Simulation Study of a Semi-Automated Flexible Production Line

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of MEng, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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Date: 29/09/2008

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Abstract

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By

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In today's highly competitive and challenging marketplace, manufacturing process improvement is more important than ever before. Conversely, it is probably also harder to achieve than at any time in the past. This is due to several factors. High levels of capital investment combined with short product life cycles mean that maximising utilisation levels of expensive equipment is essential. Increasingly complex production facilities are difficult to analyse and improve. The possibility of worsening the situation rather than improving it means that experimentation on the line itself is often a risk not worth taking. One solution to this problem is the use of computer based manufacturing system simulation. Simulation studies are beneficial because they remove the element of risk associated with experimentation. Potential process improvement strategies can be identified, evaluated, compared and chosen in a virtual environment before eventual implementation on the factory floor. This research aimed to evaluate the use of discrete event system simulation in a real world manufacturing environment. To this end, a flexible simulation model of the main transfer line of Läpple Ireland, a large metal panel production facility, was designed and constructed using Extend simulation software. In conjunction with Läpple personnel, various 'what if' scenarios were identified and evaluated. These scenarios were aimed at deciding the best position for providing additional automation by investing in robots. From the results of the simulation modelling of the three main proposed modifications to the line, improvements of 9%, 18% and 33% in press line throughput were predicted. The negative effect on these improvements in the case that the proposed robots failed to achieve the desired speeds were evaluated. These negative effects were found to be not as dramatic as could be expected. The results were compared to those of similar research efforts elsewhere. Finally, future steps for the research to take were identified and suggestions for future areas of application for the model were made.

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1. Introduction

Manufacturing has been defined by Groover [2] as the transformation of materials or subassemblies into items of greater value by means of one of more processing and/or assembly operations. Manufacturing in various forms has been carried on for many thousands of years. However, it was only with the technological advances of the 20th century that the automated manufacturing which is so commonplace today emerged.

Today, as has always been the case, manufacturing enterprises are continually looking for means of improving the capacity, efficiency and quality of output from their facilities. For companies in the high volume and/or high technology industries, manufacturing equipment is a costly resource due to the advanced technology used. Because of the high capital cost combined with ever-decreasing product life cycles, manufacturing systems must be utilised to the maximum extent possible. Therefore these production lines often run 24 hours a day, 7 days a week. This means that experimentation with processes or system parameters to improve operations is impossible as any loss in efficiency resulting from this experimentation or downtime caused by it would prove extremely costly.

Conversely, the competitive nature of these industries means that the company must ensure that the equipment is put to the best possible use to maximise productivity. This means not only identifying the best possible process parameters, but also having effective planning and scheduling methods, material handling systems and preventative maintenance procedures to ensure that where possible, the installations have an uninterrupted supply of the necessary components or materials and are reliable and efficient enough to deliver the required production levels to meet company targets and product demand. So how can these industries improve their processes, procedures or system parameters without impacting on production in any way?

One solution that presents itself is to use computer based modelling and simulation techniques. This allows system analysis and experimentation to be performed on the model rather than the actual system. When an accurate model of a production line is built any experiments or 'what if' scenarios can then be explored using the model. This removes the risk associated with experimenting with the line itself. However any potential improvements identified following the experiments can be implemented on the line itself based on the results from the model. In this way the company is safeguarded from the disadvantages of experimentation with the production line while still enjoying the potential benefits of any experimentation efforts.

The objective of this research work was to design, develop and implement a flexible discrete event simulation model of a press transfer line with both automated and manual stations. Some what-if scenarios are explored which aim to investigate the effect of reducing process time variability by adding additional automation to the line. The use of simulation in this context is evaluated and the general findings are compared with similar research. In Section 2 of the thesis the history of manufacturing and manufacturing modelling and simulation is outlined. The steps to be followed when conducting a good simulation study are identified, compiled and summarised. The modelling software is chosen and described. Having identified a suitable production line in the partner manufacturing company, the system to be modelled is described in detail in Section 3. The modelling steps identified in Section 2 are followed in Section 4 and the progress made is documented. The model building process is explained in detail along with the challenges which were overcome on the way to building an accurate and flexible model. The experiments to be performed on the model are outlined in Section 5, the desired outputs from the model are generated and the results presented. The implications of these results are discussed in Section 6. Based on the results some recommendations are made which if implemented would improve the throughput of the line.

2. Literature Review

This section begins by giving a brief overview of different types of manufacturing. The specific areas of interest of this research are explained in more detail. The concepts of modelling and computer based simulation are introduced. The benefits and potential pitfalls of using simulation are described. The recommended steps to follow to perform a valid simulation study are identified and documented. Finally, some examples of the application of simulation to similar problems to that found in this research are presented. The differences and similarities between the literature and this project are discussed.

2.1. Classification of Manufacturing Systems:

There are many methods of classification which can be used to describe manufacturing systems. They can be grouped based on production type, production volume, flow or layout or the level of automation.

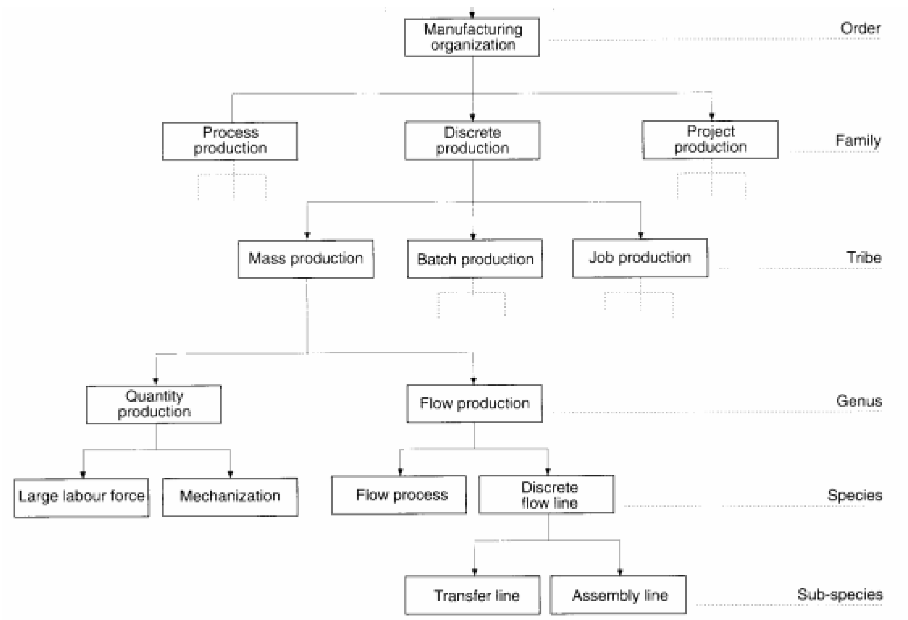

Figure 2.1: Manufacturing Dendrogram, adapted from McCarthy [1]

McCarthy [1] compiled a preliminary manufacturing dendrogram incorporating many of these classification methods. This dendrogram can be seen in Figure 2.1. This section of the thesis will follow the path of the dendrogram from the manufacturing organisation order all the way down to the assembly and transfer line sub species. Particular attention is paid to the areas most relevant to the production line which forms the subject of this research.

According to Banks et al [3] and Law & Kelton [4] systems can usually be defined as continuous or discrete. This also applies to manufacturing systems and is shown in the dendrogram in Figure 2.1. Examples of continuous manufacturing systems include oil refineries and other chemical industries. Discrete manufacturing systems include any type of production where individual items are produced, e.g. automotive manufacturing. This research deals with a discrete manufacturing system.

There are three main types of discrete manufacturing system, job, batch and mass production. These have been identified by McCarthy [1] and described in more detail by Groover [2] and are discussed in the following sections. It should be noted that a combination of the methods outlined below is also possible, for example job shop production may be combined with batch production.

2.1.1. Job Shop Production:

A job shop usually makes low volumes of specialised products. It consists of general purpose equipment which is operated by a highly skilled work force. Depending on the product in question, the layout may be fixed-position or a process type layout. Fixed position layout is used where the product is too large and/or heavy to move around the factory. In this case workers and processing equipment are brought to the product in sequence as the build progresses. Examples of the application of this type of production would be ship building, aircraft production and other heavy machinery.

With the process type layout, the factory is arranged with machines of a certain type grouped together. For example, milling machines would be in one section, lathes in another area and so on. As the product is manufactured it must move from one area to another as each operation is required. This layout is very flexible and can accommodate a large variety of product types. It is therefore ideally suited to low volume, diverse production. However, it is not suitable for higher volumes as the methods used are not designed for high efficiency.

2.1.2. Batch Production:

In the medium quantity production range, batch production is often used. In this type of production the equipment is configured to produce a certain type of product. The required amount or batch of this product is manufactured, and then the equipment is re-configured to manufacture a different product. Orders for each product would be repeated frequently. Process type layout as described in the previous section is frequently used for medium quantity production although for high quantities a flow line type layout may be used. In these cases the system would be a hybrid of batch production combined with a high volume assembly or transfer line.

2.1.3. Mass Production:

Mass production is the term used to describe the high volume range of manufacturing. In these cases the production facility is dedicated to the production of a single product. There are two main categories of mass production and these are described in this section.

Quantity Production:

Quantity production is the mass production of single parts on multiple pieces of equipment.

Flow Production:

Flow-line production involves multiple pieces of equipment arranged in sequence. Products start at one end of the line and are physically transferred from one machine to another where operations are performed until the completed product emerges at the end of the line. The machines are designed specifically for that product to maximise efficiency. The layout is called a product layout. There are two main types of flow line, the assembly line and the transfer line. The difference between the two is in the type of operation performed at each workstation.

Perhaps the most common type of flow line is the assembly line. Pioneered by Henry Ford in the early 20th century it quickly became popular throughout the manufacturing industry. The product moves along the line from station to station. This is usually done by means of a mechanical conveyor. At each station another part is added to the assembly until at the end of the line the product is complete.

A transfer line is very similar to an assembly line in terms of layout. The principal difference is that processing rather than assembly operations are performed at each station of a transfer line. It should be noted that transfer line in this context does not mean that all work pieces are transferred simultaneously as with an indexing machine. Instead there are buffers between each machine and parts can move between machines independently. In a pure transfer or assembly line there is no variation in the product produced. However pure assembly or transfer lines are less common in modern manufacturing systems. Group Technology originated in the United States in the mid 1920s and was developed over the following decades eventually becoming widely used by the mid 1960s [2]. Group technology involves the identification and grouping of similar parts in order to take advantage of their common characteristics by using similar processes and equipment to produce them. Batch model production lines which incorporate aspects of batch production into their methods are widespread in today's manufacturing environment. The manufacturing system which forms the subject for this research is an example of this type of transfer line. The machines are arranged in a flow line layout but products are manufactured on a batch basis. In other words a pre-determined amount of products of a particular type are made, the line is then re-configured to manufacture a different product type. There are a finite number of types of product and orders are repeated regularly. In this way the system incorporates elements of batch production but in a mass production environment.

Modern Manufacturing Systems:

More recently, there has been a move away from traditional mass production of standard products towards more flexible systems which can produce semi customised items to meet the diverse demands of today's marketplace. Increasingly, companies are switching to 'build to order' production methods which require manufacturing systems which are more flexible and intelligent than ever before. Dell Computers Inc. is a common example of the build to order philosophy [5]. Also in recent times the automotive industry has moved towards build to order methods. Build to order has two main advantages for manufacturing companies. The first of these is that the customer can specify the product to suit their requirements exactly. Therefore the risk of losing sales due to customer requirements not being met is reduced. The second advantage is that the company can minimise the amount of WIP and stock on hand at any given time as an order will be received for each product before it is manufactured or assembled. The market-led demand for production methods of this type has created a new set of challenges for manufacturing systems designers. Some of the systems designed to overcome these challenges are described in this section. Flexible manufacturing systems were among the first of the new technologies to emerge to respond to the demand for greater flexibility. Flexible manufacturing systems (FMS) usually consist of a group of workstations connected by a material handling system [6]. They are capable of dealing with changes in part type with minimal downtime due to setup required. Variations in the number, order and type of operations performed on each part can easily be made. In this way the system can produce a variety of parts with short lead times compared to traditional transfer or assembly lines. As manufacturing systems technology developed, so too did management and control methods and philosophies. These methodologies were designed with the goals outlined above in mind, namely to increase flexibility and efficiency by controlling inventory. Material requirements planning (MRP) was one of the first of these control methods to emerge in the 1960s. As the name suggests, MRP works by planning material requirements and using that information to schedule jobs and purchase orders to satisfy external demand [7]. One of the limitations of MRP is that it fails to take into account several factors which can undermine the effectiveness of an MRP system. In an effort to overcome this, the ideas behind MRP were incorporated into a larger construct called manufacturing resources planning or MRP II [7]. Again as the name suggests, MRP II goes beyond simply planning for materials to satisfy demand, and instead looks at the manufacturing system in its entirety, taking into account all resources to do with manufacturing. Still more recently, the scope of MRP II has been broadened still further to include all aspects of the enterprise. This system is known as enterprise resource planning (ERP) [7].

While the MRP systems were being developed, mainly in the U.S.A., in Japan a different philosophy was employed. This gave rise to the just-in-time (JIT) management systems. JIT aims for zero inventory, which is of course impossible to attain in reality. However, having zero inventory as a goal means that a continuous improvement philosophy is maintained. To implement JIT on the factory floor, the Toyota motor company devised the kanban system of controlling flow of materials through the use of cards [7]. Production is governed by demand as with the MRP model, but the JIT system operates on a 'pull' production control system. When a part is removed from final inventory, the last workstation on the line is authorised with a kanban card to replace that part. That workstation then passes a kanban card to the next upstream station to authorise it to replace the part it has just used. In this way material is 'pulled' through the system. With the MRP model no authorisation is required and workstations will perform operations as long as there are parts available and 'push' completed sub assemblies to the next workstation. Just as MRP evolved into separate movements like MRP II and ERP, JIT has given rise to other systems such as total quality management TQM and lean manufacturing.

Intelligent Manufacturing Systems:

Both the MRP and JIT systems, along with the variants they spawned have strengths and weaknesses which mean that neither provide an ideal solutions to the challenges faced by manufacturing systems going forward. In an attempt to address this, in 1995 the Intelligent Manufacturing Systems (IMS) research programme began. It was originally proposed with the objective of developing new forms of manufacturing to meet the needs of the 21st century. Several advances in manufacturing techniques have emerged from the IMS research projects. These include holonic and reconfigurable manufacturing systems.

The concept of holonic systems was first described by Koestler [8] in the early 1970s. Koestler proposed the term holon to describe the fact that in many social organisations or living organisms, each part is both an identifiable entity in itself, and yet is comprised of more basic parts and is also part of a larger whole. According to the HMS consortium, the strength of holonic organization is that it enables the construction of very complex systems that are nonetheless efficient in the use of resources, highly resilient to disturbances (both internal and external), and adaptable to changes in the environment in which they exist [9]. Holonic manufacturing systems (HMS) are designed to take on board some of these characteristics. The consortium prepared the following list of definitions to aid understanding of holonic concepts and their application in a manufacturing context [9]

- Holon: An autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part. A holon can be part of another holon.
- Autonomy: The capability of an entity to create and control the execution of its own plans and/or strategies.
- Cooperation: A process whereby a set of entities develops mutually acceptable plans and executes these plans.
- Holarchy: A system of holons that can cooperate to achieve a goal or objective. The holarchy defines the basic rules for cooperation of the holons and thereby limits their autonomy.
- Holonic Manufacturing System (HMS): A holarchy that integrates the entire range of manufacturing activities from order booking through design, production, and marketing to realize the agile manufacturing enterprise.
- Holonic Attributes: The attributes of an entity that make it a holon. The minimum set is autonomy and cooperativeness.
- Holonomy: The extent to which an entity exhibits holonic attributes.

Reconfigurable manufacturing systems (RMS) are designed to be capable of rapid changes in structure, hardware and software in order to in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in requirements [10]. RMS design includes both line structure and control aspects.

The IMS programme and other researchers continue to explore new methodologies for the next generation of manufacturing systems to meet the demands of the rapidly changing modern marketplace. For example one area of interest which could in theory be applied to the type of system which forms the subject of this research is that of man-machine interaction. In the past one of the main aims of many manufacturing system designers was to remove human interaction from the system in favour of automated systems. More recently however, the role of humans has been re-evaluated. Sun and Frick [11] have noted that many companies move towards the computer integrated manufacturing paradigm (CIM), which has very little human interaction, first and experience lower performance, then shift from CIM to the computer and human integrated manufacturing (CHIM) paradigm. The reason for this is that implementation of automation without properly considering the human factor in many cases mean that the envisaged benefits of automation are not achieved [12]. With this in mind, Shin et al [13] presented a formal modelling method for describing and controlling a system of this type. Additionally, according to Dell [5], semi-automated systems like the model they employ are more flexible than fully automated systems. "Excessive" automation prevents dynamic change and leads to less efficient manufacturing systems, especially in the mass customization/build to order environment.

2.2. Manufacturing Systems Analysis:

This section outlines some systems analysis principles and the effects of certain system characteristics which will be referred to later in the thesis. Common manufacturing management and control philosophies dating from the 1970s to the present day are also described.

2.2.1. Manufacturing Systems Performance Measurement

There are many parameters which are measured to evaluate how a manufacturing system is performing. For example machine or operator utilisation as a percentage of overall production time can be used [14]. Another commonly used measure is to determine the amount of work in progress (WIP) on the line. Other measurements include machine cycle time, downtime, time between failures of machines, part defect rates and line throughput. Possibly the most commonly used measurement is the throughput or rate of production of the line. This is usually stated in terms of parts per hour or parts per shift. Throughput is the measurement by which the manufacturing line which forms the subject of this research is measured.

2.2.2. Bottlenecks and the Theory of Constraints

The theory of constraints is a management philosophy designed for all organisations to improve their systems and achieve their goals. It was introduced by Goldratt & Cox [15]. In essence the theory states that any organisation at any given time has at least one constraint which is the limiting factor on system performance or throughput. According to the theory of constraints the following steps should be followed to achieve system goals:

- Identify the constraint.
- Decide how best to exploit the constraint.
- Subordinate all other processes to the constraint.
- If it is still necessary, permanently increase the capacity of the constraint.
- If the constraint has now moved to another part of the system, return to step 1.

This theory applies to manufacturing systems where one operation or workstation sets the capacity of the entire line. This limiting operation is known as a bottleneck [7]. Obviously, if the capacity of the bottleneck is increased beyond the point where it ceases to be the bottleneck, then any further increase in capacity will not affect the throughput of the line. This is because another workstation or operation now forms the bottleneck and therefore sets line capacity. Therefore the theory of constraints is a continuous improvement strategy.

2.2.3. Variability in Manufacturing Systems

Variability can be defined as non-uniformity of a class of entities [7]. There are many areas in manufacturing where variability is found. Two main types of variability are of particular interest for the manufacturing facility which was the subject of this research project. Hopp & Spearman [7] identified these and they are summarised below.

The first of these is natural variability of process times. Process times can refer to any operation which takes a certain amount of time. The process referred to may be a direct production or processing operation or a material handling or part moving step. Process times of all types are usually subject to natural variability. Natural variability excludes unscheduled downtime, changeovers or setups or any other defined external influences. A high proportion of these unidentified sources of variability are related to operators on the line, therefore manual operations usually have a much higher level of natural variability than automated processes. The second main variability type of interest is the variability of process time which results from unscheduled downtime of workstations or operations. Variability of either type at upstream workstations will propagate downstream affecting other workstations. Generally speaking, frequent, short stoppages are preferable to more infrequent, longer stoppages as they will have less of an effect on downstream operations.

The production line which forms the basis of this research exhibits both types of variability described above. As part of the experimental stage, the impact of reducing this variability is explored. This has long been an important factor in improving manufacturing system performance, ever since the introduction of scientific management by Taylor [7]. Johnson [16] presented a study based in the sheet metal manufacturing area which reported that reducing the natural variability of worker cycle times improved process flow through the line. In the Johnson case the reduction in variability was achieved by moving from a traditional assembly line to an assembly cell layout. Schoemig [17] presented a paper on the effects of variability with specific application to semiconductor manufacturing. He found that variability of process time caused by unscheduled machine and tool downtime has a significant negative effect on line performance. Schoemig does not touch on natural variability as the semiconductor manufacturing process is highly automated and as such natural variability levels are very low.

2.3. Modelling:

In this context, a model can be defined as a mathematical, visual or graphical representation of the structure and operation of a system. A model should be detailed enough to approximate the actual system to the required level of accuracy while still remaining as simple as possible to promote ease of understanding and experimentation. It effectively forms the foundation of any system analysis as all subsequent steps are based on the model. Consequently, it is of paramount importance to ensure that the model is as accurate as possible as any mistakes made at this stage will propagate throughout the analysis.

2.3.1. Modelling Approaches:

Many modelling methods can be used for manufacturing systems. These range from basic graphical methods like flow charts [14] to more formalised modelling languages such as the ICAM Definition Languages (IDEF) [18]. Other methods used include mathematical models such as Petri Nets [19]

Flow Charts:

Flow charts are a very common graphical modelling technique. They can be used to model either physical flow of items through a process or information or data relating to that process. In either case they consist of a number of different shaped blocks which represent processing steps, inputs/outputs or decisions. These blocks are connected with arrows which indicate the direction of flow of items or information through the process. They are very useful to represent the major steps in a manufacturing process and to get a good overall view of the system but they also lack the capability to include useful information which is necessary for a completely accurate model.

IDEF:

The ICAM Definition Languages were brought about in the late 1970s as a result of the U.S. Air Force Programme for Integrated Computer Aided Manufacturing [20]. The USAF had a diverse network of contractors across the world. It realised the need for a common means of analysis and communication between the many different groups with the overall aim of increasing efficiency and productivity. The result of this initiative was a series of 3 ICAM Definition Languages. These were:

1. IDEF0 – a function model, used to represent processes and activities ongoing within the system.
2. IDEF1 – an information model. Represents the structure of information within the subject area.
3. IDEF2 – a dynamics model, used to describe the behaviour of a system over time.

2.4. Simulation:

Simulation is defined as the operation of a model of a system [21]. When the model is in place work can then begin on simulation. If the model and simulation parameters are correct, then the simulation results should closely follow those of the actual system. In this way the results of a series of simulation model runs can be analysed in order to better understand and therefore improve the operation of the system itself. Simulation modelling and analysis techniques can be applied to a broad range of systems. Traditionally, the manufacturing sector has been at the forefront of simulation technology and has been one of the primary users and beneficiaries of the technique. This research is based in the area of manufacturing and the applications of simulation to manufacturing systems are described in more detail later in this section. However, many other types of system also utilise and benefit from computer based simulation. Some simulation applications outside of the manufacturing sector include the following examples. The military sector, particularly the U.S. military, has made extensive use of simulation over the years. A recent example is the evaluation of troop deployment strategies prepared by Yıldırım et al [22]. The healthcare sector has seen an increase in the number of simulation studies being carried out in recent years. Gunal & Pidd [23] presented a hospital model which incorporated interconnected models of A&E, inpatient and outpatient departments. Service industries such as call centres are also an increasingly popular area of application for simulation modelling. The stochastic nature of demand for these types of services makes them an ideal subject for simulation. Huerta [24] constructed one such call centre model which can help the user to deal with issues such as staffing levels. Construction and project management is another area where simulation has been applied in recent times. Marzouk et al [25] used computer based simulation to prepare a framework to aid contractors in planning bridge deck construction. Chan et al [26] used simulation to find the most cost effective installation sequence for the complex steel framework of the "bird's nest" stadium used to host the 2008 Olympic Games in Beijing. Other systems where simulation modelling has been applied include public services, transportation and business performance modelling.

