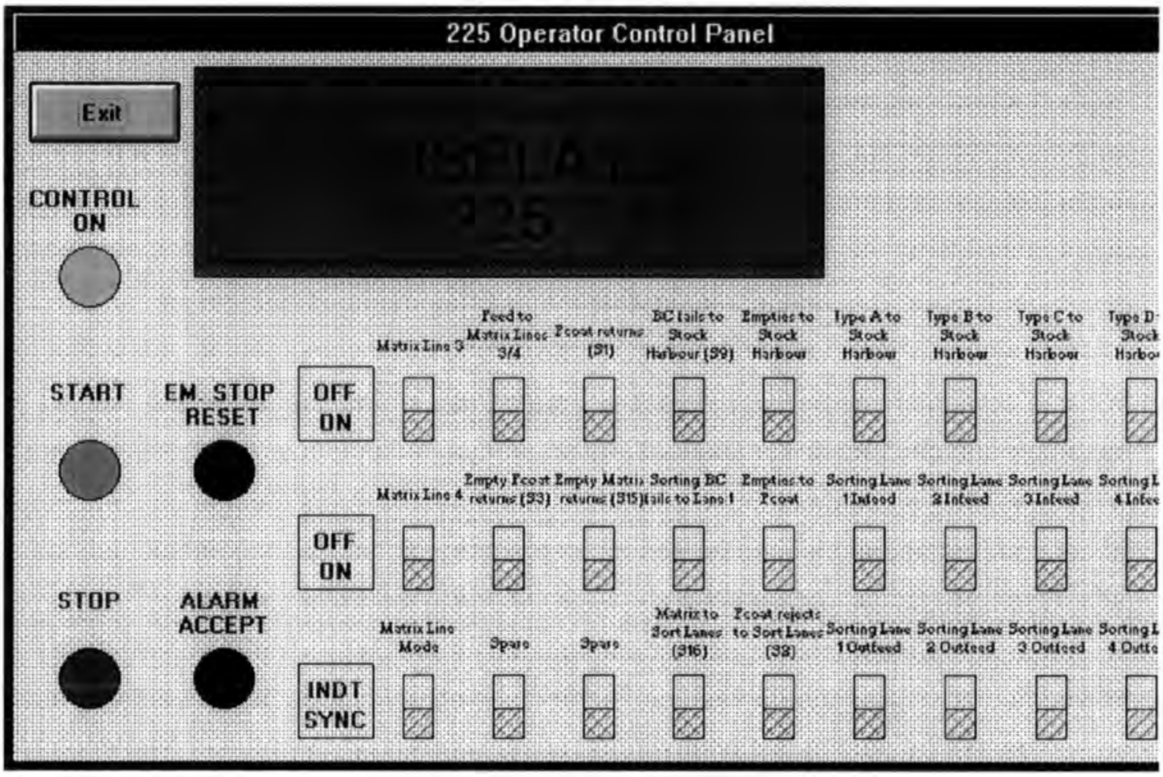


Figure A19. Simulation Interface Display of Operator Control Panel - 225 System.

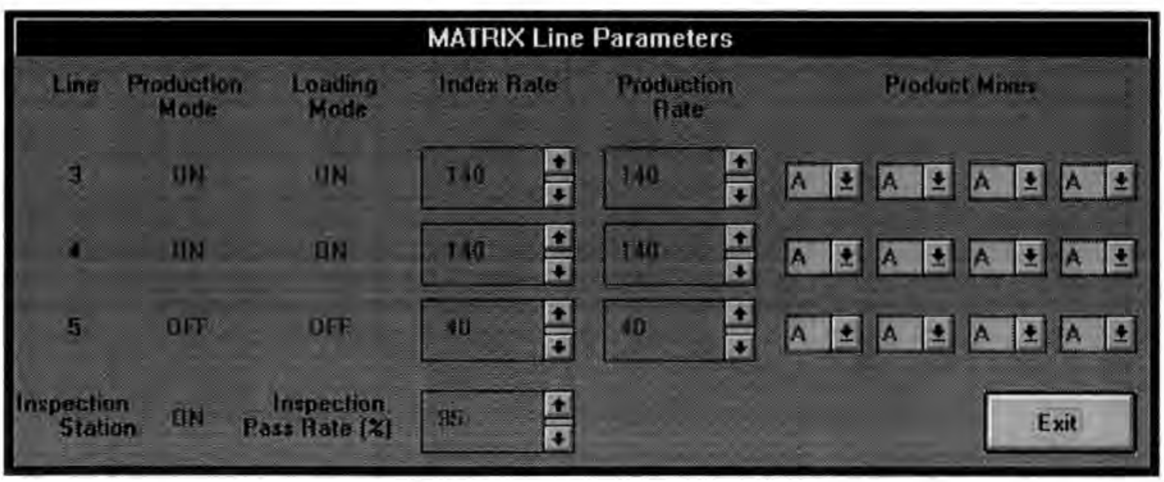


Figure A20. Simulation Interface Display of Production Settings - Matrix Lines 3, 4, and 5.