2.4.1. Simulation and Manufacturing:

Simulation is a widely used tool for the analysis and design of modern manufacturing systems. It is also very versatile. It can be used for almost any system which has a bearing on the manufacturing process. For example, transportation and supply chains are a common subject for simulation modelling. Supply chains are increasingly complex and often involve multiple organisations so simulation has found many applications in this area. Liu et al [27] used simulation modelling techniques to evaluate supply chain configurations and investigate the effect of information sharing. Within the manufacturing facility itself the applications are equally diverse. Material handling is an area where significant productivity gains can be made by increasing throughput. Simulation studies in this area have been carried out by El-Kilany [28] and Williams et al [29]. Production planning and scheduling is another area which has proven popular with simulation analysts. Arisha [18] used simulation to improve scheduling of semi-conductor manufacturing. Additionally, simulation can be used to aid in the design new manufacturing facilities or layouts, as demonstrated by Longo et al [30]. It can also be used to evaluate strategies to improve the performance of existing systems. The method used for deciding on improvements to existing systems generally involves estimating or predicting performance parameters such as line throughput [14] and evaluating 'what if' scenarios [31]. This is the specific area of interest of this project and this is discussed in more detail in Section 2.4.2.

2.4.2. Simulation for Transfer and Assembly Lines:

As described in Section 2.1.3, assembly and transfer lines are very similar in their behaviour. Consequently, simulation models of either class of line are very similar in their construction. The type of process flow is seen in many transfer or assembly lines. It fits the network modelling approach of most simulation packages very well [32]. Many researchers have successfully completed simulation studies on lines of this type [33] [14] [31]. In fact, production lines of this type are a very common subject of simulation studies, so much so that Banks [3] and Law & Kelton [4] both included a simulation of an assembly line as an example in their books covering the area of discrete event system simulation in general. Seppanen [32] has completed a simulation study on an operator paced assembly line similar to the transfer line which forms the basis of this research. A simulation study of a batch production flow shop which shares certain characteristics with the press line dealt with in this thesis was carried out by Geraghty and Heavey [34]. However, neither line appears to have the same levels of flexibility as that of the press line in this research. Consequently neither model would have the same complexity as the press line model. As described in Section 3 of the thesis, the press line is a batch production transfer line, incorporating high levels of flexibility and variation in product type, batch size, layout, level of automation and process flow. This in turn means that the model must be highly flexible in order to deal with these variations. The implications of this are dealt with in detail in Section 4 of the thesis.

Another characteristic of the line which forms the subject of this simulation study is the fact that it features both manual and automated sections. One of the aims of the simulation work was to determine the effect on line throughput of automating certain tasks which are currently performed manually. Ramírez [35] used discrete event simulation in a similar case study in an engine plant of the GM car corporation. In the GM case manual material handling was replaced by an automated material handling system as part of a move to a JIT manufacturing system. Dramatic reductions in WIP were recorded along with a slight decrease in throughput. The effect of a transition from manual to automated material handling is of specific interest in the simulation study conducted here. In contrast reductions in WIP or a transition to JIT were not part of the aims of this research. Another case of some interest, although it does not involve simulation, is that presented by Neumann et al [36]. In this paper, the results of moving from a manual to an automated material handling system are again discussed. The move to the automated system resulted in a 50% increase in line throughput. Neumann's case also concentrated on the ergonomic implications of this for the remaining manually completed tasks. This aspect of his research is beyond the scope of this project.

2.4.3. Types of Simulation Model:

Simulation models may be classified according to several criteria, some of these include the following [3]:

Data Type:

Is the system model behaviour stochastic or deterministic? In simple terms the difference between these terms is that stochastic simulation models can take into account random, uncertain or other unforeseen events while deterministic models cannot. In reality most manufacturing systems have at least some stochastic elements so the simulation package used must be capable of replicating this type of behaviour for accurate results to be obtained. Such packages use random number generators to cause the required chance or random events. These types of simulations are also known as Monte Carlo simulations. For simulations of this type, some form of averaging and distributions must be used to find the mean and range of the results.

Technique:

Is the model discrete event or continuous? Discrete event models model the process one step or item at a time, this is suitable for most manufacturing systems which deal with individual entities on a production line. Continuous models see the system as a single flow through the line without discrete items. Applications of continuous models include simulation of electrical circuits, control systems and chemical industries.

Data Status:

Is the data static or dynamic? Static data is used for steady state models which use equations to describe the relationship between input and output variables. Dynamic simulation models describe the changes over time in the system output in response to the changing input variables.

2.4.4. Advantages and Disadvantages:

As the popularity and availability of manufacturing modelling and simulation packages increases, it is important to understand the many different potential benefits simulation offers in order to get the most from a simulation study. It is also essential to be aware of the possible pitfalls to avoid. These benefits and pitfalls have been discussed by Banks [37], Maria [21], Arisha [18] and Centeno and Carrillo [38] and are outlined below.

Advantages:

- Promotes understanding; simulation will provide a good overview of the system and how each element interacts with others. It is easy to observe the system in detail thus gaining a better understanding of its operation
- Good decision aid; where an accurate model of a system is in place, simulation will allow quick, easy and relatively inexpensive evaluation of any proposed change or addition to the system before a final decision on the change is made. It should be noted, however, that this type of analysis requires a 'static' system so that any changes planned are still effective when implemented.
- Allows time compression or expansion; speeding up or slowing down time is very useful in order to thoroughly examine and understand the workings of a system.

- Visual aid; most simulation packages incorporate some form of animation. Some even have the capability to display a model in 3-D. This can be a useful feature to help visualise how a model works.
- Versatility; simulation models are versatile. Once built they can be used repeatedly for different types of analysis.
- Cost; The cost of a simulation software package may be recouped many times over by the improvements made to the process as a result of the simulation model.

These benefits of using simulation mean it can be a powerful tool for problem solving, planning changes to existing systems and designing new and better installations.

Disadvantages and Limitations:

- Model building requires special training and is time consuming. Therefore simulation is not readily applicable to rapidly changing systems.
- Simulation software can be expensive, particularly for small businesses.
- Implementation of the model depends largely on the support of key personnel, e.g. for data availability. If this is not forthcoming it is impossible to generate an accurate model.
- If the model is not accurate then the results generated will not be reliable. However, this is not always obvious until it is too late.
- Inappropriate use of simulation. Simulation is sometimes used where an analytical solution is possible or even preferable.
- The design of the simulation model is too complex or too simple for the task at hand.

2.4.5. Simulation Software:

There are many different types of software which can be used to model manufacturing systems. The most basic of these are general purpose programming languages, from these some specific simulation languages emerged and finally some simulation packages which have an interface between the user and the code which allows the user to concentrate on defining the system and the problem to be answered.

Programming Languages and Simulation Languages:

Initially, many simulation models were created using languages such as FORTRAN, C++ or Pascal [39]. This approach entailed writing routines for each process or facility required in any simulation. This was very time consuming and impractical so many languages designed specifically for simulation developed. Examples of these include SIMAN, SLAMII, SIMSCRIPT, SIMULA and GPSS. Many of these languages have special modules containing items specific to manufacturing systems such as workstation or material handling features. This approach is very flexible but is time consuming and requires the user to have expertise in the language used in order to construct a valid model within the constraints of the language.

Simulation Packages:

Over the past 3 decades a different type of simulation software tool has largely taken over. These packages separate the user from the program with a visual interface. In the most common type of interface the user selects blocks with the desired functionality from a series of libraries. These blocks are then connected in such a way as to behave in the same way as the system being modelled. These packages require little or no programming knowledge and are quite intuitive to use. Examples of these packages which can be used for manufacturing system simulation include Arena, eM-Plant, Extend, SIMFACTORY and Witness.

Choosing Simulation Software:

Literature which provides guidelines to help simulation analysts choose simulation packages and also which compare model implementation in various modelling languages and packages is widely available. Hlupic and Paul [40] prepared a set of guidelines for selecting simulation software. According to Hlupic and Paul the intended use of the simulation package must always be taken into account as the criteria for judging software suitability may change depending on the intended application. For example selection of a package for educational purposes will have different criteria to selecting a package for industry. Ease of learning and availability of tutorials and demo models are essential for a simulation package for use in education. Many software providers also make an academic licence available which allows educational access to their simulation packages at reduced rates. These features are less important for use in industry than other criteria may be, for example scheduling features or ready availability of certain performance measures. Even within industry, the area of application and the type of simulation model to be constructed must be taken into account. Certain packages will be more suitable for rapidly constructing general models while others provide superior features for detailed or complex models. Extensive literature is available which compares implementation of models in various simulation packages. For example Redman and Law [41] compared the Extend, Arena and Silk based on several criteria including queuing, scheduling of simultaneous events, changes in capacity and event rescheduling.

The primary modelling and simulation package chosen for this project was Extend. There reasons for this choice were as follows:

- Extend is already in use successfully within the Enterprise Process Research Centre (EPRC) in DCU. This facilitates cooperation on various projects. It also made learning the package quicker and easier as help and advice could be sought when needed.
- Extend is currently more affordable than many other simulation packages. It offers an academic network licence which makes purchasing several licences cheaper.
- Extend contains a comprehensive library of common manufacturing related entities. It is very well suited to modelling manufacturing systems and has a proven track record in this area.

<u>Some Details on Extend Simulation Software:</u>

Extend is a general purpose simulation package offered by a U.S. based company; Imagine That Inc. The graphical user interface consists of an initially empty model window and a series of libraries containing blocks which represent various entities. The user selects these blocks from the relevant library and arranges them in the model window. They are then connected in such a way as to replicate the functionality of the system being modelled. Other relevant details can be added to the blocks after accessing the block dialog box by double clicking on it. The various libraries mean that Extend can be used for a variety of simulation problems. Both continuous and discrete systems can be modelled, from business processes to manufacturing. Most distinct types of system have their own library which contains items specific to that field. For example the Manufacturing library contains blocks which represent common items found in manufacturing systems, such as machines, conveyors, labour, queues etc.

If the desired behaviour cannot be replicated using existing blocks then the user has two options. The first of these is to access the code of an existing block and modify it to give the desired result. Alternatively the user can design and code a new block from scratch. In either case the resulting blocks can be saved in a new library for future use.

Another useful feature of Extend is the ability to include unlimited levels of hierarchy in a model. For example if the user connects several blocks together to replicate the functionality of a single complex machine, these blocks can be grouped together into a single block. On the first level of hierarchy this block is all the user can see but by double clicking on the hierarchical block the constituent parts can be revealed. This means that even extremely complex models can, at the highest level, appear quite clear and are easy to follow.

2.5. The Simulation Modelling Process:

This section describes a series of seven steps which should be followed when performing a sound simulation study. These seven steps will form a road map for the work to follow in Sections 3 and 4 of the thesis. They are summarised below. These steps have been previously identified by several researchers, including Banks [37], Maria [21], Centeno and Carrillo [38], Carson [42], Law [43] and Law & Kelton [4]. Additionally, it should be noted that this is not usually a rigid or sequential process. In fact it is more desirable that some of the steps should be undertaken simultaneously or as an iterative process, with the model growing in scope and complexity as the modelling process progresses, as stated by Sadowski et al [44].

Step 1 - Identify the problem.

Every simulation study begins with the problem to be addressed being identified and documented. It is essential at this stage that the system and problem must be described accurately enough to be understood correctly by the simulation analyst.

Step 2 - Establish objectives.

At this stage the requirements of the proposed simulation must be identified. The following aspects are considered:

- The overall objectives of the study.
- Specific questions to be answered by the model.
- What measures will be used to evaluate the improvements to the system?
- Scope of the model.
- System configurations to be modelled.
- What software will be used?
- Schedule for the study and allocation of resources.

This is a very important stage in the modelling process. It can be tempting to start straight into the actual system modelling and leave this stage until afterwards. This is almost always a mistake. Very often the problem to be addressed or question to be posed will have a large impact on how detailed the finished simulation model will need to be. Models that are too detailed are a waste of time and other resources. Models that are too simple are of no benefit. It is important to get the complexity balance correct. Taking the time to undergo this stage in the process is essential if this is to be achieved.

Step 3 - Data collection and processing.

This is a critical stage in the process as the accuracy of the simulation model will depend on the quality of the date collected at this stage (garbage in = garbage out). The data must be collected, sorted and converted into a format which can be accepted by the simulation modelling package. Sometimes the data itself is not used as a direct input to the model, but is rather used to form a suitable data set for use as a model input. In practice data collection and processing is probably the most challenging aspect of a sound simulation study. The types of data usually required are described in this section. Some common processing stages and difficulties to be overcome are also outlined.

Two types of data are usually collected for modelling existing systems. The first data set is that required for the actual construction of the model. The second data type is output data from the actual system. This data is used for validating the model following its construction. For the first stage of data collection the following information must be collected and processed:

- System layout data. This is required to define the structure of the model to ensure it accurately represents the actual system.
- System operating procedures information. This data is necessary to define the flow of items through the model.
- Data to specify model inputs and probability distributions. This is normally the final set of data to be incorporated into the model. It normally consists of accurate process and delay times or suitable statistical distributions which are derived from empirical data. Assuming the model structure is correct this data should ensure that model outputs closely match system outputs.
- Document the model assumptions, algorithms and data summaries in a conceptual model. This will also help with the model building stage.

Once the data listed above is collected it should then be possible to build a complete and fully functional model of the system. The second stage of data collection involves the following:

- Collect data on the performance of the existing system. This will be necessary for the validation stage later in the study.

In many cases, reliable data on certain system parameters may be very difficult to obtain. A common example of this is the difficulty in measuring unscheduled downtime. In such cases, it will sometimes be necessary for the user to make a judgement based on their knowledge and observation of the system [4]

Data Processing – Input Distributions

When carrying out simulation studies on stochastic systems, random elements in the system parameters must be incorporated into the model inputs. Generally this is done by fitting a statistical distribution to the empirical data [4]. Take for example a manual processing operation, the duration of which is variable. To fit a statistical distribution to this operation, firstly a suitable number of samples of the duration are taken. This data is compiled into a histogram. The data can be fitted to a distribution in two ways. The first of these methods is to look at the shape of the histogram and choose an appropriate distribution accordingly. The second method, which may or may not be available depending on the simulation package used, is to input the empirical data into an automatic data fitting package, e.g. Stat-fit in Extend. This package takes the empirical data and fits a number of different types of distribution to it. The results are rated by the package and presented to the user in order of preference.

Data Collection – Ensuring High Quality:

System data that is available 'off the shelf' must be processed to ensure it is valid. This type of data will rarely have been collected with a simulation study in mind and therefore there are several potential difficulties with the data. Law & Kelton [4] identified some of these difficulties. Data may contain measurement or recording errors or may be biased due to other factors. One example of another factor which may lead to bias is the well documented "Hawthorne effect" which was observed during experiments carried out between 1924 and 1932 at the Hawthorne Works of the Western Electric Company in the USA [45]. The Hawthorne effect describes the fact that subject's knowledge that they are in an experiment or that their work is being observed causes their behaviour to change from what it would normally be. The potential implication for simulation analysts is that data measured from production lines may be skewed or biased due to this effect. Care must be taken to ensure that measured data is representative of the system as a whole and that it is not biased due to the fact that the measurement process was observed by the subjects.

Data sources are usually diverse incorporating databases, manual records, automatic or semi-automatic data collection systems, sampling studies and time studies. These sources are compiled and used by many different departments within the system. Therefore this stage is not a trivial task. Data can almost never be simply collected and used in its raw state without some processing being performed first. A great deal of effort and time may be required to extract the relevant data from the different sources, compare the different data sets and compile them into a single database for use by the model.

According to Law & Kelton [4], confidence intervals are often used to quantify the difference between two data sets. As outlined in the model validation section of the thesis (Section 4.6), production data from different sources was used for model validation purposes. In order to compare these data sets to ensure their consistency, a confidence interval measurement should be employed. In this case the data sets are of differing sizes. For data sets of this type Law & Kelton [4] recommends the use of a Welch modified t-test. The test works by first calculating the mean and the variance of both samples. Next the degrees of freedom are approximated using the Welch-Satterthwaite equation. From the degrees of freedom value and the required percentage confidence interval a t-value is interpolated from tables. This t-value is used to calculate the confidence interval, called the Welch confidence interval. In this case the aim will be to show that the two samples do not differ to any significant extent. For two samples which are identical, the t-value will be zero and the confidence interval will take on the form [-x, x]. Any results which exhibit low t-values and reasonable symmetry of the confidence interval about zero imply that in statistical terms the data sets are not significantly different from each other.

Another difficulty when dealing with data from different sources is that there is often substantial overlap in the data and this can lead to conflicting information in data sources for the same parameter. For this reason it is always important to interact with key personnel who are familiar with the system on a regular basis to confirm the accuracy of the data in question. Despite the vast quantities of data collected and stored by many manufacturing companies, this type of one to one interaction is often the only way for the simulation analyst to be confident in the data collected.

Step 4 - Model building and coding.

As stated in Section 2.3, a model can be defined as a visual or graphical representation of a system (in this case part of a manufacturing facility). Methods of representing the system include simple block diagrams and more formal standards such as IDEF0 (Integration Definition for Function Modelling) Once a model of this nature is in place work on the model coding can begin. This can be done using a programming language or using a purpose built simulation package. For this project the modelling package of choice is Extend. More information on Extend can be found in Sections 2.4 and 4.2. Models in Extend are composed of blocks of various types which are connected together to form an accurate model of a system. Usually model building is an iterative process which starts out with a basic model of the system with limited functionality. Once this is in place more detail and flexibility are added until the model has all the desired functionality in order to replicate the operation of the system being modelled.

Step 5 - Model Verification and Validation.

Verification in this case means ensuring that the simulation model is operating as intended and no errors have been made in the transition from conceptual model to simulation model. Banks [3] suggested the following steps for use in the verification process:

- Make a flow diagram which shows each possible path for items to take in the model. Follow the model logic to ensure that each event type results in the correct path being taken.
- If available, utilise the animation feature of the simulation package. Many errors can be observed through animation.
- Examine the model outputs for reasonableness. Vary the input parameters and re-examine. Have the model generate a wide range of outputs and examine each one.

Validation of a model of an existing system involves evaluating the model by comparing it to the operation of the actual system under known conditions. Both the data from the model and the data from the system should be subjected to various measurements and statistical tests after which they are compared. If the data from the model closely matches that of the validation data then the model is considered valid [4]. How close the match has to be will depend on the intended use of the model and will have been decided at the model objectives stage.

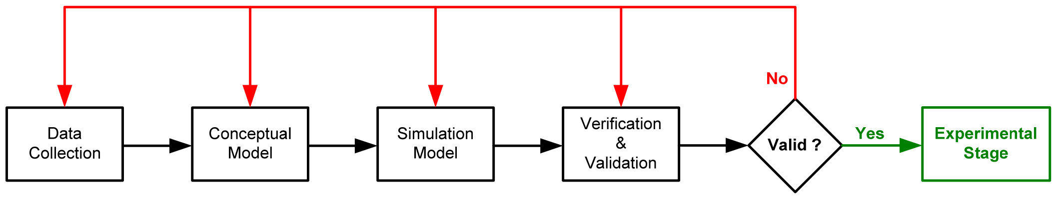

Figure 2.2: Flow Diagram Showing the Iterative Nature of the Model Validation Process

If the model data does not form a sufficiently close match then it is necessary to return to some or all of the previous steps in the modelling process to correct mistakes or omissions. The iterative nature of this process is shown in Figure 2.2.

<u>Step 6 - Experimental Stage</u>

At this stage the experiments to be performed on the system are designed, conducted and the results analysed. The results of the experiments should meet the initial project objectives set out in step 2. Depending on the project, the experimental objectives may be clearly laid out and straightforward to implement or the issues to address may be broader and more ambitious. In this case the objectives are clearly laid out so this stage is relatively straightforward.

<u>Step 7 - Document model for future use.</u>

Documentation of the objectives, assumptions, inputs etc. will allow the model to be used at a later date if required.

3. Problem Identification and Model Goals:

This section documents the first three steps in the modelling process as outlined in Section 2.5. These are; identify the problem, establish objectives for the model and collect and process the data required for the model.

3.1. Company Background:

Läpple is a system supplier to the sheet metal industry. The company engineers, designs, manufactures and supplies dies and tools for non-cutting sheet metal forming, moulds, prototypes, stampings, assemblies, and components as well as production facilities, world-wide. Since its foundation in 1919, the company has developed from a medium-sized family business to an internationally operating group of companies. The setting up of new production plants in South Africa, Ireland and Germany (Teublitz) as well as the acquisition of the FIBRO Co. give evidence of these forward-looking activities. Figure 3.1 shows a map of Läpple's worldwide activities.

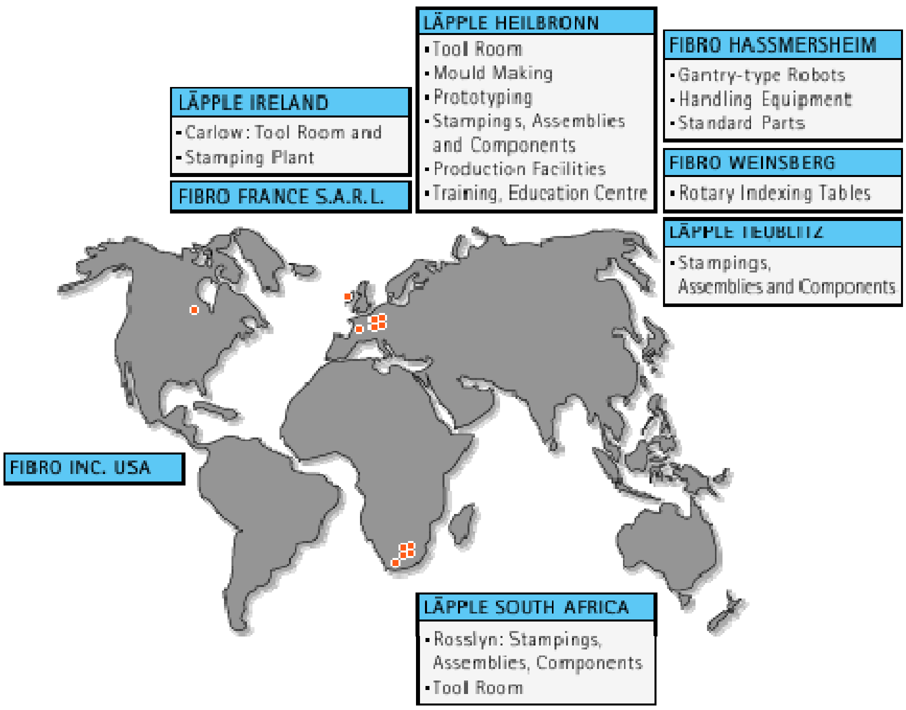

Figure 3.1 World map showing Läpple factories worldwide

3.2. Factory Background:

Läpple Ireland Limited was established in Carlow, Ireland, in 1974. The Company was a wholly owned subsidiary of August Läpple GmbH & Co KG of Heilbronn, Germany. Läpple Ireland produced high quality tools and dies for the production of auto body parts for domestic products and for the motor industry. The Company also used such tooling for the production of auto body parts, mainly for the U.K. market. The company had a reputation for high quality products and engineering expertise. Its customers included leading car manufacturers in Europe, Asia and the U.S.A. Läpple Ireland employed 350 people at its height and was one of the most significant trainers of toolmakers and highly skilled machinists in Ireland. Unfortunately, in April 2007 it was announced that Läpple Ireland was to cease operating. The factory closed its doors for the last time in July 2007.

3.3. General Description:

This project focuses on the parts production element of the Carlow plant. As already stated in Section 2.1.3, the manufacturing line which forms the basis of this research is a transfer line which also features some elements of batch style production. The characteristics of batch production are seen in the overall structure and operation of the line. The machines are general purpose presses which are fitted with dies to stamp a specific part. By changing the dies a different part can be made. A batch of predetermined size of a specific panel is made, then the dies are changed over and a different type of panel is manufactured. This closely mirrors the batch production model outlined in Section 2.1.2. On the other hand looking at the transfer line model it can be seen that there are strong similarities here also. This line consists of 4 presses into which dies are fitted. A steel sheet is placed in the first press; this sheet is stamped and passed on to the second press where another stamping operation is performed. This process continues until the finished panel emerges at the end of the line. Each panel produced is identical with no variation. This is the classic transfer line structure. So it can be seen that while the line is running a batch of a certain panel it functions as a pure transfer line. On the other hand the flexibility of the line in changing over to manufacture different types of panels shows some characteristics of batch type production.

3.4. <u>Model goals</u>

The goals for the model were outlined at this stage following the identification of the subject of the model. The principal goal of the thesis is the design, development and implementation of a flexible discrete event simulation model of the press transfer line. This model should be capable of dealing with all parts produced in the Carlow plant. This means the model must be able to switch from manual to automated mode and also switch configuration without direct input from the user. The aim is for the functionality to be built into the model so it can be controlled externally from a database. The objectives following the construction of the model are to firstly evaluate the use of discrete event simulation in this context and also explore some what if scenarios which will investigate the effect of reducing variability of cycle times on the line by introducing additional automation. These specific areas are described in more detail below:

Specific Issues to be Investigated:

When an accurate model of the system is built it will be used for examining the effect on line throughput of the scenarios listed below. These were decided upon in conjunction with Läpple personnel. Although it is described in detail in section 3.6, it is useful at this stage to note that while some parts of the production line are currently automated for certain part types, the initial loading of raw material and final unloading of finished parts from the line remain manual operations.

1. Replacing the existing manual unloading of fully formed parts from the end of the line with an automated robot.
2. Installing a robot at the start of the line to automate the current manual loading of Press 3.
3. Fully automating the line for certain part types by implementing both of the possibilities above.
4. An additional requirement was to investigate the effect on the throughput if the robots could not perform the task as quickly as manual operators.

Once the results of the first two scenarios were known, a decision was to be made on which would be more beneficial to adopt, taking into account potential benefits versus difficulty of implementation. The performance measure used for the line is throughput expressed in terms of parts per hour or parts per shift. These will be the criteria on which the model outputs are judged.

3.5. Detailed Description - Element types:

This section lists each element type contained within the line. The line consists of presses, operators, conveyors, robots and stillages. The operation of these elements and how and where they fit into the production process is described in detail in the following sections.

3.5.1. Presses:

As stated in Section 3.3, the presses are the main machines which form the panels. There are 2 main types of press for sheet metal forming, mechanical presses and hydraulic presses. The press line in the Läpple Carlow plant contains two of each type of press. The presses are made by a German company Müller Weingarten AG.

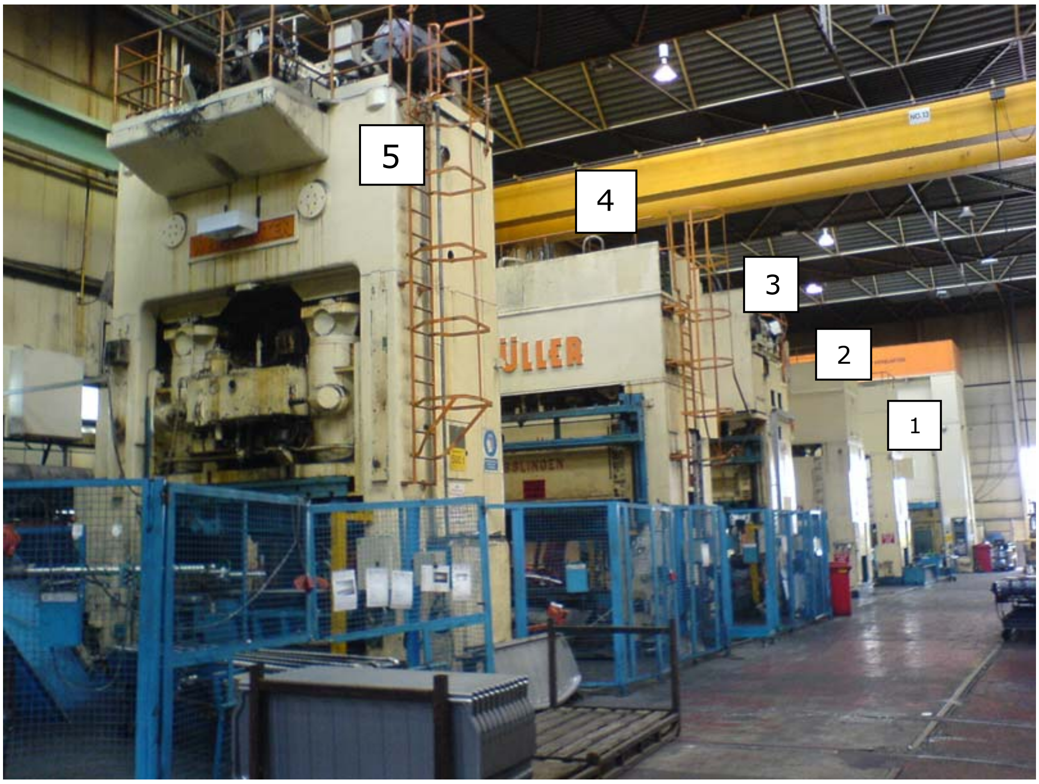

Figure 3.2: View of press line showing mechanical Press 5 in foreground and hydraulic Presses 3 & 4 in background.

The press line in the Läpple Carlow plant contains two of each type of press. The presses are made by a German company Müller Weingarten AG. Pictures of each type of press can be seen in Figure 3.2 and Figure 3.3. Presses 1 & 2 which are not used for panel production can also be seen.

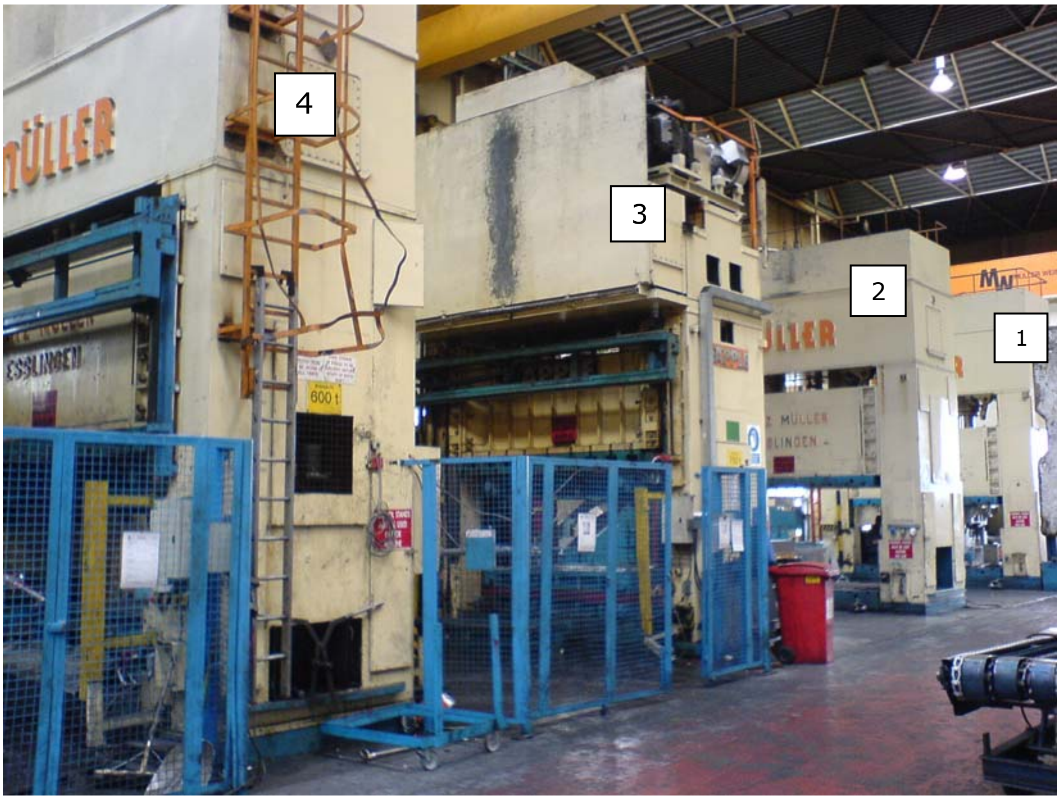

Figure 3.3: View of press line showing hydraulic Presses 3 & 4 in foreground and tryout Presses 1 & 2 in background.

Mechanical presses work by rotating a cam which then acts on the die to give the required force to form the part. Hydraulic presses use hydraulic cylinders to produce the force needed. Hydraulic presses are generally regarded as being superior to mechanical presses. They offer more flexibility in every aspect of the pressing operation. Their cycle time can be tailored to suit whichever part is being made at any given time. Free speed, pressing speed and retract speed can all be specified. Stroke length can be altered to avoid excessive movement and the resultant increase in cycle time. If a dwell time is required at the bottom of the stroke it is easily incorporated. In addition the full tonnage is available throughout the stroke of the hydraulic rams. This is in contrast to mechanical presses where the full force is available only towards the end of the stroke.

Mechanical presses do not have the capability to alter dwell time at the bottom of the stroke. In addition free speed, pressing speed and retract speed cannot be altered independently. The whole cycle must always be completed with each operation taking the same time relative to the others. Consequently, in order to reduce the cycle time, the whole cycle must be speeded up. This means that in general, there are only 2-3 standard cycle times for any given mechanical press (slow, medium, fast) and the appropriate speed is then chosen depending on which die is in the machine. In contrast a hydraulic press may in theory have an infinitely variable cycle time.

The press operations are governed by a series of safety features and interlocks. The exact procedure and sequence of events varies depending on whether human operators or robots are transferring the partially completed panels between the presses. Where parts are transferred between presses manually, the presses operate as shown in Figure 3.4.

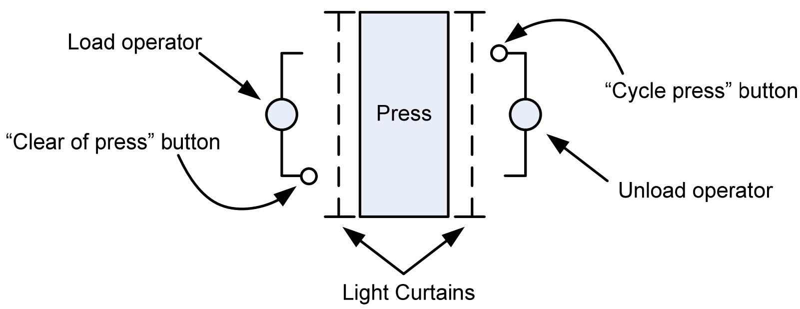

Figure 3.4: Press Operation in Manual Transfer Mode

When the press finishes a cycle, the unload operator removes the partially completed panel from the press and places it on the conveyor which will take it to the next press. Then they press and hold the "cycle press" button. Meanwhile the load operator loads the next panel into the press. They then press the "clear of press" button the press will then begin the next cycle providing that the "clear of press" and "cycle press" buttons are both pressed and that the safety light curtains have not been broken. As an additional safety feature, if the light curtains are broken at any stage during the press cycle, the press will immediately stop and will remain stationary until it is reset.

With automated transfer between presses the setup is slightly different. In this mode the safety light curtains are disabled. This allows the robots to wait closer to the press than would otherwise be the case. For safety, the entire area between the presses is closed off while the line is running in automated mode. If one of the access gates to the restricted areas is opened while the line is running, the robot in that area as well as both presses will immediately cease to operate. There are a series of micro-switches on both the presses and robots which form a closed loop system of control which sets the sequence of operation in automated mode. Taking Figure 3.5 for example, when Press 1 finishes a cycle a switch at the top stop of the press signals to the robot that it is now safe to enter the press to remove the panel. When the robot has removed the panel from Press 1, another switch signals that Press 1 can now be loaded with the next panel from the other side. Meanwhile the robot moves to Press 2 where it will load the panel into Press 2 provided that press has finished its cycle and been unloaded.

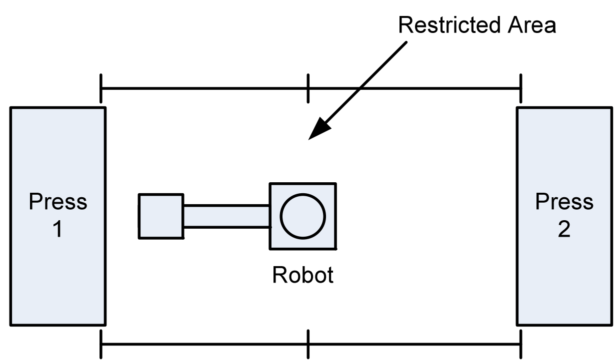

Figure 3.5: Press operation in automated transfer mode

There are seven presses in total in the main transfer line of the press shop area. These are arranged as described below and as shown in Figure 3.6.

- Presses 1 & 2: These presses are used as try-out presses by the die shop and are not used for production.
- Press 3 - Press 6: Theses are the presses that form the full time production line. Capacities range from 500-750 Tonnes.
- Press 7: This 1200 Ton press is used primarily by the die shop but is also used for production for particularly large panels because of its high capacity rating.

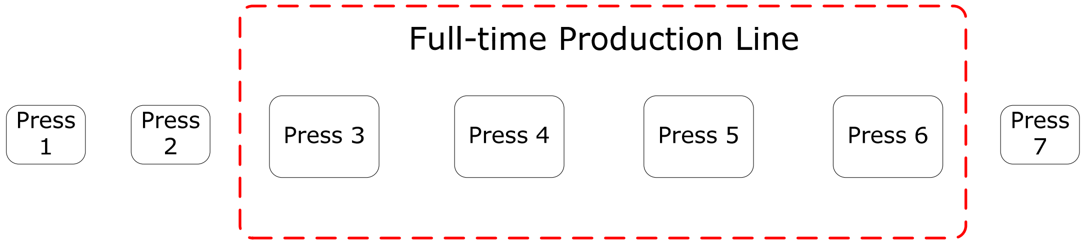

Figure 3.6: Press Line Layout

As Presses 3-6 form the full time production line, they are the focus of this research project. Presses 3-6 are arranged in a flow shop type layout as shown in Figure 3.6. Details on the presses are as follows:
Press 3: Hydraulic, 750T rating.
Press 4: Hydraulic, 600T rating.
Presses 5 & 6: Mechanical, 500T rating.

The company defines the stages involved in producing a panel as follows. There are 6 operations, OP10-OP60 inclusive. OP10 is the first stage. In most cases this corresponds to the cutting of a flat sheet of steel to the correct dimensions. The raw material supplied to the factory in Carlow is in the form of pre-cut steel sheets so OP10 is not part of the production process in the press shop. OP20-OP60 are the actual stamping stages, which progressively form the shape of the panel. Most of the time more than one operation can be incorporated into at least one die so that five separate dies and presses are not required. For some parts the die can be designed so that more than one operation can be incorporated into a single pressing movement. For certain other parts the partially completed panel is stamped, then rotated or moved to another part of the die and stamped again, so effectively there are two dies within one. In this case there are two panels in the press at any given time. Four dies is the maximum number required for the parts produced in Carlow. For some parts only three dies are required to produce the finished panel.

3.5.2. Operators:

There are five main sets of tasks which are manually performed by operators on the production line. Each of these operators performs a different task on the press line. These tasks are identified in this section.

The exact work steps followed by each operator are listed. It should be noted that the safety procedures and interlocks are not included in these tasks as they have already been described in Section 3.5.1.

<u>Task Set 1:</u>

These are the tasks completed by the worker who loads Press 3 (the start of the line). When requested to do so by the operator at the start of the line, a forklift deposits a bale of steel sheets in front of Press 3. Bales are delivered one at a time meaning when the old bale runs out there is a delay while the new one is delivered. Each part type uses a different bale, with steel sheets of different sizes, shapes and thickness. The number of sheets in each bale also varies with part type. The operator discards the top sheet of each bale as they may have become damaged in transit. The operator loads the sheets into Press 3 as follows.

1. When Press 3 has cycled and returned to the top position, the panel in the die is removed from the press from the other side. This is either performed manually by another operator or automatically by a robot, depending on the part type in question.
2. Once this panel has been removed the operator can load in a new steel sheet, ensuring it is located correctly. Press 3 then cycles and the process repeats itself. This sequence continues for the rest of the sheets in the bale apart from the last sheet, which is discarded.

<u>Task Set 2:</u>

This set of tasks involves unloading the partially completed panel from each press and placing them on a conveyor to be brought to the next press. Therefore, in the case of manual transfer of parts between presses, this task set is performed at the output side of Presses 3, 4 and 5.

<u>Task Set 3:</u>

This is the operator who takes the partially completed panel from the conveyor and loads it into the next press. Therefore this type of operator may be positioned at the input side of Presses, 4, 5 and 6. When the press has cycled and the operator on the output side of the press has unloaded the previous panel this operator takes the next panel from the conveyor and places it in the press.

Task Set 4:

This operator unloads Press 6 and loads the finished panel into the rack or 'stillage'.

Task Set 5:

This is another end-of-line operator required when the line is running in 3 die mode. Instead of removing the panel from the press they remove the panel from a conveyor and place it in the stillage. When the line is operating in three die mode this task set replaces task set 4.

3.5.3. Conveyors:

Conveyors are placed between the presses and carry the partially completed panels from the output side of one press to the input side of the next. They are only used in manual part transfer mode. They also act as small buffers between presses. The capacity of each conveyor and thus the buffer size varies according to several factors. These include the size and shape of each panel produced as well as how neatly the operator arranges the parts on the conveyor. This variation in capacity must be accounted for in the model.

3.5.4. Robots:

Under certain circumstances robots are used to transfer parts between presses. One robot takes the place of two operators and a conveyor. The robots simply remove the panel from the first press, rotate and place it in the next press, then return to wait near the first press for the next part.

Over the past few years many parts have been automated and those that remain manual do so for one or more of the following reasons:

- The production quantities do not justify the investment required for automation.
- The part is nearing the end of its life or is only a short-term arrangement so the investment would not be recouped before the part is discontinued or moves to another factory.
- The design of the dies prohibits the use of robots. Many of the older dies were designed with manual operation in mind. So for example some would require the operator to remove some scrap material as well as

remove the panel. Dies designed for robots, on the other hand, are designed in such a way that scrap material would fall away automatically. Also, certain parts have 2 stages within one die, so a part is placed in the die, stamped, then moved to another part of the die and stamped again before being removed. Automating this procedure would be a complex task.

3.5.5. Stillages:

Stillages are the specially designed storage and transportation racks for the completed panels. Each part type has a different stillage, which is designed to hold the parts securely and efficiently. Each stillage has a different capacity, depending on the size and shape of the part it is designed to carry. Stillages are placed at the end of the production line. When completed panels exit the final press in the line, they are placed in the stillage ready for storage or shipping. Due to space constraints only one stillage can be placed at the end of the line at any given time, so when it is full there is a delay in production while it is replaced with an empty unit.

3.6. Detailed Description - Layouts

There are two possible layouts for the line, depending on the number of dies required to make a specific panel. This can be either three or four dies depending on the part in question. Also, within each layout transfer of parts can either be manual or automated depending on the part in question. This gives a total of four possible combinations for the line.

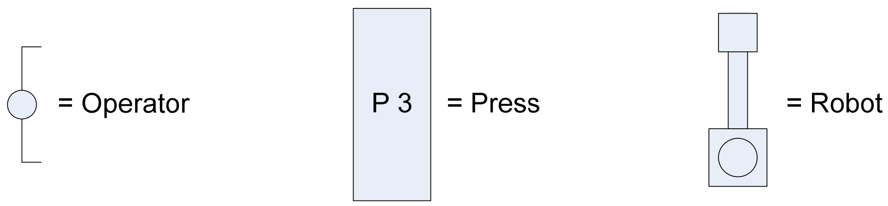

Figure 3.7: Key for diagrams

The production line structure and procedure for each layout is described in this section. The key for the diagrams can be seen in Figure 3.7. The operators are numbered according to the press at which they are situated. In addition they have a letter, A or B, to indicate whether they are on the input or output side of that press respectively. For example operator 3.B is on the output side of Press 3 and is therefore responsible for the unloading of Press 3, operator 5.A is on the input side of Press 5 and is responsible for loading panels into Press 5 and so on.

3.6.1. Four Die Line With Manual Transfer:

For manual transfer of panels between presses the operation of the line is as follows: When Press 3 has cycled the operator removes the panel and places it on a conveyor where it is carried along to Press 4. The panel travels down the conveyor to where another operator picks it up and loads it into Press 4, assuming the operator at the other side of Press 4 has removed the previous panel from the press. This procedure is repeated until the end of the line where the operator unloads the finished panel and places it in the stillage. The layout of the line is as seen in Figure 3.8.

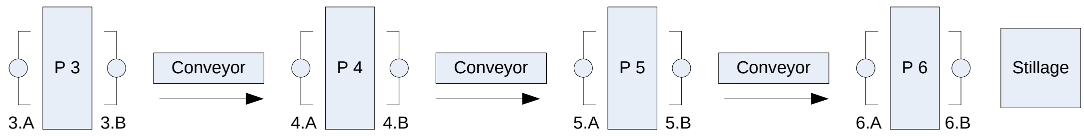

Figure 3.8: Four line with manual transfer

3.6.2. Four Die Line With Automated Transfer:

When automated as opposed to manual transfer between the presses is used, the two operators and one conveyor situated between each press are replaced by a single robot. This layout is shown in Figure 3.9.