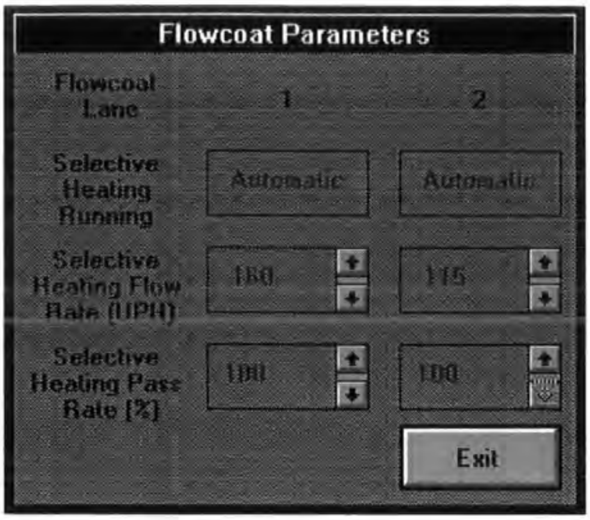


Figure A21. Simulation Interface Display of Selective Heating Production Settings.

C. AMS Circuit Simulation Display

Figure A22., illustrates the simulation display created for the first design scenario of the AMS Circuit layout project. This design was eventually accepted from the three alternatives, and installed as the new AMS Circuit.

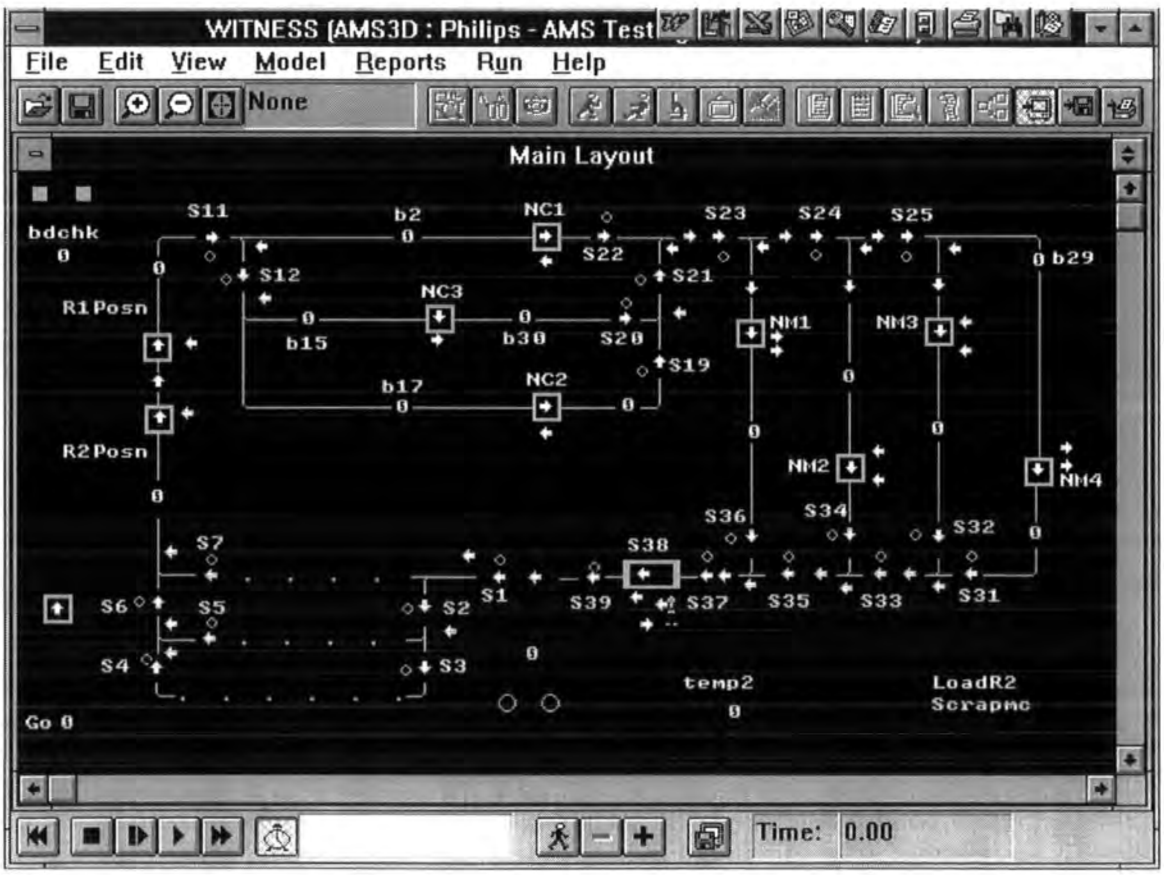


Figure A22. Simulation Display of the New AMS Circuit.

Appendix 4 - Data Tables for AMS Simulation Experimentation

The following tables consist of the input and output data used for experimentation and validation of the AMS base model.

A. Input Data Tables

Table A1., displays the a partial data collection table used to build the model. This table was structured in correlation to the data required per element in the WITNESS simulation package, to facilitate model build. "O", "B/D " and S/U" refer to operations, breakdowns or equipment set-ups, respectively. Table A2., displays the production scheduling options for incoming type mix to the Circuit. Tables A3., A4., and A5., display the parameters input for each of the three different model experiments.

B. Output Data Table

Table A6., is a summary of hourly throughput results from the three experimental runs, in comparison to actual hourly throughput based on the same input data. The daily throughput averages were used to analyse the range of simulated values obtained against actual results, to observationally assess model performance for validation.

Table A1. Data Summary Table - AMS Circuit.

I. MACHINES						Breakdown Information	
Name	**Function and comments**	**Quantity**	**Labour**	**Cycle Time (sec./product)**	**Reject Rate (%)**	**Avg/day**	**Avg time (min)**
Robotic Transfer	Transfer tubes from 604 Conveyor to AMS Circuit. Matched to the 604 speed.	2	B/D	17.1	0	5.0	5.0
Insulation Machine 1	Perform insulation tests on incoming tubes. Cycle time includes travel into machine.	1	B/D & S/U	21.0	0	0	0
Emission/High Tension Machine 1	Perform combination emission and high tension test on incoming tubes. Cycle time includes travel into machine.	1	B/D & S/U	36.8	5.0	0.3	4.0
Magnetising Machine 1	Perform magnetising function on incoming tubes. Note above comments on cycle time.	1	B/D & S/U	50 - 2 shots 59 - 3 shots	4.0	1.0	5.5
S1	Stop Station prior to Sorting Buffers on AMS Circuit.	1	B/D	6.6	N/A	N/A	N/A
D1	Divert prior to Sorting Buffers on AMS Circuit.	1	B/D	5.0	N/A	0.1	4.4
Unload Station	Unload good and reject tubes from AMS Circuit, and load to outgoing conveyors.	1	O	8.0	N/A	N/A	N/A
II. Conveyors						**Breakdown Information**	
Name	**Function and comments**	**Quantity**	**Labour**	**Carrier Pitch (m)**	**Speed (m/min)**	**Avg/day**	**Avg time (min)**
604 Conveyor	Fixed, continuously moving conveyor delivering tubes to front of AMS Circuit for load.	1	none	0.812	2.8	0.7	4.0
AMS Circuit Conveyor	Power and free handling system for transporting tubes in AMS Circuit.	N/A	B/D	1.0	11.8	N/A	N/A
III. Labour							
Name	**Function and comments**	**Quantity**					
AMS Circuit Operator	Unloads tubes for AMS Circuit and loads them to the appropriate outgoing conveyor. Also tends to any equipment breakdowns.	1					
Process Control Operator	Performs 3 checks per week per testing and magnetising station to set-up station parameters.	1					
IV. Parts							
Name	**Function and comments**	**Quantity**					
MN Tubes	Mini-neck television tubes processed in AMS Circuit.	unlimited					
NN Tubes	Narrow-neck television tubes processed in AMS Circuit.	unlimited					
MN Pots	Carriers used on AMS Circuit Conveyor to transport MN tubes.	0 - 43					
NN Pots	Carriers used on AMS Circuit Conveyor to transport NN tubes.	0 - 43					

Table A2. Incoming Pattern Mix Variants from 604 Conveyor.