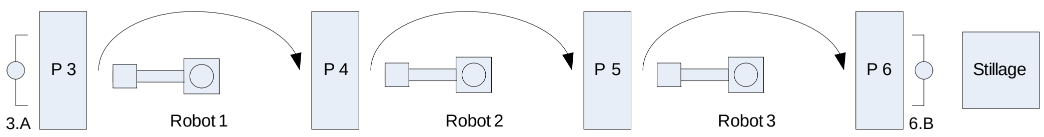

Figure 3.9: Four Die Line With Automated Transfer

As can also be seen from the figure, the layout and therefore the load and unload procedure at the start and end of the line remains unchanged compared with manual transfer mode. In between the presses the three robots take the place of the three conveyors and six operators. These robots take the partially completed panel from Presses 3-5 and place it in the following press in the manner outlined in Section 3.5.4.

3.6.3. Three Die Line With Manual Transfer:

For a three die line-up with manual transfer the procedure is as shown in Figure 3.10. The procedure is the same as the four die line with manual transfer until the part is placed on the conveyor after it exits Press 5. Instead of continuing along to Press 6 it moves along the conveyor at a right angle to the direction of flow through the line where it is picked up by either one or two operators depending on the size of the panel. It is then placed in the stillage.

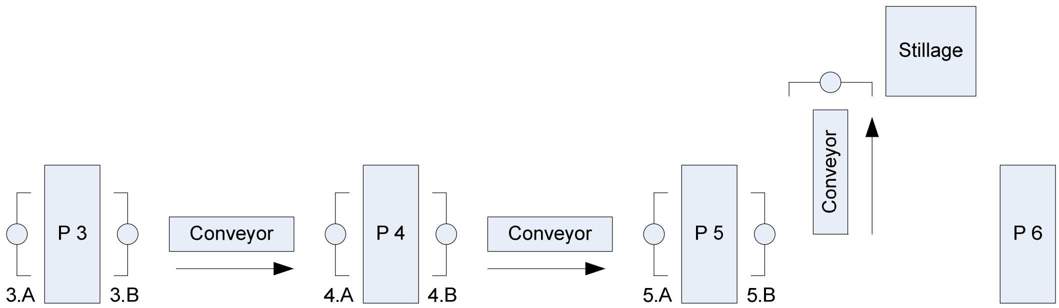

Figure 3.10: 3 die line with manual transfer

3.6.4. Three Die Line With Automated Transfer:

For a three die line with automated transfer the layout is the same as the four die automated line until the part exits Press 5.

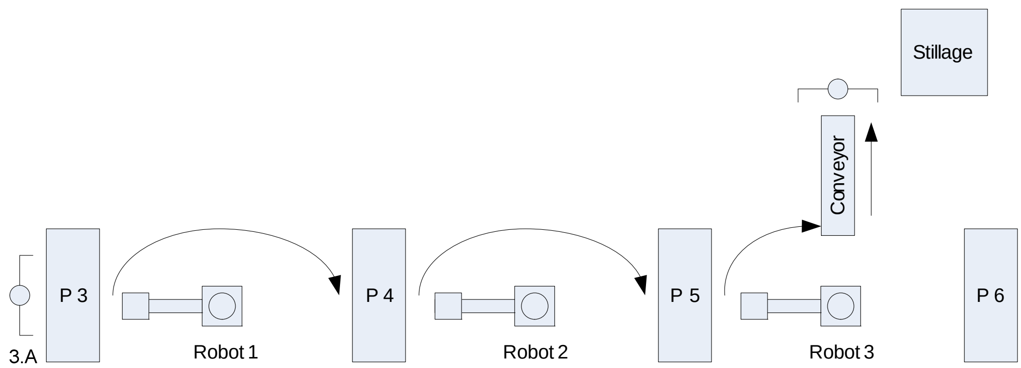

Figure 3.11: Three Die Line With Automated Transfer

At this stage instead of the robot placing the panel in Press 6 it is instead placed on a conveyor where it is carried along to an operator who removes it from the conveyor and places it in a stillage. The layout is shown in Figure 3.11.

3.7. Detailed Description - Operational Information:

Some additional information is necessary in order to build an accurate model. This information is contained in this section. It does not necessarily relate to the physical structure of the model. However it is still needed in order to construct an accurate model that replicates the behaviour of the line.

3.7.1. Shifts:

The line runs 3 shifts per day, Monday-Friday. The day shift is from 08:00-16:00 Monday-Thursday, and 07:00-14:00 on Friday. The evening shift is from 16:00-00:00 Monday-Thursday and from 14:00-21:00 on Friday. The night shift is from 00:00-08:00 Monday-Wednesday, 00:00-07:00 on Thursday night and 21:00-05:00 on Friday night.

3.7.2. Scheduling and Recording of Production:

Scheduling is performed manually on a week-by-week basis. The requirements for the week ahead are examined and parts are scheduled on a shift basis. Each shift is taken as a block and different parts are run in different shifts. If the required number of parts are not made in a shift then the schedule is changed as other parts are moved further down the list.

The factory has a system which records production data in a semi automated manner. For each shift a job number is entered into a computer system called Penta. This system records the number of operators, total time, number of panels produced and the downtime for each job. This information is stored on the system and can be accessed via the job number at a later date. The system is described as semi automated because it is still dependent on operators on the factory floor for its inputs. The status of the line and total panels produced are not automatically gathered in real time but instead require manual input from an operator. This has certain implications for the model building stage. These are discussed in more detail in Section 4.6.1 (Page 73).

For this section two types of data were collected for two separate purposes. The first of these was data collected in order to build the model and the database. The second was data that was used in order to validate the model outputs. For each part the following information was required for the model building stage:

1. The Läpple part number.

Each panel type has a part number allocated to it for identification within Läpple. This part number is also used in the model database.

2. Whether it is manual or automated.

The method of transferring parts between the presses must be noted for each part type, i.e. manual transfer or transfer by robots.

3. Number of dies (three or four).

As described in Section 3.6, the line may consist of three or four dies depending on product type. This information is required for each part type so that the model can replicate the real world scenario.

4. Number of sheets per bale.

Different parts have different numbers of sheets of raw material in their respective bales. This information is recorded and added to the database so that the model can select the correct number of sheets for each part type.

5. Number of slots per stillage.

Similarly, each part type will have a different number of available slots in each stillage, this information is also contained in the database.

6. Number of stages for each press (one or two).

As stated previously, certain panels have a two stage operation within one press, if this is the case it must be noted in the database so that the model can run this two stage process accordingly.

7. All processing times.

All the processing times for the parts to be modelled are a basic requirement. This information was not readily available from any source so had to be manually recorded. This is described in detail in this section. Table 3.1 shows the processing steps which had to be measured for automated transfer of parts between the presses. As can be seen from the table, steps 1-13 are the same for both automated layouts. However, following Press 5 the partially completed panel will follow one of two paths, depending on whether that particular part uses a three or four die setup. The different steps for each setup are shown in Table 3.1.

Processing Times to be Recorded – Automated Transfer:	
1. Operator 3.A Load Press 3	
2. Press 3 Cycle	
3. Robot 1 Unload Press 3	
4. Robot 1 rotate	
5. Robot 1 Load Press 4	
6. Robot 1 return	
7. Press 4 Cycle	
8. Robot 2 Unload Press 4	
9. Robot 2 rotate	
10. Robot 2 Load Press 5	
11. Robot 2 return	
12. Press 5 Cycle	
If 4 Die Setup:	**If 3 Die Setup:**
13. Robot 3 Unload Press 5	13. Robot 3 Unload Press 5
14. Robot 3 rotate	14. Conveyor time
15. Robot 3 Load Press 6	15. Operator Load Stillage
16. Robot 3 return	
17. Press 6 Cycle	
18. Operator 6.B Unload Press 6	
19. Operator 6.B Load stillage	

Table 3.1: Processing Steps for automated transfer between presses

Table 3.2 shows the list of processing steps which need to be measured for both types of manual transfer line. Again after the part exits Press 5 it follows one of two possible paths, both of which are shown in Table 3.2.

<table>
<tr><th colspan="2">Processing Times to be Recorded - Manual Transfer:</th></tr>
<tr><td colspan="2">1. Operator 3.A Load Press 3</td></tr>
<tr><td colspan="2">2. Press 3 Cycle</td></tr>
<tr><td colspan="2">3. Operator 3.B Unload Press 3</td></tr>
<tr><td colspan="2">4. Conveyor 1</td></tr>
<tr><td colspan="2">5. Operator 4.A Load Press 4</td></tr>
<tr><td colspan="2">7. Press 4 Cycle</td></tr>
<tr><td colspan="2">8. Operator 4.B Unload Press 4</td></tr>
<tr><td colspan="2">9. Conveyor 2</td></tr>
<tr><td colspan="2">10. Operator 5.A Load Press 5</td></tr>
<tr><td colspan="2">12. Press 5 Cycle</td></tr>
<tr><th>If 4 Die Setup:</th><th>If 3 Die Setup:</th></tr>
<tr><td>13. Operator 5.B Unload Press 5</td><td>13. Operator 5.B Unload Press 5</td></tr>
<tr><td>14. Conveyor 3</td><td>14. Conveyor 3</td></tr>
<tr><td>15. Operator 6.A Load Press 6</td><td>15. Operator Load Stillage</td></tr>
<tr><td>17. Press 6 Cycle</td><td></td></tr>
<tr><td>18. Operator 6.B Unload Press 6</td><td></td></tr>
<tr><td>19. Operator 6.B Load stillage</td><td></td></tr>
</table>

Table 3.2: Processing steps for manual transfer between presses

Because of the large amount of data to be recorded a decision was made at this stage to only record full processing times for a certain number of part types. The parts which were chosen were common part types which were regularly produced. This meant that sufficient production records would exist for these parts for the purposes of model validation. The process times listed in Table 3.1 and Table 3.2 were also easier to measure as these parts were being made regularly. An additional consideration when choosing the part types was the necessity to utilise each possible layout of the model. This means that both manual and automated transfer is covered by the data collected, along with three or four die line setup and single or double stage stamping.

8. Bale change time.

When a bale of steel sheets at the front of the line runs out there is a delay while a new one arrives to replace it. This delay had to be measured.

9. Stillage change time.

When the stillage at the end of the line is full there is a delay while it is removed and an empty one is put in place. The length of this delay had to be measured.

Additional data was also needed for model validation:

1. Production Schedule:

The schedule is decided by the line supervisor at the beginning of every week. The relevant schedules have been gathered so that a comparison may be made between the outputs of the line and the model for a given input.

2. Production Records:

For each shift where relevant parts are being stamped the job number is recorded so the production records from that run can be accessed.

Production results data is automatically recorded by a computer system. It can output the following information:

- Job Number.
- Panel Number.
- Panel Name.
- Production minutes.
- Downtime minutes.
- Setup minutes.
- Quantity produced.
- Panels produced per hour.

There is a list of job numbers and the panel numbers they correspond to in the press shop office. It should was possible to look up the production data based on these job numbers. Sometimes the data entered into the computer system is not accurate. The times allocated to production, downtime and setup are often incorrect. The panels per hour figure is calculated on the basis of production minutes and therefore if the production minutes figure is wrong then the panels per hour figure is wrong also. An additional source of information is the QC Production Report. This is completed for each job number. It records the part type, dates, shifts, bale numbers and total number of panels produced for each job number. The difficulties faced and methods used to overcome these difficulties are discussed further in Section 4.6.1.

4. Model Building:

This section describes the model building process as undertaken in this simulation study. This process corresponds to the model building and coding stage and the verification and validation of the model as outlined in Section 2.5. Firstly, in Section 4.2 some modelling terms and items specifically relating to Extend are introduced. These concepts are referred to in the description of the model building process (Sections 4.3 and 4.4) as well as Sections 4.5 and 4.6 which relate the model verification and validation steps. Therefore it is useful to introduce them at this stage. Following this the main constituent parts of the model are introduced and the methods used to construct them are described. Other issues relating to implementing the correct process flow through the model and extracting the required information from the model are outlined. Finally the model verification and validation stages and some initial results are presented.

4.1. System Modelling:

Before work could begin on the simulation model, a basic model of the production line was constructed. For this stage simple flow chart modelling combined with the hierarchical feature of the formal IDEF0 modelling standard was used. It was not necessary to use the formal IDEF0 standard as the model was only intended for use by one individual and the system to be modelled was relatively simple.

Figure 4.1: Top level view of system

The top level view of the system can be seen in Figure 4.1. This shows the overall flow of parts through the line. The raw material is placed in front of the press line. It is then fed into the press line where it is processed in stages until it emerges as a fully formed part. From there it is placed in a stillage ready for shipping to the customer.

The next flow chart models inside the press line block of Figure 4.1. It shows the individual presses and the flow of parts through the press line. This is also a relatively simple model and is shown in Figure 4.2. The parts make their way from Press 3 to Press 6 by way of the part transfer operations.

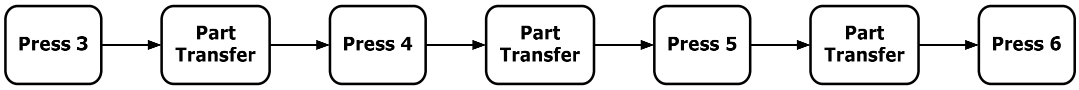

Figure 4.2: Model of press line

Each hierarchical press block and part transfer block have the same constituent parts. The internal Press block flow diagram is shown in Figure 4.3. The processing stages vary depending on whether the part uses a single or double stage pressing.

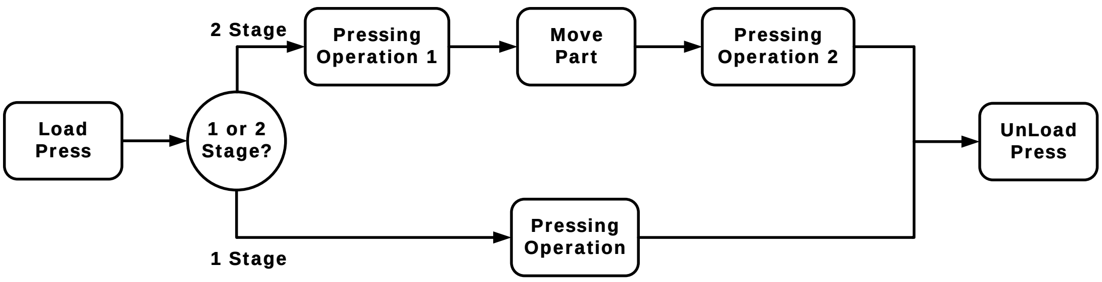

Figure 4.3: Model of pressing operation

For single stage pressing the part is loaded into the press, a single pressing operation follows before the part is unloaded and transferred to the next press. For two stage pressing after the first pressing operation the part is moved to another part of the die for a second pressing. It should be noted that in this case there are two parts in the die at any given time.

Part transfer operations between presses also vary depending on whether the part in question uses manual transfer between presses or robotic transfer. If the part is manually transferred between presses it must pass through three separate operations. The first of these is a manual unloading step. The part is then transferred onto a conveyor to make its way to the next press before being manually loaded into the next press. In contrast if the part is transferred automatically then the robot performs all three tasks. The possible steps are shown in Figure 4.4.

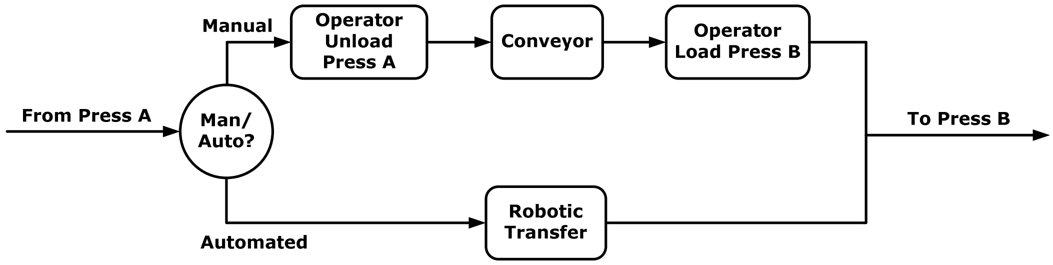

Figure 4.4: Part transfer model

4.2. Extend-Specific Modelling Concepts:

Before explaining the construction of the model in detail it is useful at this stage to explain some of the relevant characteristics which relate to Extend models. The concepts described in the following sections have been used extensively throughout the simulation model.

4.2.1. Simulation Order, Hierarchy and Random Seed Numbers:

The order in which the blocks are simulated must be considered when building the model. Generally, in Extend the order runs from left to right but the simulation order may be checked using the 'show simulation order' feature which numbers each block according to where it fits into the simulation.

A useful feature of Extend is the ability to include unlimited levels of hierarchy in a model. For example, if the user connects several blocks together to replicate the functionality of a complex machine, these blocks can be grouped together into a single block. On the first level of hierarchy only the single hierarchical block is visible but by double clicking on the block the constituent parts can be revealed. This simplifies the structure of the model and makes navigation much easier. It is also useful where a particular combination of blocks is used repeatedly throughout a system. An example of this would be where several identical or very similar machines are connected together to form a production line.

Random seed numbers and the random number generator are the internal mechanisms used by Extend to include randomness in models. This ability to model stochastic systems is a very important feature of simulation packages, as previously stated in Section 2.4. The random number generator in Extend produces a stream of random numbers which are then used by any blocks in the model which incorporate a degree of random behaviour, e.g. the unscheduled downtime block. The specific stream of pseudo-random numbers depends on a number called the random seed. This number automatically changes with each simulation run unless the user inputs a specific number. This is desirable when investigating the effect of any changes made to the model on model output. Specifying the same random seed for the model run before and after modifications to the model means that any changes in model output are due to the modifications made, as all other aspects of model behaviour are unchanged.

4.2.2. Databases, Attributes and Gates:

Another useful feature of Extend is its ability to import a database from an external application such as Excel. For this model a database was built in excel which contains all the part and line information necessary to run the model. Each block in the model was then set up so that it looked up its parameters from a specific entry in the database. This method meant more work in the initial modelling stage but much less work thereafter. This is because that any changes to data or block parameters can be easily made in excel and the changes will then populate automatically throughout the model when the revised database is imported to Extend. This is obviously much easier than manually going through the model making changes. It also removes the possibility of incorrect information being entered in some blocks due to human error.

Each item generated in the model is given a tag or label to identify which part type it is. In Extend these are known as attributes. Whenever any information specific to that part type is required the part type attribute for each item may be accessed and a lookup table is used to find the information needed. An example of this is shown in Figure 4.5. As the item passes through the get attribute block the attribute is read and fed into the lookup table. This lookup table should contain a list of possible part types and the delays associated with them. The correct delay for the part type will be found in the lookup table and sent to the variable delay block, which will then hold the item for the appropriate amount of time.

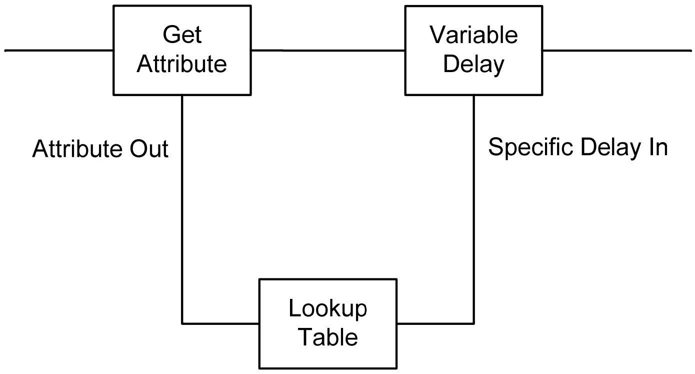

Figure 4.5: Example of using attributes in Extend

This block layout is used extensively throughout the model. Different part types have different delay times for most delay operations, for example press loading and unloading. Using the model structure shown in Figure 4.5 ensures that the processing time required is fed into the delay block which then accurately models the stamping operation for that part.

Gate blocks only allow a specified number of items to enter a user-defined section of the model at any given time. The block records each item entering the restricted area up to the user-defined maximum. Thereafter it prevents items from entering the restricted area until items have exited at the other side of the restricted area. One example of where gates are used in the model is to ensure that only one part can be in a press at any given time for a single stage pressing operation, or two parts for a double pressing operation. However, a limitation of the gate block compared to some other blocks in Extend is that the number of items permitted cannot be easily changed while the model is running. This means that two separate paths are needed, one for single stage pressing and one for two stage pressing. The single stage path passes the item through a gate with a maximum number of items allowed of one, while the two stage path passes the item through a gate with a maximum number of items allowed of two. The path is chosen using a decision block.

4.2.3. Decision Blocks and Machine Blocks:

Decision blocks are a feature of Extend which allow different paths to be selected for items in the model based on user defined criteria. Programming statements such as 'if' and 'for' loops in conjunction with mathematical operators such as =, < and > are used to decide the path. So, taking the example of a decision to be made as to whether a part uses single or two stage pressing, the first thing to do is look up this information from the database. The result of this query is then used as the input for the decision block. A simple 'if' loop can then be used to set the path accordingly.

All process delays in the model are implemented using the machine block in Extend's manufacturing library. Upon initial examination it appears that delay blocks could also be used to give the same functionality. The machine block in Extend behaves in the same way as the delay block but has an additional connector which allows the user to replicate unscheduled downtime in the model. Therefore machine blocks were chosen over delay blocks to take advantage of this feature.

4.3. Building the Simulation Model – Press Line Structure

The model is built by following the basic structure and layout of the production line itself. This means that the items representing the steel sheets arrive at the start of the model where they are fed into blocks modelling press 3, presses 4-6 then follow in the model followed by the stillage and finally the exit from the line and the model.

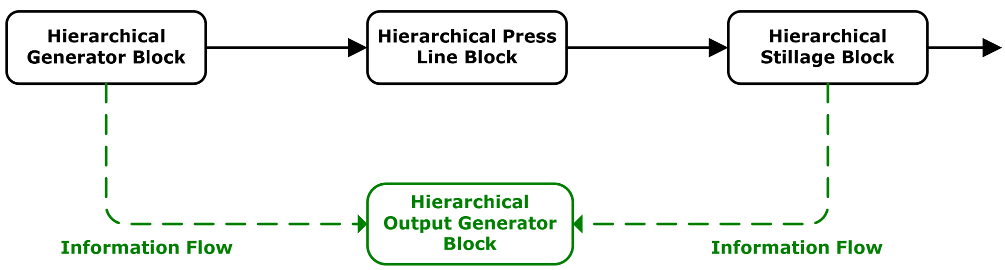

Figure 4.6: Overall hierarchical model structure

An overall 'top level' view of the structure of the model can be seen in Figure 4.6. In the figure the black blocks form the actual line itself with the black lines showing the direction of material flow through the line. The model begins with a hierarchical item generator block, which deals with the supply of raw material to the line. For some types of model the generator block in Extend would suffice for this purpose but the behaviour of the press line in question meant that it was necessary to add in extra functionality by designing and building a unique hierarchical block. The hierarchical press line block models the functionality of Presses 3-6. The stillage and line exit block represents stillage loading and removal following the unloading of the completed panels from Press 6. The dashed green lines show the direction of flow of information which is directed to the green output generator block. This block is responsible for generating the required outputs from the model. In certain situations, model outputs are very straightforward to generate. This was not the case with the required outputs from this model.

Each of the blocks shown in Figure 4.6 is explained in detail in the following sections. The many challenges faced and issues which were overcome in order to build an accurate, flexible and reliable model are presented. The most important constituent parts of each block and the modelling methods used to construct them are outlined. The flow of items through the model is explained and compared with that of the actual press line.

4.3.1. Supply of material to the line

For some system models, simulating the supply of items into the system can be achieved by simply adding the 'generator' block from the discrete event library in Extend. This was not the case for the press line model. This was due to two factors. Firstly, a single item, a bale of steel sheets, was delivered to the line but then it is opened to reveal a large number of individual sheets. Secondly, there was a delay associated with delivering a new bale of sheets to the line when the previous bale was used up. The generator block in Extend alone could not provide this functionality. Therefore, a hierarchical generator block was developed to model the steel bales being transported from the storage area to the production line. This block acts as the supply to the whole line. It must supply a bale of steel sheets to the front of the line whenever requested with an appropriate delay time. It must also open the bale to reveal the individual sheets. This block also deals with part changeover delays. The operation of the more important blocks contained in the hierarchical generator block is described in this section.

Figure 4.7 illustrates the differences and similarities in the actual system and the model. The green and red boxes show the areas of the diagram which represent the actual system and simulation model, respectively. The vertical dashed lines link the areas of the model with the elements of the actual system which they replicate.

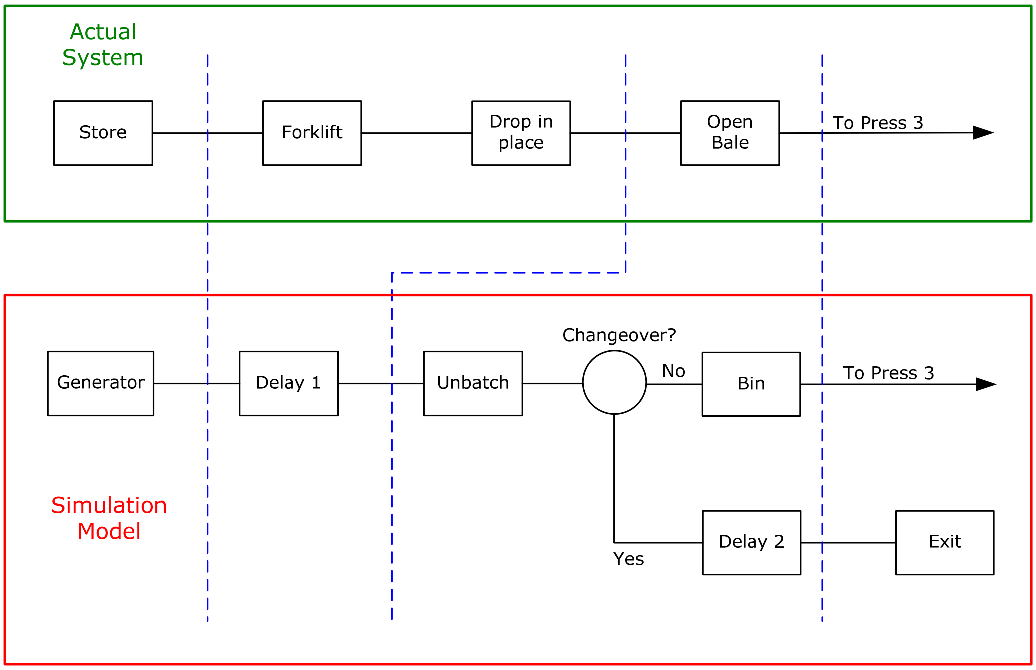

Figure 4.7: Comparison between system and model – line supply vs. hierarchical generator block (simplified version)

The item generator block is used to model the supply of steel bales in the store. This supply is assumed to be always available when needed. This is a direct relationship between the model and the system. The delay 1 block is used to represent the time it takes for a new bale to be brought to the line and opened once the previous one has been used up. This delay 1 is variable and it is set in the database based on measurements of the time taken for a new bale to arrive on the line itself. It can be seen from Figure 5.2.1 that a single delay block in the model is used to represent two separate operations on the line. The unbatch block in the model is used to represent the opening of the steel bale. The delay involved in opening the bale has already been dealt with so this simply converts the single item (the bale) into a certain number of individual items (the steel sheets). Attributes are used to determine the correct number of sheets per bale for each part type and this number is fetched from the database and sent to unbatch block so that the correct number of items are generated. The bin block at the end is the stack of steel sheets in front of Press 3. When the supply is exhausted a new bale must be ordered from the stores and the whole process begins again.

Because of the way Extend steps through the simulation several other gates and logic blocks in the Generator are necessary to form a system to ensure that a new bale is only released when all the sheets in the previous bale have been used up. In order to simplify the diagram these blocks are not shown in Figure 4.7. However, Figure 4.8 shows a screenshot of the hierarchical block in full detail, with all 23 blocks displayed.

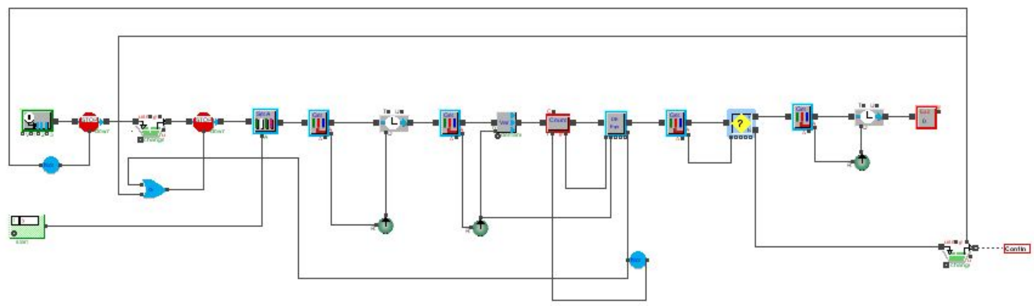

Figure 4.8: Extend screenshot showing the full contents of the hierarchical generator block

This is also a good example of why the hierarchical modelling structure described in Section 4.2.1 is so useful, as this view is hidden in the overall model view and is only accessed when required. It should be noted that for the remainder of Section 4, only the simplified diagrams will be referred to and the actual Extend models will not be shown. However, they have been included in Appendix A for reference if required.

This section of the model also deals with the changeover delay. This is modelled by creating a ‘dummy’ changeover part type to be passed through the line after each batch of a certain part is made. The 'delay 2' block in the generator section of the model represents the delay caused by changing dies in the presses. This delay 2 block is avoided by all other part types using a decision block. The decision block selects a path for all normal part types which does not pass through the changeover delay 2 block. Although it does not seem from the diagram to fit in visually with any one section of the system, it produces the desired effect when the model is running, i.e. it prevents any items from entering the line for the length of time that the changeover is taking place.

4.3.2. Modelling the presses:

The operation of the presses in the model would be quite straightforward if all parts had the same number of stages in each pressing. One machine block could then be used to model each press. However, as described in Section 3.5, while the majority of parts are stamped using a single operation in each press, two-stage pressing is used by certain parts.

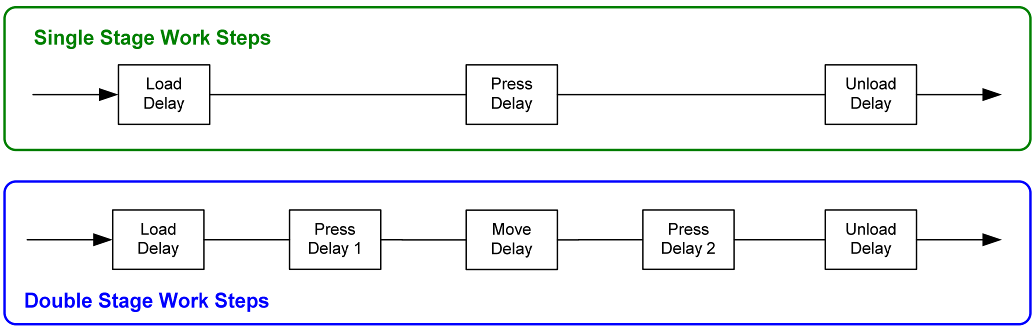

Figure 4.9: Work stages for parts with one stage and two stage pressing

Figure 4.9 shows the stages that each type of part must go through. With one stage pressing the panel is loaded into the press, the press cycles once and then the part is unloaded. For two-stage pressing, after the press cycles for the first time, there is another delay while the part is moved into the part of the die which will perform the second pressing. Then the press cycles for the second time before the part is unloaded and makes its way to the following press. It should be noted that for two stage pressing operations there are two parts in the die at any given time. Also, the load, move and unload delays shown in Figure 4.9 are always of the same duration as the press cannot cycle until all three operations have been completed.

To provide the model with the required functionality and flexibility, a system of decision blocks and gate blocks was designed and constructed within each press to select either a one or two stage pressing as appropriate. A simplified version of this system is shown in Figure 4.10. The green dashed line encircles the path followed by a one stage pressing part, while the lower blue line shows the path that would be followed by a part requiring two pressings.

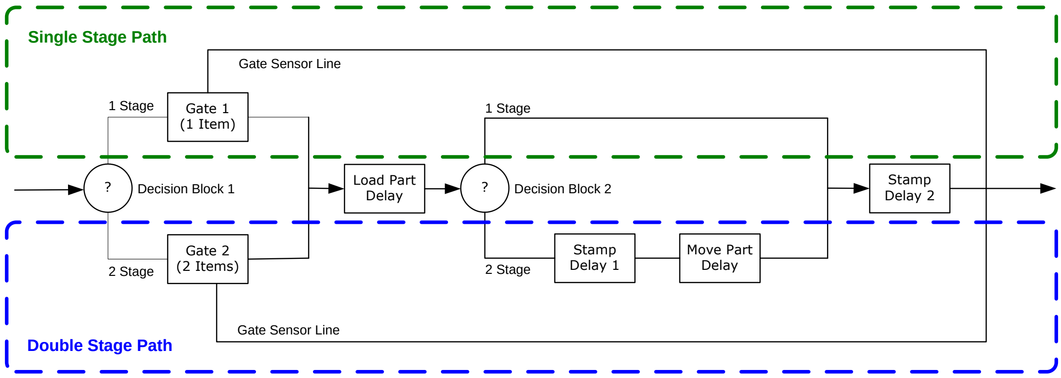

Figure 4.10: Simplified press hierarchical block diagram showing paths for single and double stage pressing capability

When the partially completed panel reaches the press model, it enters the first decision block. This decision block gets a signal from a lookup table which is set to look up whether a specific part type requires a one or two stage pressing for that press. If the part uses one stage pressing, the decision block sends that part through gate one, which only allows one item in its restricted section at a time. This is because with single stage pressing only one part is in the press at any given time. If the part requires two pressings, then it is sent through gate two, which allows two items in its restricted section. This two item gate is necessary as there are usually two panels in a press which is performing a two stage operation. The reason that two separate gates are required is because as stated in Section 4.2.2, the number of items allowed in a gate’s restricted area cannot be changed while the model is running.

Once the item passes through the correct gate, the two paths converge as they both need to pass through the press load delay block. Following this block is another decision block which again splits the paths according to the number of pressing stages needed. The two stage parts take the lower path which includes press delay block 1 and the rotate part delay block. The one stage parts are routed along the upper path which bypasses both of these blocks. Following this the two paths converge once again and pass through press delay block 2. In this way the stages for either single or double stage pressing as shown previously in Figure 4.9 are performed as required.

The appropriate delay times or press cycle times are all extracted from the database using the part type attribute feature as described in Section 4.2.2. The required blocks for this are not shown in Figure 4.10 in order to simplify the diagram. Press downtime is modelled using an unscheduled downtime block which is connected to the 'downtime in' connector of the machine block. The frequency and duration of random stoppages is set in the downtime block. These parameters are decided based on observation and measurement of downtime on the line. Again this is not shown in Figure 4.10. The downtime issue is discussed in more detail in Section 4.4.3.

4.3.3. Part Transfer between Presses:

Section 3.6 described how the transfer of partially completed panels between the presses on the line may be accomplished by either a manual or an automated process, depending on the part type being manufactured. The implications of this variation for the model are described in this section. The methods of modelling both manual and automated transfer are described and the differences between them are outlined.

The comparison between the manual process and the model can be seen in Figure 4.11. As the diagram shows the relationship between the system and the model is direct. This means that each operation on the press line corresponds to a single block in the model. The manual load and unload at the start and end of the line and the manual unload and load between the presses are modelled using machine blocks for reasons outlined in Section 4.2.3. The conveyors used with the manual transfer setup are modelled using the ready-made conveyor block in Extend. The capacity of the conveyor will vary depending on part type and once again attributes are used to look up the capacity in the database and modify the conveyor capacity accordingly.

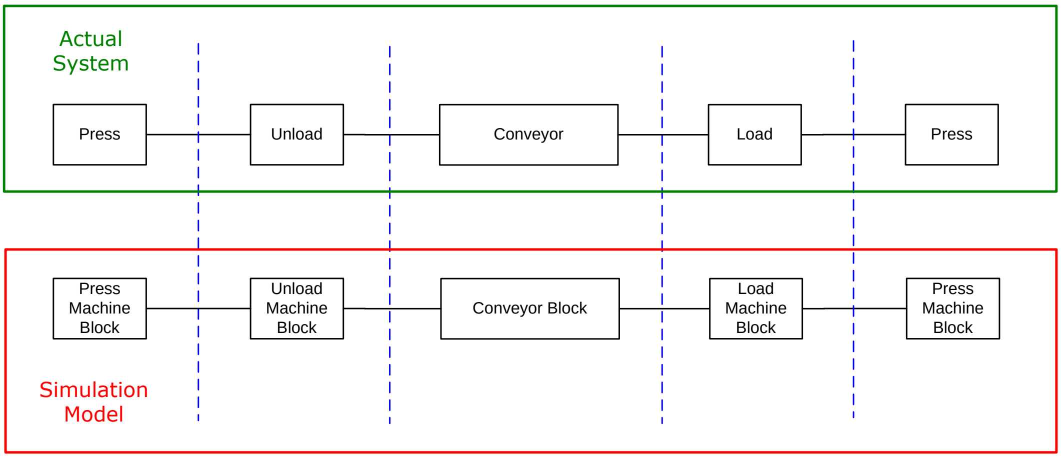

Figure 4.11: System/model comparison - manual transfer between presses

The delay time of each machine block when manual transfer is in place is subject to a distribution which represents the inconsistencies of the cycle time of the manual operation. This distribution is decided upon based on actual measurements from the line. These measurements are described in more detail in Section 4.6.1.

The situation is slightly different when the automated transfer setup is employed. The conveyor blocks used for manual transfer are omitted from the path through the model when an automated transfer part is being stamped. The robot which is responsible for unloading the panel from one press, moving it to the next press and loading it into the die is modelled using three machine blocks. These blocks are the same ones used for the manual transfer setup. However, the second block delay time now includes the time taken for the robot to rotate between the two presses as well as the time taken to load the die into the press. Unlike with manual part transfer, the robot's cycle time is constant, so there is no variation in the process time. Consequently, there is no need for the statistical distribution on the machine blocks so it is omitted. This automated transfer setup is shown in Figure 4.12.

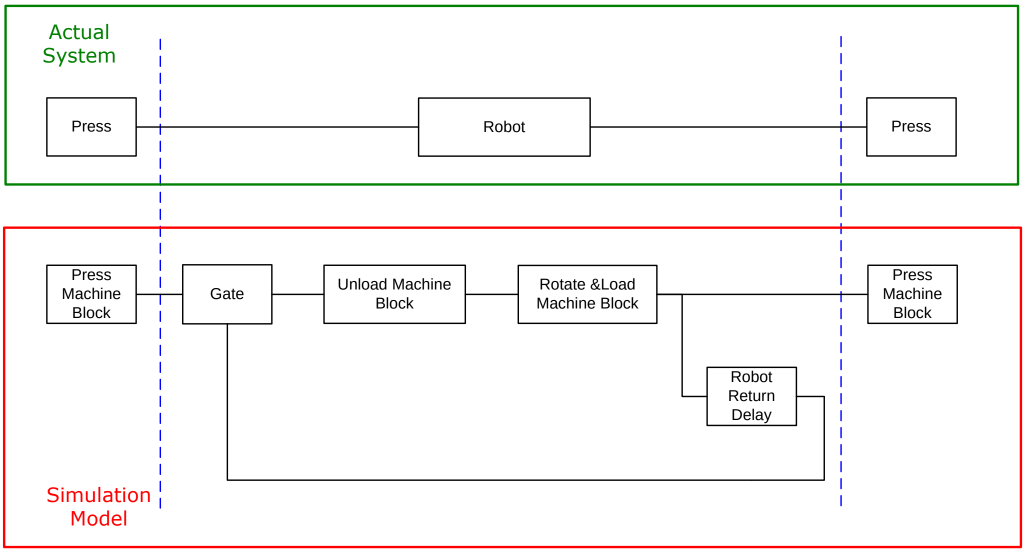

Figure 4.12: System/model comparison - auto transfer between presses

A gate is used to incorporate the delay experienced when the robot must return to the first press after loading the second. As seen in the diagram the gate has a restricted section that runs from before the unload block to after the robot return delay block. This gate ensures that an item cannot leave the first press until the robot has returned from loading the next press. It should be noted that the return delay block is not included in the main line of the model, as it does not necessarily affect the time taken for an item to pass through the line.

After Press 5 the parts pass through a decision block that has two alternative paths. Depending on the line configuration for the part type in question it will either allow them to move along the line to Press 6 or select a path which omits Press 6 and moves them directly to the end of the line. The model structure for this feature is shown in Figure 4.13.

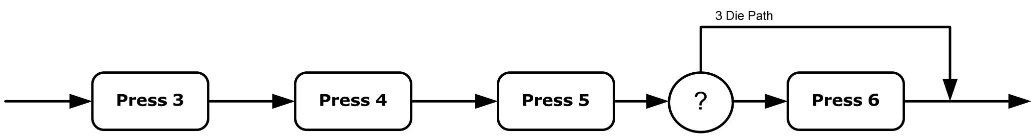

Figure 4.13: Hierarchical view of the model showing three or four die flexibility.

When the part exits Press 5 it must pass through a decision block. This decision block reads in part information and sets the appropriate path for the layout used by that part type. The 4 die path allows the part to pass through Press 6 and from there to the stillage and the end of the line and model. The three die path omits Press 6 and takes the part directly to the end of the line. This ensures that the model replicates the operation of the line correctly. The information regarding the number of dies used by each part is contained in the database and is accessed via a 'get attribute' block and a lookup table.

4.3.4. The end of the line

At the end of the line parts are removed from either Press 6 (in a four die setup) or from a conveyor placed after Press 5 (in a three die setup). They are then placed into a stillage. The comparison between the model and the line is shown in Figure 4.14. This assumes a four die setup but the model structure is essentially the same for a three die line.

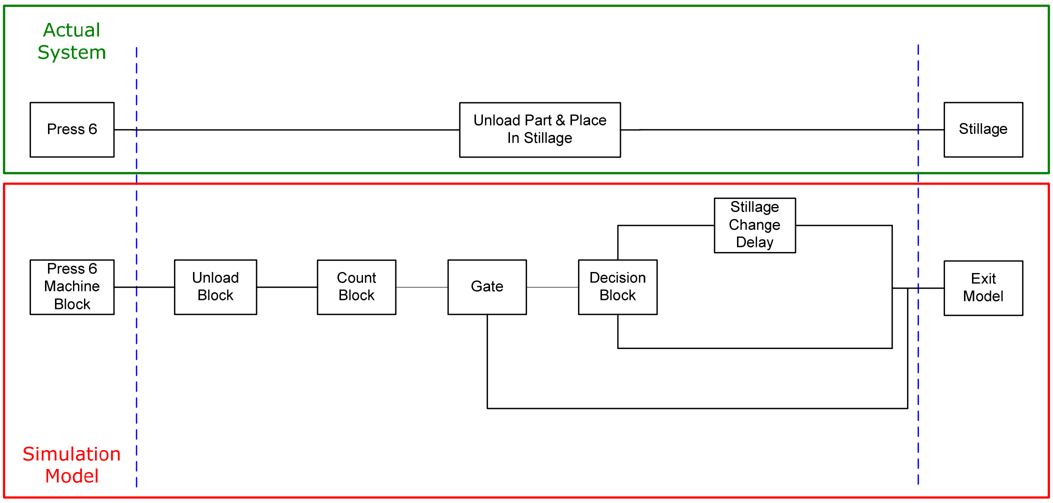

Figure 4.14: Schematic diagram showing system/model comparison - end of line

The way the line works has already been explained. The model replicates the line as follows: The unload block models the time taken for the operator to remove the finished panel from Press 6 and place it in the stillage. The rest of the blocks together form a system which will cause an appropriate delay when the stillage is full. Firstly, the count block counts the number of items which have passed through it since the last time the block was reset. This number is compared to the number of available slots in the stillage for whichever part is being manufactured. This information is stored in the database. When the number of items which have passed through the count block equals the number of slots available in the stillage then obviously the stillage is full. In reality this means there will be a delay while the full stillage is removed and replaced with an empty one. The model deals with this within the decision block. Up to the point where the stillage is full the decision block selects the lower path which allows the parts to exit the model without any delay. Once the stillage is full the decision block re-routes the last part along the upper path through the delay block which represents the time taken to replace the full stillage with an empty one. The gate block ensures that only one part can be in this area of the model at any given time. This means that no other part can exit press 6 while the stillage replacement delay is in progress.

Once this part exits the line the count block is reset to zero and the process begins again with the empty stillage. Once again it should be noted that certain blocks have been omitted from the schematic diagram for clarity. The exit model block provides a gateway for the items to exit the model. It also provides a count of all items which have exited the model since the beginning of the simulation run. This feature is also utilised to generate the required output from the model, using the method which is described in Section 4.4.5 (Page 68).

4.4. <u>Building the Simulation Model – Non Structural Issues :</u>

Section 4.3 dealt with building the basic structure of the model. However, there were a number of other items to take into account and difficulties to overcome. These are summarised in this section.

4.4.1. Building the Database:

As described in Section 4.2.2, Extend has the capability to import data from an Excel database for use in the model. This database was mentioned in Section 4.3. It is useful at this stage to describe the construction of the database which was built for the model. This database is one of the key features which provide the model with the required flexibility to deal with different part types, layouts and process flow without any modification by the user. An Excel add-on for Extend databases is available from the Extend website. This provides the user with the capability to build databases in Excel and then export them directly to Extend. The database is imported into the model before the model is run. As described in Sections 4.2 and 4.3 the blocks in the Extend model can then look up the required parameters in the database. If any changes are made to these parameters the database is simply exported to Extend once again and the blocks automatically receive the new parameters as the model is running. As well as being used for model inputs, the database can also be used to process and display model outputs. When the model is finished running, the model database can be directly exported to Excel where the results can easily be processed and analysed. The database designed and constructed for this model consists of four sections; line parameters, part parameters, production schedule and production results. The first three sections are used as model inputs, the last section receives and processes the model outputs. The line parameters section includes details on shift times and shift numbers. Part parameters is split into two sub sections. One section lists the processing times for all operations from Press 3 load to Press 6 unload on all parts. It also includes data on bale and stillage change times as well as die changeover times. The other part parameter section includes other information apart from processing times including the parameters which will determine process flow through the line for that part type. This includes whether the part is manual or automated transfer between presses, how many dies the part uses, the number of pressing stages for each press, the number of sheets in each bale of raw material and the number of slots available in each stillage. The production schedule section of the database is the section that allows the user to determine which parts to manufacture during a simulation run and how many shifts each part will be run for. The production results section takes the outputs from the model at the end of each shift and calculates the number of parts that were manufactured in that shift. This gives the model outputs directly in the required format of panels per shift. The nature of the flexible model means that the database is the primary interface between the user and the model. Virtually any scenario can be evaluated without physically modifying the model in any way. A sample model database is included in Appendix B.