Sequence No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Pattern 1	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Pattern 2	X	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O
Pattern 3	X	O	O	O	O	X	O	O	O	O	X	O	O	O	O	O	O	O	O	O
Pattern 4	X	O	O	O	O	X	O	O	O	O	X	O	O	O	O	X	O	O	O	O
Pattern 5	X	O	O	O	O	X	O	O	X	O	X	O	O	O	O	X	O	O	O	O
Pattern 6	X	O	O	O	O	X	O	O	X	O	X	O	O	O	O	X	O	O	X	O
Pattern 7	X	O	O	X	O	X	O	O	X	O	X	O	O	O	O	X	O	O	X	O
Pattern 8	X	O	O	X	O	X	O	O	X	O	X	O	O	X	O	X	O	O	X	O
Pattern 9	X	O	O	X	O	X	O	X	X	O	X	O	O	X	O	X	O	O	X	O
Pattern 10	X	O	O	X	O	X	O	X	X	O	X	O	O	X	O	X	O	X	X	O
Pattern 11	X	O	X	X	O	X	O	X	X	O	X	O	O	X	O	X	O	X	X	O
Pattern 12	X	O	X	X	O	X	O	X	X	O	X	O	X	X	O	X	O	X	X	O
Pattern 13	X	O	X	X	O	X	O	X	X	X	X	O	X	X	O	X	O	X	X	O
Pattern 14	X	O	X	X	O	X	O	X	X	X	X	O	X	X	O	X	O	X	X	X
Pattern 15	X	O	X	X	X	X	O	X	X	X	X	O	X	X	O	X	O	X	X	X
Pattern 16	X	O	X	X	X	X	O	X	X	X	X	O	X	X	X	X	O	X	X	X
Pattern 17	X	O	X	X	X	X	X	X	X	X	X	O	X	X	X	X	O	X	X	X
Pattern 18	X	O	X	X	X	X	X	X	X	X	X	O	X	X	X	X	X	X	X	X
Pattern 19	X	X	X	X	X	X	X	X	X	X	X	O	X	X	X	X	X	X	X	X
Pattern 20	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

X = Narrow-Neck Tube

O = Mini-Neck Tube

Table A3. Input Data Table for AMS Simulation Experimental Run No. 1

EXPERIMENT NO. 1												
Production Week No.	Week 9					Week 10						
Weekday	MON	TUE	WED	THU	FRI	MON	TUE	WED	THU	FRI	Actual Average	Simulated Data Used
SYSTEM YIELD	84.5	88.5	86.2	87.5	87.8	86.8	86	89.1	87.3	87.1	87.1	87.1
TOPSY CCT STOPS	15	19	20	15	12	9	26	13	16	24	16.9	
TIME LOST	100	99	115	115	65	55	155	95	87	258	114.4	
AVERAGE TIME LOST PER STOP											6.77	6.7
EQUIPMENT STOPS	50	26	18	1	4	10	20	8	6	1	14.4	
TIME LOST	208	128	162	20	4	205	49	72	35	445	132.8	
AVERAGE TIME LOST PER STOP											9.22	4
MN POTS	41	41	41	41	39	37	37	39	41	41	39.8	40
NN POTS	4	4	2	4	4	2	0	0	0	0	2.0	2

Table A4. Input Data Table for AMS Simulation Experimental Run No. 2

EXPERIMENT NO. 2												
Production Week No.	Week 14					Week 15						
Weekday	MON	TUE	WED	THU	FRI	MON	TUE	WED	THU	FRI	Actual Average	Simulated Data Used
SYSTEM YIELD	83.4	82.2	85.2	84.2	83.1	84.6	86.5	86.8	84.6	84.6	84.5	84.5
TOPSY CCT STOPS	17	7	14	8	13	9	25	13	9	8	12.3	
TIME LOST	103	35	70	46	117	55	135	125	70	40	79.6	
AVERAGE TIME LOST PER STOP											6.47	6.5
EQUIPMENT STOPS	6	37	62	29	5	4	3	6	4	6	16.2	
TIME LOST	77	89	106	411	95	105	95	40	145	190	135.3	
AVERAGE TIME LOST PER STOP											8.35	4
MN POTS	33	33	33	33	33	33	33	33	33	33	33.0	33
NN POTS	8	8	8	8	8	8	8	8	8	8	8.0	8