4.4.2. Shift Times:

As stated in Section 3.7.1, the line ran continuously from 8am on Monday mornings until 5am on Saturday mornings. There were three 8 hour shifts per day from Monday to Thursday and then three 7 hour shifts on Friday. The line did not run at weekends. The 'value schedule' block in extend proved ideal for modelling this aspect of the line. It outputs a certain value based on time elapsed in the model. The schedule for one week of production was converted into minutes (the default time step in the model) and put in an excel sheet. An output value of 1 meant the line was stopped, a value of 0 meant the line was running. The output from the value schedule block was connected to a 'Stop' block which was inserted at the start of the line. When the stop block receives a value of 1 it prevents any items from passing through. When the value is changed to 0 it allows items through without any restriction. These two blocks connected in this manner replicate the behaviour of the line perfectly. So for example at 8am on Monday morning the output from the value schedule is 0 as the line is running. At this stage the stop block is inactive. The value schedule block output changes to 1 at 9:45am, causing the stop block to shut down the line for the morning break. It changes to 0 again at 10am as the line is back running after the break. The schedule is set to repeat every 10,080 minutes, which equates to every week.

4.4.3. Selecting Input Probability Distributions

Many system parameters which were used as model inputs incorporated a certain amount of randomness or unpredictability. This had to be taken into account in order for the model to behave as accurately as possible. These stochastic model inputs fell into two main categories.

The first category included all operations that were carried out manually on the line. This included loading of Press 3 and unloading of Press 6 for all part types, along with unloading of Press 3, loading and unloading of Presses 4-5 and loading of Press 6 for those part types which did not utilise robotic transfer between presses. Other operations which fell into this category are delivering and opening full bales of sheets to the front of the line and stillage changes at the end of the line. All operations of this nature were subject to variation due to differences in human performance and other factors. This was taken into account in the model by following the steps to fit a statistical distribution to the data as outlined in Section 2.5. As no data existed for the duration of these manual operations, it was necessary to measure each one before processing the data. Once this was complete work could begin on fitting the data to a suitable distribution for use in the model. The 'Stat-fit' distribution fitting software is built into Extend so it was used for this stage. The values which had been measured from the line were entered into a Stat-fit document. The program then automatically fitted a series of statistical distributions to these values. These values were presented to the user in order of best fit, as judged by the software.

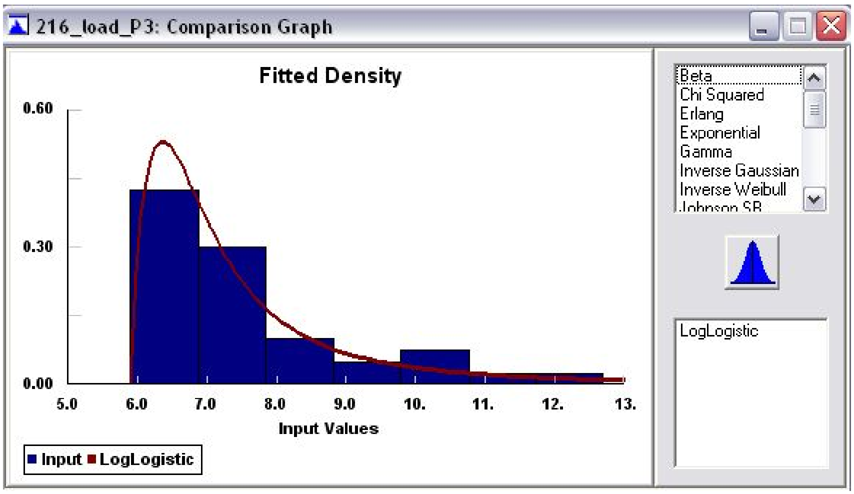

Figure 4.15: Press 3 Load Input Distribution as Presented by Stat-fit

Each of these distributions can be viewed by the user to aid the selection process. The user selects the most suitable distribution for use in the model and it is exported directly to Extend from Stat-fit. For these operations the log logistic distribution was chosen as it closely follows the nature of the recorded data. An example of the distribution used for Press 3 load can be seen in Figure 4.15.

This shows that the data has a relatively well defined lower bound but that there are a number of very long processing times meaning the upper bound is less well defined. The log logistic distribution as fitted by the software closely follows the pattern of the data. This distribution has been identified by Law & Kelton [4] as being suitable for modelling the time to complete a task.

Following observation of the line it was noted that the operations carried out by manual operators were subject to random, unscheduled downtime. This was the second category of random model input to be incorporated into the model. Fortunately, Extend already has a block designed for such a purpose. The ‘downtime (unscheduled)’ block is used to schedule random downtime occurrences. The output from the block is connected to the downtime connector on the machine block which is used to replicate all delay operations in the model. The user can specify the time between stoppages and also the duration of the stoppages. The user can select from constant values or from a variety of statistical distributions. Getting a reliable and accurate measure of this type of downtime is extremely difficult. It is almost impossible to measure as when the workers can see that measurement is taking place then the downtime is less likely to occur. This can often lead to inaccuracies with model results and problems with model validation. In this case the distributions and values for time between stoppages and stoppage duration which were judged to be best suited to the situation observed on the line were selected. There is also a lesser amount of downtime associated with the robots. This is generally due to removal of scrap metal pieces from the press or the path of the robot. It is incorporated into the model in the same way as for the manual transfer downtime. The distribution chosen for the unscheduled downtime was the lognormal distribution. This distribution takes on a similar shape to the Weibull distribution which is commonly used for time-to-failure of machines [4]. The reason lognormal is used in this case instead of the Weibull distribution is because the parameters for defining the lognormal distribution in the unscheduled downtime block in Extend are more intuitive. This is useful for these model inputs as the frequency and duration of the unscheduled downtime are manually defined using judgement based on knowledge and observation of the line.

4.4.4. Number of Dies to be used:

As with the line itself, the model must be able to switch easily from a three die to a four die setup depending on the particular part that is being manufactured. This functionality was relatively straightforward to implement in the model. It was achieved by firstly adding an additional piece of information to the database to be associated with each part type. This simply stated whether each part type used a three or four die setup. Then by placing a decision block after Press 5 and reading this information from the database, the appropriate path could be chosen for the items to follow. They either pass through Press 6 in the case of a four die setup or skip it altogether in the case of a three die setup. This provides the model with the required flexibility to fully replicate the behaviour of the line.

4.4.5. Automation of System Performance Parameter Generation:

The measure of performance used by the company for the production line was line throughput stated in terms of panels produced per hour for each shift. The production reports which will be used for validation of the model record the number of panels produced in each shift. Therefore the model must be capable of outputting the total number of panels produced for each shift that it runs, even in the case where multiple shifts are run consecutively in the model.

This was implemented in the model by firstly adding a new table with two columns into the database called ‘production results’. This table lists the shift number in one column and the total number of panels produced in the other. Now, as mentioned in a previous section, the ‘exit’ block includes an additional connector which supplies a count of all items which exit the model from the start of each run. This can be used in conjunction with a ‘DB Write’ block which writes a value it receives into a selected field in a database table, in this case the ‘panels produced’ column of the ‘production results’ table.

This alone would be sufficient if the model were to be run one shift at a time but for runs of more than one shift it is not adequate as it would simply output the total number of parts produced at the end of every run rather than giving individual shift-by-shift figures. To overcome this issue, the setup shown in Figure 4.16 was designed and implemented.

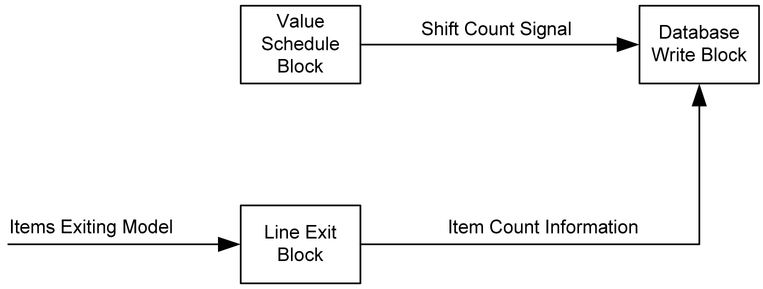

Figure 4.16: Automatic Process Performance Parameter Generation

A value schedule block was added to the model which starts with an output of 1 and increments this by 1 at the time which corresponds to the end of each shift. This in effect provides a shift count while the model is running. The output from this block is connected to the 'Record In' connector of the DB Write block. This means that the DB Write block will write the value from the exit block at the end of each shift into successive entries in a 'production results' table which was included in the database. From this production results table the number of panels produced in each shift is automatically calculated using simple arithmetic.

4.5. <u>Model Verification:</u>

The model verification stage involved ensuring that the model works as intended and is accurately built and structured in order to replicate the workings of the actual line correctly. Most verification work was carried out as an iterative process within the overall model building process. The first incarnation of the model was a very simple version which was verified as a proof of concept. Following this verification stage more detail was added into the model. Another verification stage followed. This cycle repeated itself until the model contained all desired detail and functionality.

Even though a lot of verification work had been carried out by the time the final model was built, it was still necessary to carry out an overall verification to ensure that the different sections interacted with each other as intended. The verification process followed the steps outlined in Section

2.5. The first two steps were combined into a single stage meaning there were two steps in the verification process for this model. Both of these steps were completed at various stages in the model building process as well as after the final version of the model was completed, meaning that multiple verifications were completed during the course of the construction of the model. The model building stage initially concentrated on implementing the structure of the model before addressing other operational issues. The verification process follows the same procedure.

The first step involved verifying the model structure by ensuring that all parts followed the same path through the model as they would on the press line itself. This verifies the structural elements of the line as described in Section 4.3. A flow diagram showing all possible paths for different part types was constructed before the simulation model building stage began. It was used for reference during model construction. Now it was used again in conjunction with the animation feature of Extend to verify the model. With the animation switched on and the running speed of the model slowed down it was possible to visually track the movement of parts through the line and compare the routing with the flow diagram to ensure everything was working as required.

The second stage of verification is to examine the reasonableness of the model outputs. For this stage several additional blocks were added into the model to generate additional outputs. These outputs were not required for the completed model but were very useful for the verification stage. They were added in so that outputs from the model could be examined for plausibility at various stages throughout the model, rather than just at the end as the finished model would require. They were removed following the verification stage in order to minimise the duration of each simulation run.

Each of the four main model blocks identified in Section 4.3 were tested using this two stage process.

4.5.1. Verifying the Generator Block

To test the generator block meant checking three main functions; the delay involved in getting a new bale of steel sheets to the line, the unbatch block representing the opening of this bale of sheets and the decision block which dealt with the dummy changeover item. The first step was to verify the block structure by examining the paths taken by items. There are two possible paths in the generator block. One is the path taken by the changeover item, the other is the path taken by all other items. Running one of each type through the block confirmed the decision block responsible for choosing the correct path was operating as required. The next function to test was to make sure that the unbatch block was working as intended. This was to be done by visually tracking the item representing the bale of steel sheets as it entered the unbatch block, then counting the number of items exiting the block. Since the bale of steel sheets for most part types contained in excess of 250 sheets a special part type was created for the verification process. This part type had a small number of sheets per bale making it easy to verify the unbatch block.

Following this it was necessary to test the system designed to only release a new bale once all the sheets in the old bale had been used up. Once the bin in front of the line was empty the new bale should then and only then enter the delay block which represents the time taken for the delivery and opening of the new bale. This was verified to be operating as required. This concluded the visual and structural check of the generator block. Now the only remaining checks for the generator block were to verify the bale delivery and part changeover delay. To do this a 'plot' block was connected to the 'time in use' output connector of the two delay blocks. The delays were tested one at a time as no part type passes through both. To test the delays several items of the appropriate part type were run through the block, the data was then examined in the plot block and a judgement was made as to whether it was reasonable or not. For example the delay time for a new bale to reach the line and be opened up was in the order of 5 minutes, this was easily verified using the plot block. Any errors found at this stage were corrected and the verification process moved on to the next hierarchical block in the model.

4.5.2. Verifying the Press Line Block and End of Line Block

The same procedure was followed to verify the structure and operation of the hierarchical press line block and end of line block. Alternative paths for manual and automated transfer were visually verified, as were the paths for one and two stage pressings. This was repeated for all combinations of part types in all presses. Some errors were found, which were mainly due to incorrect or incomplete entries in some block parameters. For example on observation of one of the press models, it became apparent that one stage parts were following the two stage path and vice versa. Upon viewing the logic loop in the decision block responsible for setting the path the cause became apparent. The 'if' loop had the path names mixed up for each type. This was easily spotted and repaired at this stage thanks to the animation feature of Extend but would have had a large impact on the model outputs had it not been fixed.

The 'value schedule' block which deals with shift and break times was tested using a plot block. The 'plot' block was connected to the value schedule block and the model was run for a period of 4 weeks. The data in the plot block was compared to the shift minutes calculations which had been manually calculated during the model building stage. A small error was found whereby one of the Friday shifts was 8 hours in duration instead of 7. This was easily corrected and another test run verified that the value schedule was now operating correctly. All delay times were also tested for plausibility using the plot blocks method as explained in Section 4.5.1.

The end of line block was tested in a similar manner to the generator block. A part was created which had a small number of slots per stillage and this was used to visually verify the logic used to decide when a stillage was full and trigger the delay time for the full stillage to be removed and a new one deposited at the end of the line. The delay times were tested in the usual manner.

4.5.3. Verifying the Performance Parameter Generation Block

The shift counter feature of the performance parameter hierarchical generator block was the main issue requiring verification. The first step in the verification involved ensuring that the system that had been designed and built was incrementing as intended. The second step involved checking to ensure that it was incrementing at the correct time, i.e. the shift counter should switch after one shift has finished but before the next shift started. No visual verification of this block is possible as information flow is not animated in Extend. A plot block was used to compare the output from this shift count value schedule block with the line status information line which comes from the shift information value schedule block. When the output from the two blocks is graphed together a visual verification is possible. The last remaining verification task is to check that the database write block is supplying the correct information to the database. Once this was confirmed the entire model was confirmed to be error free and work could begin on model validation.

4.6. Model Validation:

The model validation stage involves comparing the outputs of the model to the outputs of the line itself under known conditions. Therefore the first step to be taken was the compilation of the data from the line that would be used to validate the model. A part was chosen at this stage, part number 1018.216, a heater plenum for a Ford van, which was used for validation and experimentation purposes. This part used four dies with automated transfer between presses.

4.6.1. Data:

As already stated in Section 3.4, the main criterion on which the performance of the line is measured is the number of panels produced per hour or per shift. Therefore this data was also used to validate the model. Line output data was gathered from three separate sources. These sources were production analysis reports, production reports for large presses and QC reports. These are explained in more detail below. Samples of each type of report are included in Appendix C.

Production Analysis Reports:

Production analysis reports were automatically generated in Microsoft excel format by a semi-automated system on the line. A line operator was responsible for entering the status of the line as it changed during each job number. There were three options, production, setup, or down time. At the end of the job the quantity of panels produced during that shift was entered and then the production analysis report for that job number was automatically generated. Close inspection of these reports revealed that while the data for most job numbers was reliable, there were definite inaccuracies in others. Impossibly high production numbers for certain jobs were discovered, as were equally improbably low numbers for other jobs. There are a number of possible explanations for this. One possibility is human error on the part of the operator which was recognised and corrected by adding in a low or high number as appropriate for a subsequent job. Another possibility is that the line supervisors were effectively 'stockpiling' panels in times of low demand; hence the low and inaccurate numbers for certain jobs. Then when demand was high or a large order for a certain panel had to be fulfilled, these panels would be brought out of storage and added into the figures for another job number. Either way, regardless of the cause of the inaccuracies, a method had to be found to sort the good data from the bad. A decision was made at this stage to explore other possible sources of production data which could be used either in place of the production analysis report or which could be used to identify the data in the production analysis reports which could be used for model validation from that which could not.

Production Reports, Large Presses Only:

The first alternative that was examined was a different type of production report that was also easily available in excel format. This report type turned out to be simply the large press line data extracted from the overall production analysis report so it had the same problems with the data as the overall report. Therefore this data could not be directly used either as a direct source of validation data for the model or to sort the good data from the bad in the production analysis reports.

Quality Control Production Reports:

These reports were compiled by QC personnel in hard copy only. They were stored on the line and only used by QC or production line personnel so there was no need for any low or high numbers to balance requirements as with the other report types. They are therefore extremely accurate having been calculated directly on the line with no external influences. The disadvantage with these reports was the way they were compiled and stored. They were hand written and stored in a somewhat haphazard fashion in the production line office. This made extraction of the data for use in model validation extremely laborious.

Data Source Comparison:

Data from the production analysis reports, large press production reports and QC reports was gathered for comparison purposes. Because of the laborious nature of collecting the QC report data, a decision was made at this stage to extract a representative sample of this data for comparison purposes.

Report Type	Mean	Std. Dev.	Range
Prod. Report Press Line	952	171.22	621 – 1481
Prod. Analysis Report	767	587.53	104 - 2363
QC Production Report	676	111.69	528 - 842

Table 4.1: Data source comparison

The mean, standard deviation and range of the samples from the three data sources were calculated. The results were compiled and are included in Table 4.1.

As can be seen in the table, the results of the three measurements vary wildly. This is due to the inaccuracies in the production analysis reports and the large press production reports. The only reliable data is the QC report data. Therefore, a decision was made at this stage to use the QC report data to effectively validate the data from the other two sources. For the part used for model validation, the results of twelve shifts were gathered from the QC reports. This data was then used to judge the suitability of the data which was already available in excel format. Data which seemed impossibly high or low was discarded. The data was selected from each of the production analysis reports and compared to the data from the QC reports. A comparison table can be seen in Table 4.2. As the table shows, the revised data from the production reports and production analysis reports forms a much better match with the QC data after the sorting process.

Report Type	Mean	Std. Dev.	Range
Prod. Report Press Line	683	97.73	500 - 853
Prod. Analysis Report	686	77.27	534 - 828
QC Production Report	676	111.69	528 - 842

Table 4.2: Data source comparison after sorting

As an additional verification of the compatibility of the data sources, a modified Welch t-test was also performed on the data sets as recommended by Law & Kelton [4]. These results are contained in Table 4.3 and as can be seen in the table the test found no significant statistical difference between the data from the three sources. It can be seen from the table that the t-values in each case are low and that the 95% confidence intervals exhibit a sufficient level of symmetry about zero.

Measure	Press Line vs Prod. Analysis	Press Line vs QC Prod.	Prod. Analysis vs QC Prod.
T Value	0.2115	0.0957	0.3252
Confidence Int. (95%)	**[-64.79, 79.88]**	**[-49.15, 44.68]**	**[-70.58, 51.02]**
Significant diff?	**No**	**No**	**No**

Table 4.3: Welch t-test results for data sources

From these results it was concluded that the data was suitable for validating the model. The data from the three sources was combined into a single table containing a total of 68 results from different shifts. These 68 shift results were then used to validate outputs from the model.

4.6.2. First Validation Run Model Results:

Now the next task was to generate some results from the model for comparison with the validation data set from the line itself. The model was run for 100 shifts and the results of the last 68 shifts were extracted. This process was completed 10 times. The random seed number for each of these runs was noted for use in future runs. This was to ensure a valid comparison when changes were made to the model. The results of these 10 runs were then compared to the 68 shift results that form the validation data set. Table 4.4 shows the comparison between the validation data set and the model outputs. Only the first five of the ten runs are shown for clarity.

Measure	V Data	Run 1	Run 2	Run 3	Run 4	Run 5
Mean	683	646	640	648	638	637
Std. Dev	90.64	57.66	58.08	56.57	57.69	59.47
Range	500 - 853	499 - 735	519 - 763	470 - 766	492 - 752	499 - 804

Table 4.4: First validation run data comparison

Table 4.4 shows that all values were consistently low. The mean is down by 10.7% compared to the validation data set. Therefore modifications to the model were required.

4.6.3. Model Modifications and Second Validation Run:

Modifications concentrated on the unscheduled downtime distributions since the rest of the process times and distributions were more reliably measured.

The list of modifications made to the model is as follows:

- To address the issue of the mean, min and max values from the model being lower than those from the validation data set, the overall throughput of the line will be increased by reducing the time between failures very slightly.
- To address the standard deviation of the model results being lower than the validation data gathered from the press line, the variation of the time between failures will be increased and the mean slightly decreased.

Once these modifications were implemented the model was once again run 10 times and the results collected. Table 4.5 shows the results of the second validation run compared to the validation data set.

Measure	V Data	Run 1	Run 2	Run 3	Run 4	Run 5
Mean	683	692	694	697	699	696
Std. Dev	90.64	59.72	59.66	62.35	68.34	64.89
Range	500 - 853	564 - 802	544 - 817	542 - 811	527 - 804	528 - 822

Table 4.5: Second Validation Run Data Comparison

It is immediately apparent from looking at Table 4.5 that the results from this model run are much closer to the validation data set. Measuring the model outputs confirmed this. The mean number of panels produced per shift was now within 4.6% of the validation data set on average. Following the successful validation of the model, the experimental work was carried out.

It should be noted at this stage that the second validation data comparison was made using the same set of data as the first validation run comparison. Ideally the second set of validation runs would have used a separate set of validation data gathered from the line. However this was not possible as all available data had been used to make up the first validation data set. Therefore the applicability of the simulation results to anything other than the validation data set is questionable. Before broadening the scope of the simulation runs to other part types some further validation runs would be required using new data. Unfortunately this is not possible as the factory is now closed so the author no longer has the ability to either measure new data or access old production records.

5. Experiments:

The experiments to be carried out were as outlined in the aims section at the beginning of the description of the modelling process, namely; to investigate the affect on line output of replacing the Press 3 load operator with a robot and/or replacing the Press 6 unload operator with a robot. With the model built and validated, this was a relatively straightforward scenario to implement in the model. There are three possible combinations with two variations in each:

1. Press 3 now loaded using a robot, Press 6 unload remains manual.
2. Press 6 now unloaded by robot, Press 3 load remains manual.
3. Both Press 3 load and Press 6 unload are robotised.

Additionally, for each of the three combinations two robot process times will be modelled. One cycle time will correspond to an average operator cycle time and the other will be approximately 20% slower. The effect on the output of the line in panels per shift will be investigated for each scenario.

5.1. Automate Press 6 Unload – Fast Robot Cycle Time

This was achieved in the model by removing the random distribution from the Press 6 unload machine block and replacing it with a constant delay time. This reflects the fact that the process time of the robot will not deviate as it does with the manual operator. Initially it was assumed that the robot could perform the unload operation in the same time as a relatively fast manual operator. This meant a process time in the region of 10 seconds. In addition the unscheduled downtime for the Press 6 load block was modified to make it broadly similar to the existing robotic installations, i.e. the transfer of panels between presses.

The modified model was run for 100 shifts. The last 68 shifts were taken and analysed. The total number of parts produced in each of the shifts was determined. The max, min, mean and standard deviation of the 68 shifts was calculated. This process was repeated 10 times and the results of these

10 experimental runs were compared to the 10 validation model runs from the previous section.

Figure 5.1 shows the comparison between the average number of panels produced per shift with the existing manual unloading of Press 6 and the projected number that would be produced if operator 6.B were replaced by a robot to automate the process. As can be seen from Figure 5.1 the mean number of panels produced in a shift rose from an average of 694 to an average of 758, an increase of just over 9%

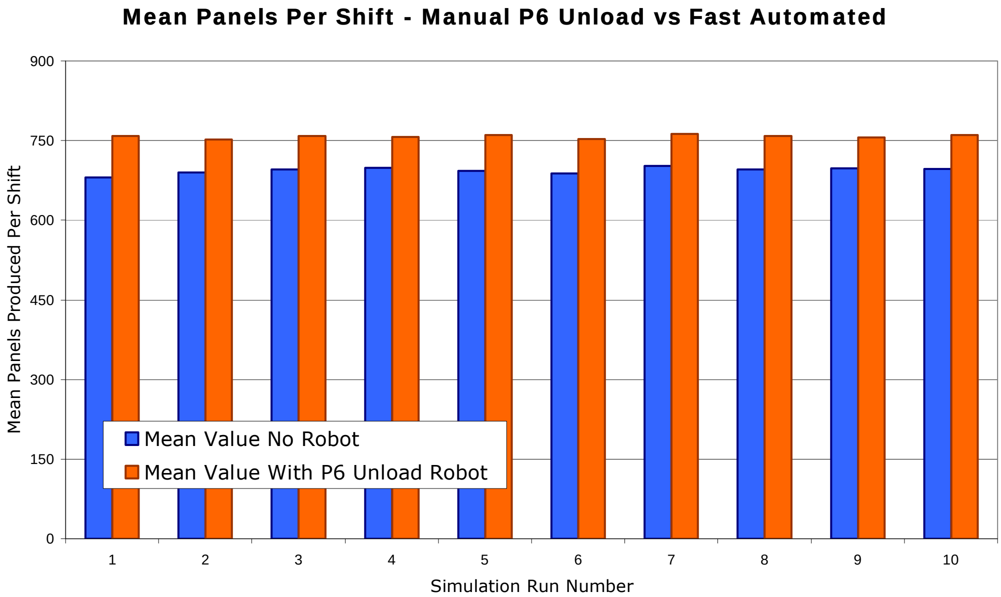

Figure 5.1: Mean panels per shift comparison, experiment 1, faster robot cycle time.

The maximum and minimum number of panels produced per shift also shifted upwards. The average maximum value across the 10 validation runs was 810. This increased to 863 with the automated Press 6 unloading. This is an increase of just under 7%. The average minimum number of parts produced per shift from the validation runs was 549. This average increased by 7.8% to 591 with the addition of the robot after Press 6.

5.2. Automate Press 6 Unload – Slower Robot Cycle Time

For the second stage of the Press 6 unload experiment the robot cycle time was increased from 10 seconds to 12 seconds. All other parameters remained unchanged. The results following 10 simulation runs can be seen in Figure 5.2.

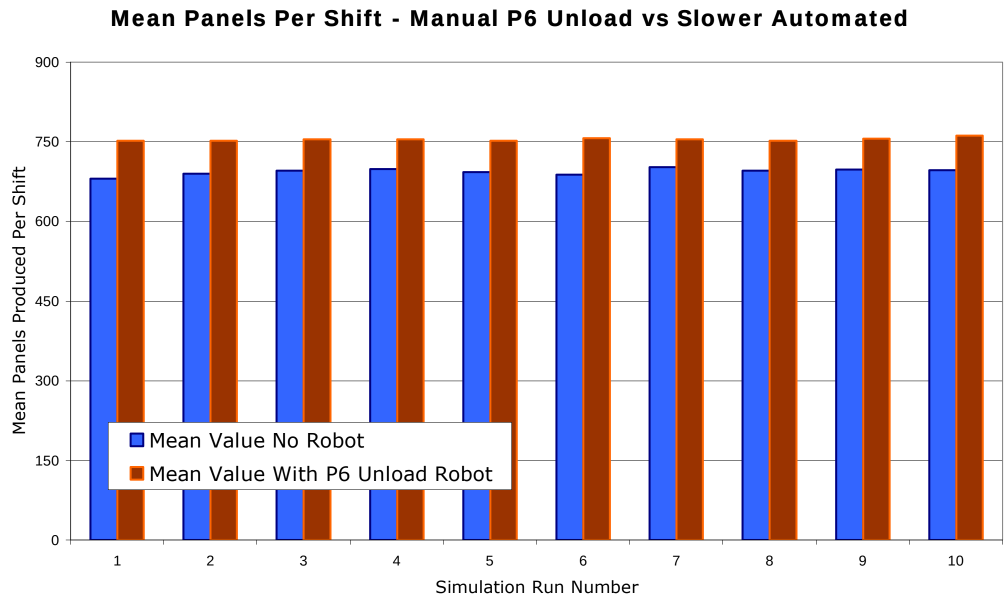

Figure 5.2: Mean panels per shift comparison, experiment 1, slower robot cycle time.

As Figure 5.2 shows, despite a 20% increase in robot cycle time the mean panels produced per shift still increased substantially. The actual increase was from 694 to 755, an increase of 8.8%.

5.3. Automate Press 3 Load – Fast Robot Cycle Time

This was implemented in the model in a similar manner to the automate Press 6 unload scenario. The random distribution from the Press 3 load machine block was removed. The cycle time for the Press 3 load delay was set to a constant value of 7.2 seconds, which corresponds to a reasonable figure for an average operator. Again the model was run 10 times for 100 shifts each time and the last 68 were taken for measurement purposes. The results are shown in Figure 5.3.

As can be seen from the figure, the average number of panels produced per shift increases with the addition of the robot in front of Press 3. The average rose from 694 to 822, an increase of 18%. In addition, the average maximum rose by 15% from 810 to 937 with the addition of the robot in front of Press 3. The average minimum increased by 21%, from 549 to 664.

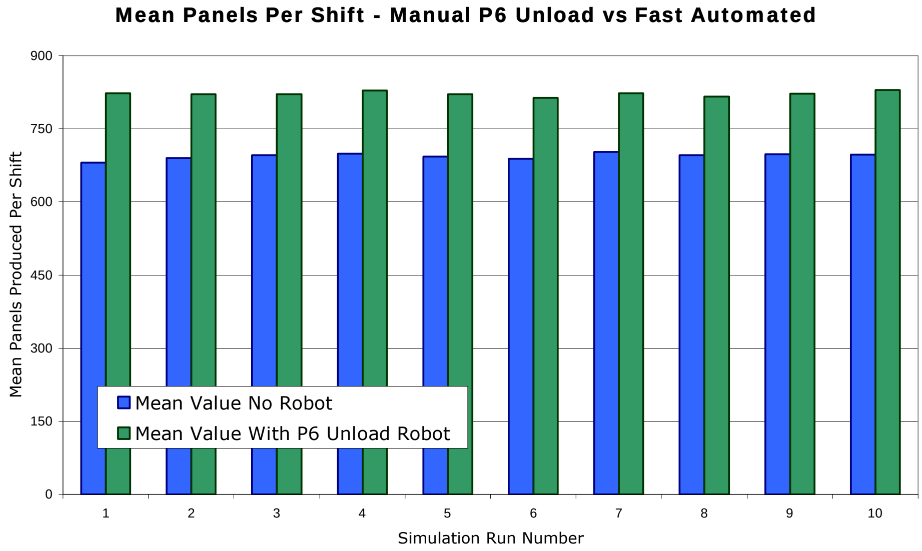

Figure 5.3: Mean panels per shift comparison, manual Press 6 unload versus robot with faster cycle time

5.4. Automate Press 3 Load – Slower Robot Cycle Time

For this experiment the Press 3 load robot cycle time was increased from 7.2 seconds to 10 seconds. All other parameters remained unchanged. The results following 10 simulation runs are shown in Figure 5.4.

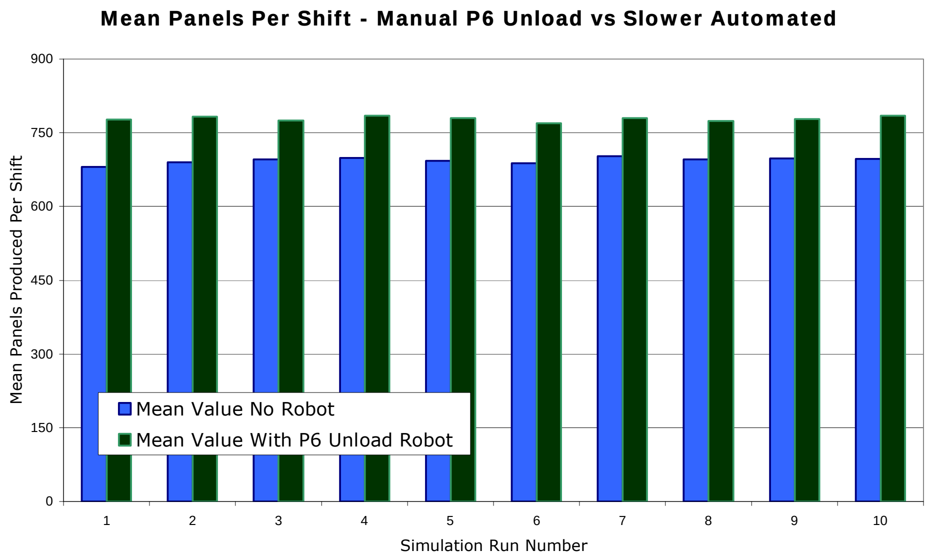

Figure 5.4: Mean panels per shift comparison, manual Press 6 unload versus robot with slower cycle time

As Figure 5.4 shows, despite the increase in robot cycle time the mean panels produced per shift still increased. The average number of panels produced per shift rose from 694 to 778, an increase of 12%

5.4.1. Fully Automated Line – Fast Robot Cycle Times

This experiment investigated the potential benefits of performing the loading of Press 3 and unloading of Press 6 with robots. The modifications made to the model in each of the first two experiments were combined into a single model which then represented a fully automated line. The faster load and unload cycle times of 7.2 seconds and 10 seconds, respectively, were used for the first set of simulation runs. The same format was followed for this experiment as for the others and the results for the mean panels produced per shift are shown in Figure 5.5.

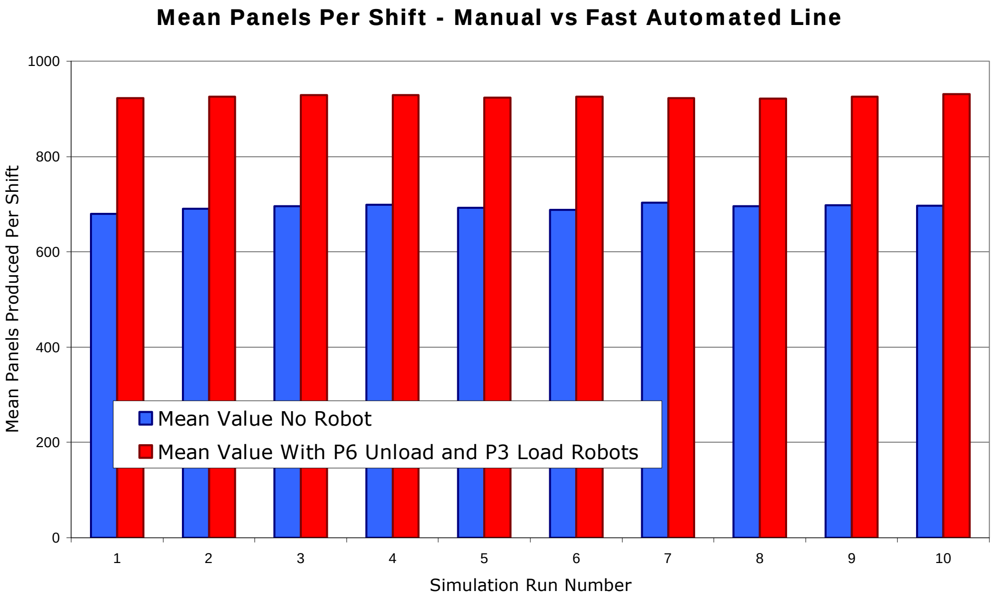

Figure 5.5: Mean panels per shift comparison, manual line versus automated with faster cycle times

As expected following the results of the first experiments, the conversion of the line from semi-automated to fully automated results in a significant increase in throughput. Mean panels produced per shift is up by a third on the normal figure, from 664 to 926.

5.5. Fully Automated Line – Slower Robot Cycle Times

The experiment outlined in Section 5.4.1 was repeated with slower cycle times to investigate the effect of this on line throughput. The slower cycle times from Sections 5.2 and 5.4 were used for this set of simulation runs.

The results of this experiment are shown in Figure 5.6. The improvement in line throughput is reduced compared with the faster cycle times. The average mean increased from 694 to 852. This represents an improvement of 26%

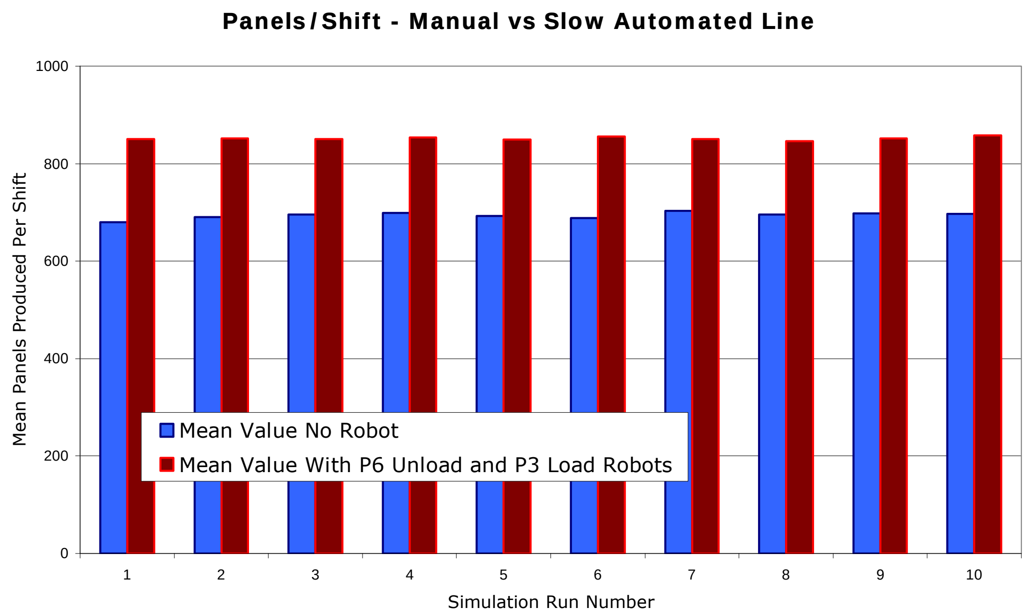

Figure 5.6: Mean panels per shift comparison, manual line versus automated with slower robot cycle times

6. Analysis and Discussion

This section discusses the general implications of the results generated in the experimental stage of the project. Specifically, the impact on press line throughput of using both slower and faster robot cycle times are compared and discussed for each experiment. The potential benefits of automating the Press 6 unload and Press 3 load tasks are compared. The difficulty of implementation of each is discussed. Based on this a recommendation is made as to the best course to follow.

6.1. Results – General Discussion

The results of the three experiments carried out in the previous section were compiled and processed and have been summarised in Table 6.1.

Experiment	Unload P6 Automated		Load P3 Automated		Both Automated	
Robot Speed (seconds)	10	12	7.2	10	10/7.2	12/10
Mean Panels/Shift	+9.2%	+8.8%	+18.5%	+12.2%	+33.4%	+22.8%
Maximum Panels/Shift	+6.6%	+7.3%	+15.7%	+9.4%	+26.5%	+17.6%
Minimum Panels/Shift	+7.8%	+8.2%	+21%	+14.5%	+38%	+26%

Table 6.1: Summary of the Impact of Experiments 1-3

Table 6.1 shows an increase in line throughput across all experimental scenarios where additional automation was added to the system. This is in line with the findings of Ramírez [35] and Neumann et al [36], who both reported increases in throughput where automated material handling was introduced and WIP levels remained constant. In the case of Ramírez, the eventual outcome of the simulation results in fact showed a slight decrease in throughput. However, this was due to the principal aim of the automation being achieved, namely the reduction of WIP on the line and the adoption of JIT manufacturing. Automation can result in many benefits depending on the system in question and the exact nature of the desired improvement. In the case of this research, throughput improvement was the desired outcome and it was achieved. Some other reasons for adding automation may be reducing WIP [35], improving working conditions or reducing costs.

The results also indicate that even in the case where the longer robot cycle times were used throughput still improved. This is despite the fact that the robots now complete the task in a slower time than the average operator. This seems counter intuitive but in fact it serves to demonstrate the effect of reducing cycle time variability on manufacturing system performance as described by Johnson [16]. The vastly reduced variability associated with the robots has the effect of smoothing out the entire process flow through the line. This results in the benefits in the form of improved throughput which are shown in Table 6.1.

6.2. Automate Press 6 Unload – Analysis of Results

As seen in Table 6.1, automating the Press 6 unload operation using a robot cycle time of 10 seconds resulted in an increase of 9.2% in the average number of panels produced per shift. This cycle time of 10 seconds is based on the time taken by an average operator to complete the task. If the cycle time is increased by 20% to 12 seconds then the mean panels per shift improvement is only marginally reduced, to 8.8%.

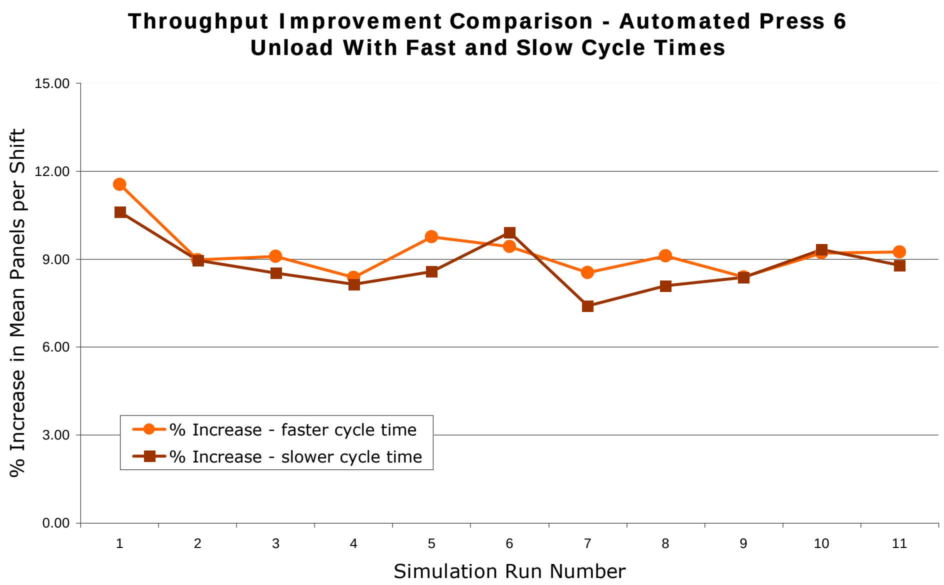

Figure 6.1: Comparison between throughput improvement with slow and fast robot cycle times for Press 6 unload

Figure 6.1 shows the comparison in the percentage improvement for each simulation run. The result of this experiment seems counter intuitive in two different ways. Firstly, how can the robot perform the Press 6 unload function slower than a human operator and yet record an increase in line throughput? The answer to this lies in the much lower levels of natural variability of the automated operation compared to the manual one. Another factor is the vastly reduced variability associated with unscheduled stoppages of this operation on the press line compared to the manually completed task. The reduction in the source of the two main causes of variability in the line results in the improvement shown.

Secondly, despite increasing the robot cycle time by 20% the gains recorded in the panels per hour rates are only marginally reduced. This would suggest that removing the constraint on the line that was the manual unloading of Press 6 has exposed another bottleneck further upstream, as described in the theory of constraints [15]. So even with a cycle time of 12 seconds, the Press 6 unload operation does not seem to be the constraint or limiting factor which is deciding line throughput. The constraint would seem to have moved to the Press 3 load operation. Therefore having a reduced cycle time of 10 seconds and therefore a larger capacity of the Press 6 unload robot, the gains are so small as to be considered almost non existent.

Hence in the case where difficulties were being experienced in implementing an automated Press 6 unload solution with an equivalent cycle time to a manual operator, this knowledge would be useful as it means that the gains will not be unduly affected even if the robot is up to 20% slower than the manual operator.

6.3. Automate Press 3 Load – Analysis of Results

The results of implementing a robot at the start of the model to replace the operator responsible for loading Press 3 can be seen in Table 6.1. When the robot was given a cycle time of 7.2 seconds, equivalent to that of an average operator, the improvement in mean panels per shift was 18.5%. Increasing this cycle time to 10 seconds reduced the gains to just over 12%. Figure 6.2 shows the increases for each of the 10 simulation runs. Again, the lower levels or variability of the robot compared to the manual operation means that increasing the cycle time from 7.2 to 10 seconds still results in an improvement in throughput. However, compared to the previous experiment, increasing the cycle time has had a much larger negative impact on the levels of improvement. This would suggest that the Press 3 load operation is the principal bottleneck on the line.