Table A5. Input Data Table for AMS Simulation Experimental Run No. 3

EXPERIMENT NO. 3												
Production Week No.	Week 37					Week 38						
Weekday	MON	TUE	WED	THU	FRI	MON	TUE	WED	THU	FRI	Actual Average	Simulated Data Used
SYSTEM YIELD	86.5	87.1	87.8	86	87.2	85.4	87.6	87.6	88.8	88.4	87.2	87.2
TOPSY CCT STOPS	8	7	17	6	8	3	11	6	7	7	8.0	
TIME LOST	44	35	100	100	70	15	110	30	35	455	99.4	
AVERAGE TIME LOST PER STOP											12.43	12.4
EQUIPMENT STOPS	0	22	31	8	8	0	19	3	29	3	12.3	
TIME LOST	0	245	150	391	255	0	140	73	533	60	184.7	
AVERAGE TIME LOST PER STOP											15.02	4
MN POTS	23	22	21	23	22	21	20	21	22	22	21.7	22
NN POTS	19	20	21	19	20	21	22	21	20	20	20.3	20

Table A6. Output Data Table for AMS Simulation Experimental Runs

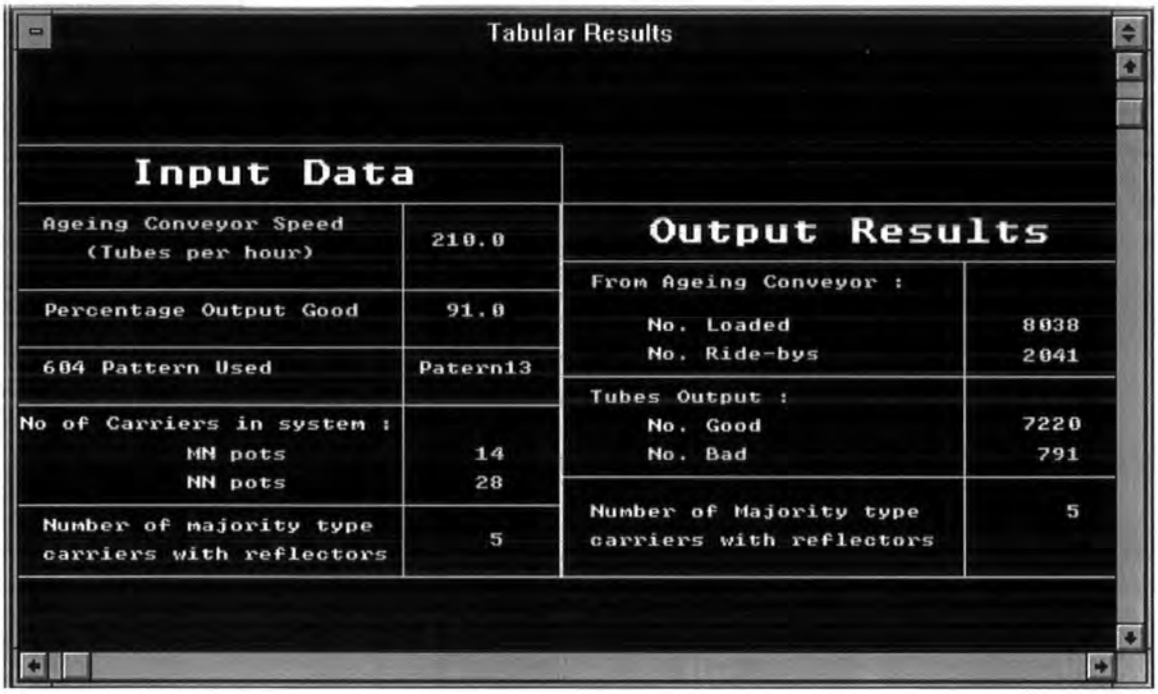
EXPERIMENT NO. 1												
Production Week No.	Week 9					Week 10						
Weekday	MON	TUE	WED	THU	FRI	MON	TUE	WED	THU	FRI	Average	STD DEV
ACTUAL TUBES PER HOUR AVERAGE	142	153	156	155	162	154	148	160	156	144	153.0	6.50
SIMULATED TUBES PER HOUR AVERAGE	147	152	151	154	155	156	147	146	143	154	150.5	4.45

EXPERIMENT NO. 2												
Production Week No.	Week 14					Week 15						
Weekday	MON	TUE	WED	THU	FRI	MON	TUE	WED	THU	FRI	Average	STD DEV
ACTUAL TUBES PER HOUR AVERAGE	135	142	146	132	140	146	145	150	141	147	142.4	5.60
SIMULATED TUBES PER HOUR AVERAGE	149	140	141	143	144	149	146	141	143	142	143.8	3.22

EXPERIMENT NO. 3												
Production Week No.	Week 37					Week 38						
Weekday	MON	TUE	WED	THU	FRI	MON	TUE	WED	THU	FRI	Average	STD DEV
ACTUAL TUBES PER HOUR AVERAGE	151	143	147	137	147	147	146	159	143	145	146.5	5.72
SIMULATED TUBES PER HOUR AVERAGE	141	142	150	152	144	156	151	150	144	147	147.7	4.88

Appendix 5 - Sample WITNESS Simulation Output Data - AMS Base Model

The following illustrations are sample output displays used for experimentation and observational validation of the base simulation model for the original AMS Circuit. The simulated hourly throughput, shown in figure A24., was compared against existing throughput behaviour, given comparable input parameters.



Tabular Results

Input Data	
Ageing Conveyor Speed (Tubes per hour)	210.0
Percentage Output Good	91.0
604 Pattern Used	Patern13
No of Carriers in system : MN pots	14
NN pots	28
Number of majority type carriers with reflectors	5

Output Results	
From Ageing Conveyor :	
No. Loaded	8038
No. Ride-bys	2041
Tubes Output :	
No. Good	7220
No. Bad	791
Number of Majority type carriers with reflectors	5

Figure A23. Input and Output Statistics Used for AMS Model Validation.

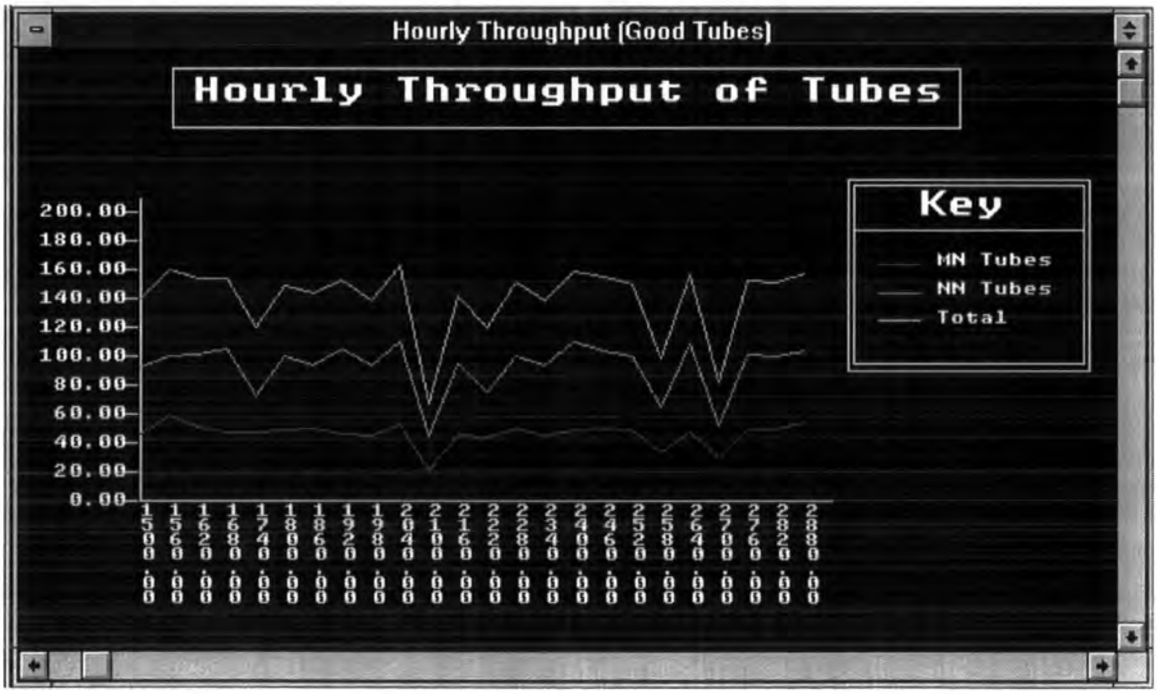


Figure A24. Sample Hourly Throughput for AMS Model.