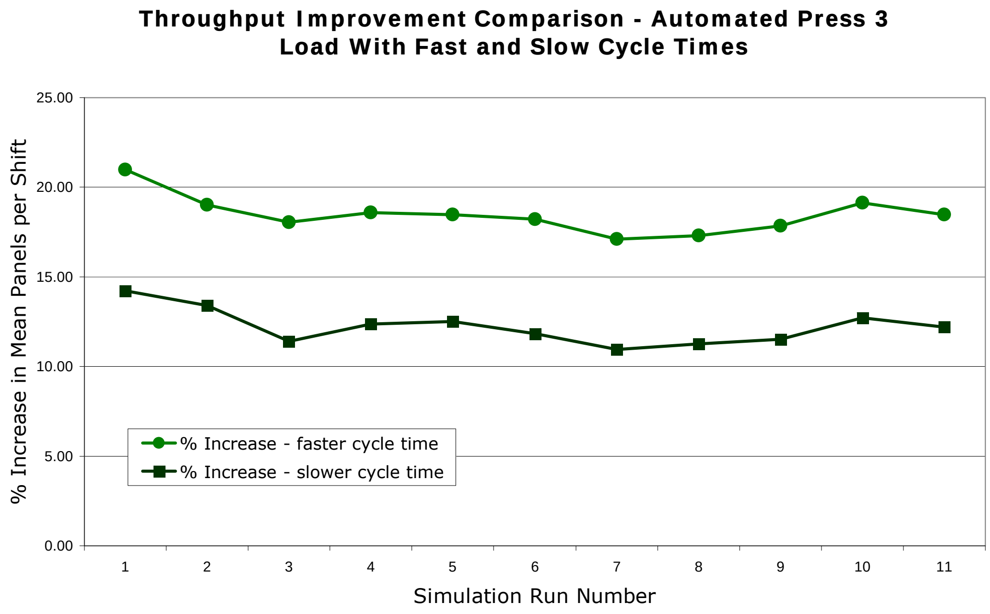

Figure 6.2: Comparison between throughput improvement with slow and fast robot cycle times for Press 3 load

Again, the lower levels or variability of the robot compared to the manual operation means that increasing the cycle time from 7.2 to 10 seconds still results in an improvement in throughput. However, compared to the previous experiment, increasing the cycle time has had a much larger negative impact on the levels of improvement. This would suggest that the Press 3 load operation is the principal bottleneck on the line. This is to be expected following examination of the setup for the part in question. As already stated, part 1018.216 uses automated transfer of the partially completed panels between the presses. These robots are far more consistent than the human operators. Having manual operation with high levels of variability upstream of these robots does lead to variability propagating downstream. This variability then has a negative impact on throughput. This is demonstrated by the dramatic 18% improvement in throughput which results from changing to automated Press 3 loading. Increasing the cycle time of the Press 3 load robot also has a direct affect on the rate of panels arriving at the other three robots, hence the reduction in throughput improvement from 18% to 12%.

6.4. Fully Automated Line – Analysis of Results

This section discusses the results of the third experiment, which involved completely automating the line by replacing both the Press3 load and Press 6 unload human operators with robots. Following the results of the first two experiments dramatic gains in throughput were expected from these runs.

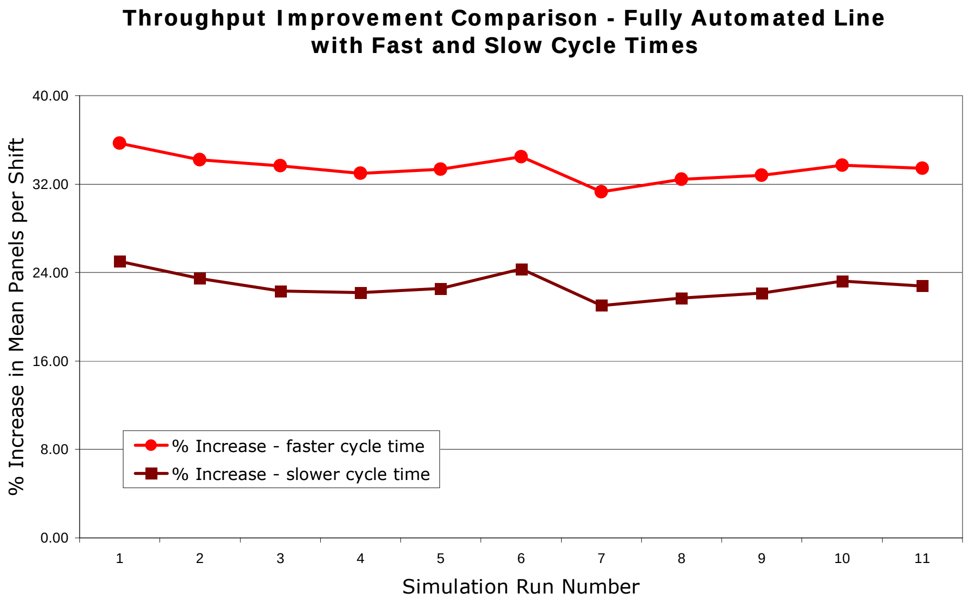

Figure 6.3: Comparison between throughput improvement with slow and fast robot cycle times - fully automated line

Table 6.1 and Figure 6.3 show that this turned out to be the case. Consistent gains averaging 33% across all ten simulation runs were recorded when using the faster robot cycle times from the first two experiments. This figure dropped to just below 23% when the slower cycle times were used. Again, the reduction in improvement when the slower cycle times were used is approximately proportional to the reduction in robot capacity. In this scenario, both principal sources of variability have been removed from the line. Additionally, both constraints identified in the first two experiments have been removed. The benefits of this are obvious from the results of this experiment.

6.5. Comparison Between Press 6 Unload and Press 3 Load Results

As shown in Table 6.1 and discussed in Section 6.4 the modification to the line which had the largest impact on throughput was the addition of robots at both the beginning and end of the line. This effectively automates the line entirely as the transfer of parts between presses was already automated for this part type.

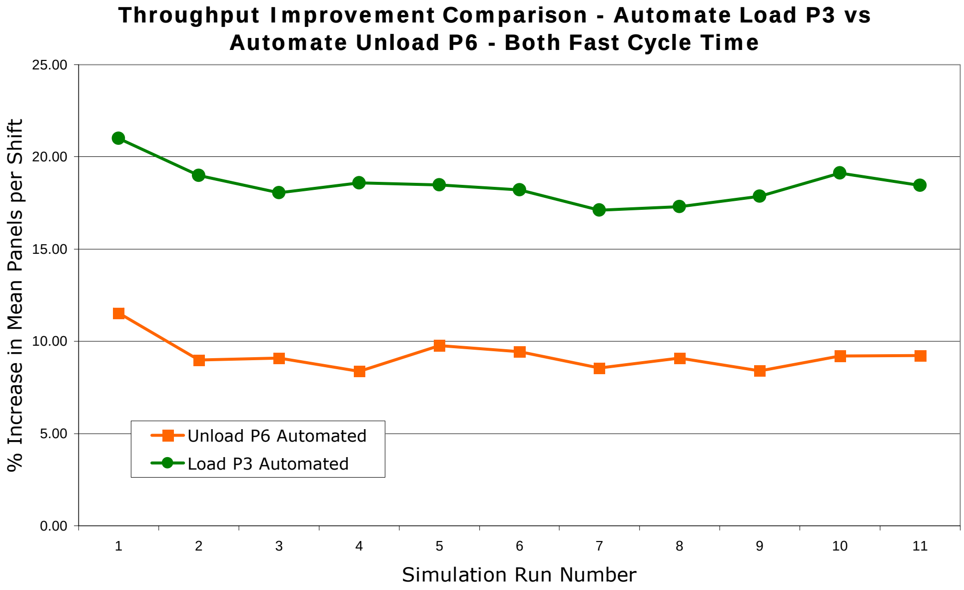

Figure 6.4: Comparison of throughput improvement for Press 3 load and Press 6 unload automation

However, given the fact that investing in robots for both locations may not be justifiable it is useful at this stage to examine and compare the results of automating the first and last steps in the line independently. As Figure 6.4 shows, implementing a robot at the beginning of the line resulted in a larger improvement in throughput than placing the robot at the end. This is most likely due to the fact that the unload Press 6 robot is still dependent on the inconsistent manual loading of Press 3 at the start of the line.

These results bear out the methods recommended in the theory of constraints, which states that upstream constraints should always be addressed before downstream ones. This is because improvements at or near the start of the line propagate throughout the remainder of the line. On the other hand improvements at or towards the end of the line which may seem to be of a similar magnitude when taken in isolation will often have less impact on overall line performance as they may be affected by upstream bottlenecks or constraints. It could be argued that the decision to implement Press 3 load automation ahead of Press 6 unload automation could have been made without the aid of simulation. However, the results of the simulation back up the theory of constraints and give the user confidence in the decision.

The case for the Press 3 load robot is further strengthened when the difficulty of implementing each option is considered. Almost all material which is loaded into Press 3 is in the form of flat metal sheets. This means only one or two fixtures for the robot would be needed. The operation is very simple and is the same for all parts; the metal sheet is picked from the bale and placed in the press. The height and exact position may change depending on the die in question but the general movement is constant. Contrasting this with the situation at the end of the line; parts are obviously fully formed at this stage so each one is a different shape coming out of Press 6. This means that several different fixtures for the robot would have to be designed in order to handle the different part types. These would have to be swapped along with the dies and existing robot fixtures at each changeover. Additionally, each part has a different stillage with the parts arranged differently. In fact some parts can have more than one type of stillage and stacking arrangement. This would be very difficult to automate. Another issue that would have to be overcome is that the stillage would have to be very accurately positioned for the robot to stack the parts correctly and safely. Given the points outlined above, the only logical choice would be to place the robot in front of Press 3 and continue with manual unloading of Press 6. It is anticipated that this would result in an 18% increase in the mean number of panels produced per shift, which is a significant improvement.

7. Conclusions and Future Work

The objective of designing and constructing a flexible simulation model was met. The model of the press transfer line was successfully implemented. A comprehensive database was built which acts as the user's interface with the model. The flexible model can deal with variations in layout, process flow, part type, scheduling and many other parameters without any physical modifications. The model was used for experimental work on the main press line of Läpple Ireland. The results of these experiments were in line with the finding of other researchers in the area of discrete event simulation modelling of manufacturing systems.

Summary of Simulation Modelling Work:

A simulation model of a batch style transfer line was designed, built, tested and used for experimental work. This model was built with maximum flexibility and functionality in mind. It is capable of dealing with all four layouts, both automated and manual part transfer, single or double stage pressing and all 35 part types found in the Carlow plant without modification. Although building such flexibility into a simulation model is more difficult and labour intensive than building separate models for each scenario, it has certain advantages which together make it a superior solution. One advantage is that the user does not need to be a simulation expert to run the model for different part types and layouts and collect and analyse the results. Also, unlike in the case where separate models are used, it is possible to decide on a production schedule which includes any mixture of part types for any number of shifts. This schedule is placed in an Excel sheet with is exported to the model and used as a model input. When the model has finished running the results can be exported back to Excel for processing and analysis. Additionally, virtually any 'what if' scenario can be easily assessed without physical modification to the model itself.

Features of Results from Press Transfer Line Simulation:

1. The effect of replacing the existing manual unloading of fully formed parts from the end of the line with an automated robot was determined as being in the order of 9%.

2. The result of installing a robot at the start of the line to automate the current manual loading of Press 3 was predicted as 18%.
3. The improvement on throughput of the press line which would result from automating both Press 6 unload and Press 3 load was investigated and found to be 33%.
4. A recommendation was made that given the choice between automating Press 6 unload and Press 3 load that the latter would be more beneficial in terms of line throughput and also easier to implement.
5. The effect on the throughput of the press line when the additional robots could not perform the task as quickly as manual operators was modelled. It was found that throughput would still increase, though not to the same extent as stated in points 1-3 above.

Comparison with Existing Research:

The findings from points 1-3 in the previous section which report an increase in throughput following automation are in line with similar research into the area of automating material and part handling tasks [36]. Although Ramírez [35] reported a slight decrease in throughput following his initial experiments, this reduction can be explained by the simultaneous adoption of JIT techniques to vastly reduce WIP on the line. In that case the reduction of WIP and implementation of JIT was of primary concern and the slight reduction in throughput was acceptable. Ramírez ran additional experiments which increased the amount of WIP allowed on the line and the results of these simulation runs showed an increase in throughput of the line as was also seen in this case.

The findings from point 5 above demonstrate the negative effects of high process time variability on the line throughput as described by Johnson [16]. In this case increasing the robot cycle time to approximately 20% slower than the manual equivalent still resulted in an overall increase in throughput. This correlates with Johnson's assertion that reducing the inherent variability in a manufacturing system improves the overall system performance. This shows the importance of minimising variability in manufacturing systems, even at the expense of maximum speed.

Limitations of the Simulation Model:

While the simulation study had a positive outcome overall, there are some shortcomings in the model which should be stated at this stage. The principal example of this is in the model validation stage. At this stage the model outputs were compared to a validation data set gathered from the actual system. The model results were found to deviate from the actual system outputs, therefore certain model parameters were changed slightly. Ideally the second set of validation runs would have used a second set of validation data gathered from the line. However this was not possible as all available data had been used to make up the first validation data set. Therefore this validation data set was used for the second set of runs also. The possible implication of this is that the model may be calibrated to this set of data and may not actually be representative of the actual system as a whole.

Future Work:

The model has potential for use in further simulation studies. There is scope for further experiments on the existing model with the part type used for this research. Further strategies could be identified and evaluated easily.

Also, the model was designed and built specifically to be capable of dealing with all layouts and part types found in the Carlow plant without modification. Therefore extending the experimental stage to cover different part types is straightforward.

As stated in Section 3.1, Läpple is a global company with several metal panel stamping plants worldwide. The elements of these lines are essentially the same as in the Carlow plant, comprising of presses, robots, operators, stillages and conveyors. Therefore the simulation model could be used to study any of these production facilities with only minor modifications to reflect the individual characteristics of the line in question.

With slightly more modification the model should be able to simulate any transfer line as the basic structure of a transfer line is in place already.

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Appendix A – Complete Extend Model of Press Line

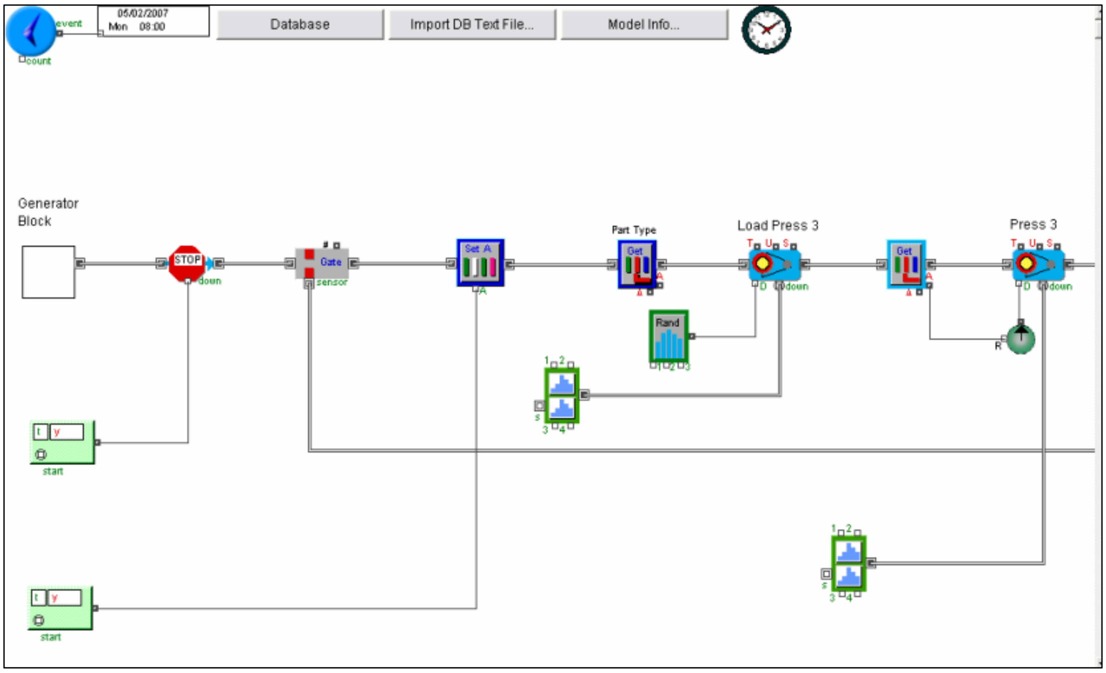


Figure A.1: Extend Model From Generator Block to Press 3 Block

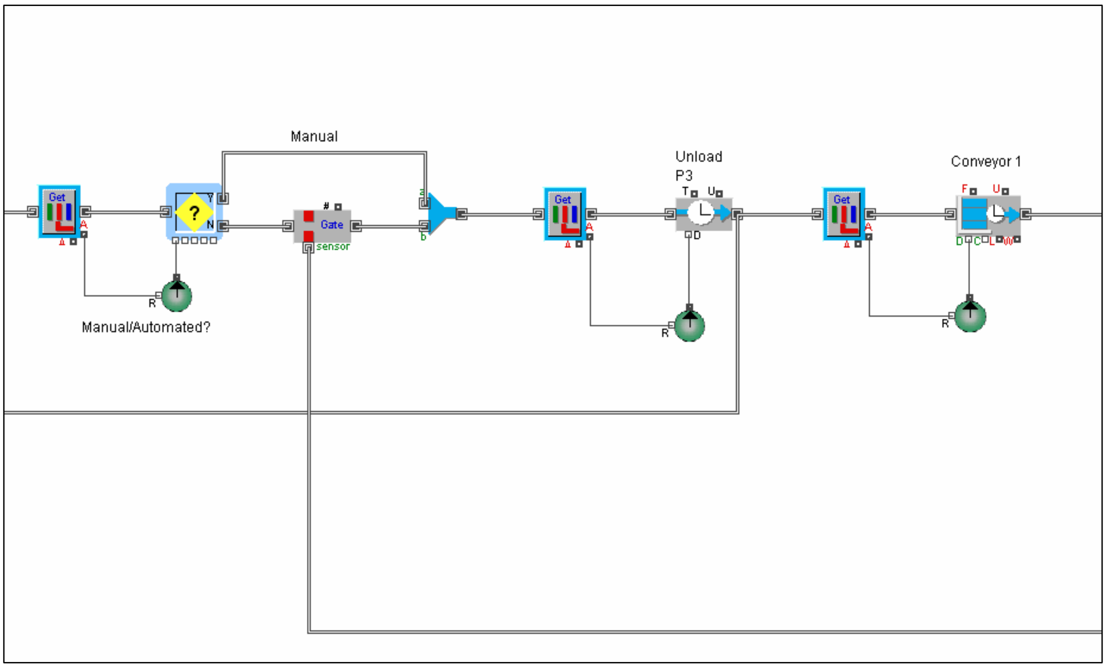


Figure A.2: Press 3 Unload and Conveyor 1

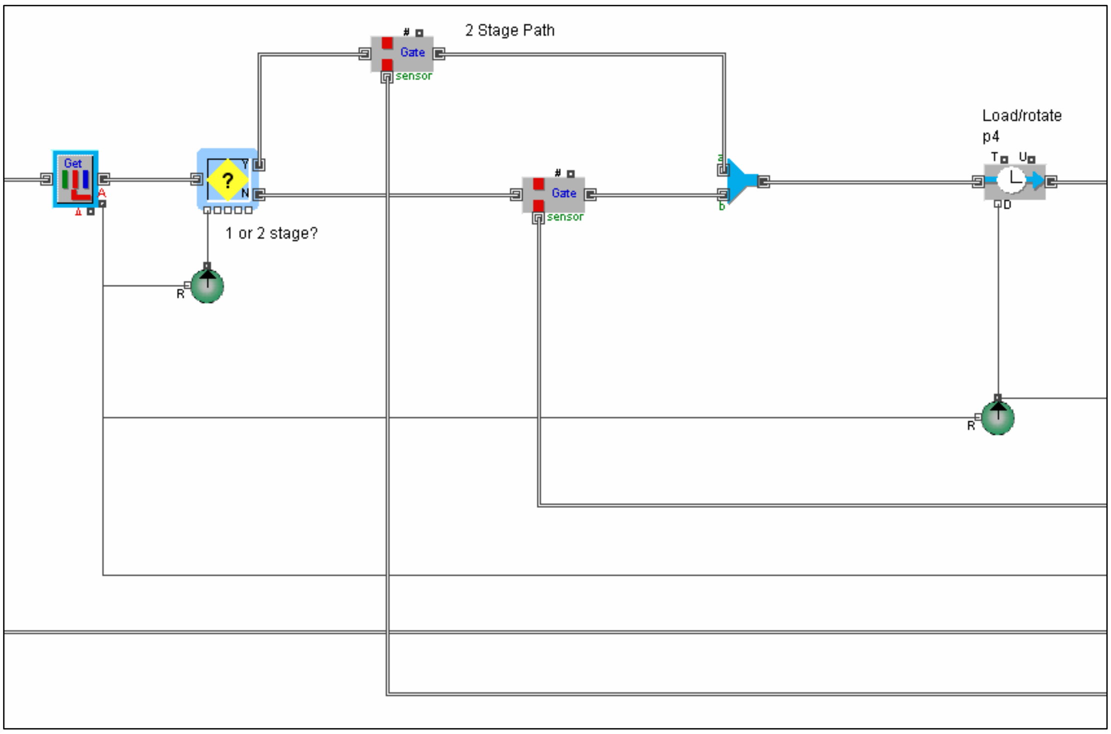


Figure A.3: Leading to Press 4, including gates for pressing stages

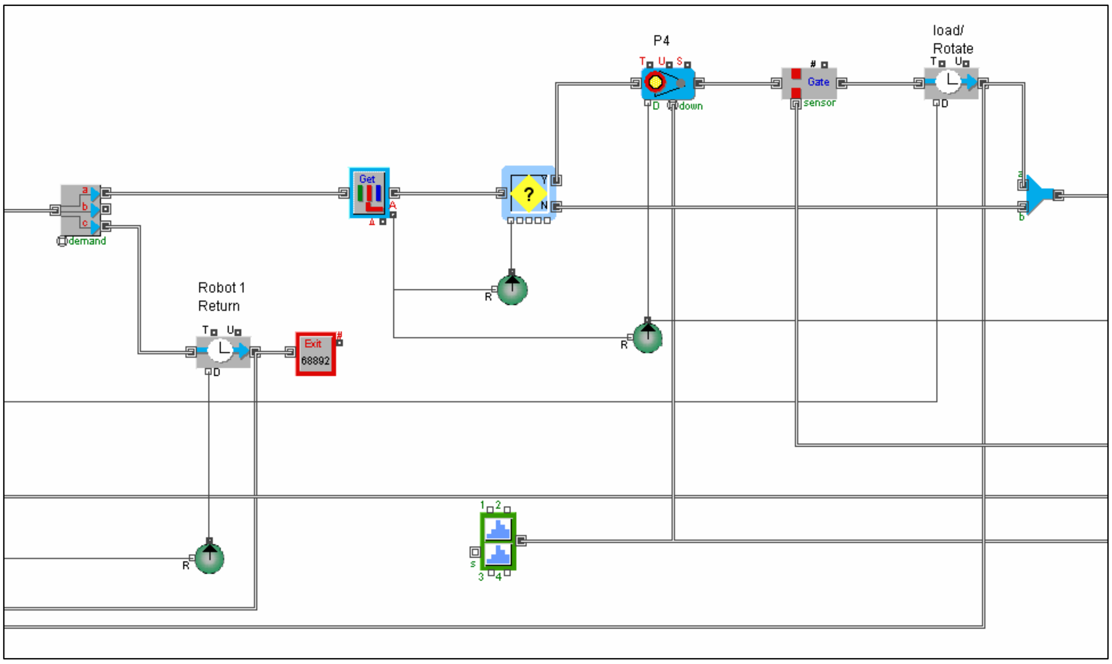


Figure A.4: Robot 1 return dummy path and first Press 4 stage.

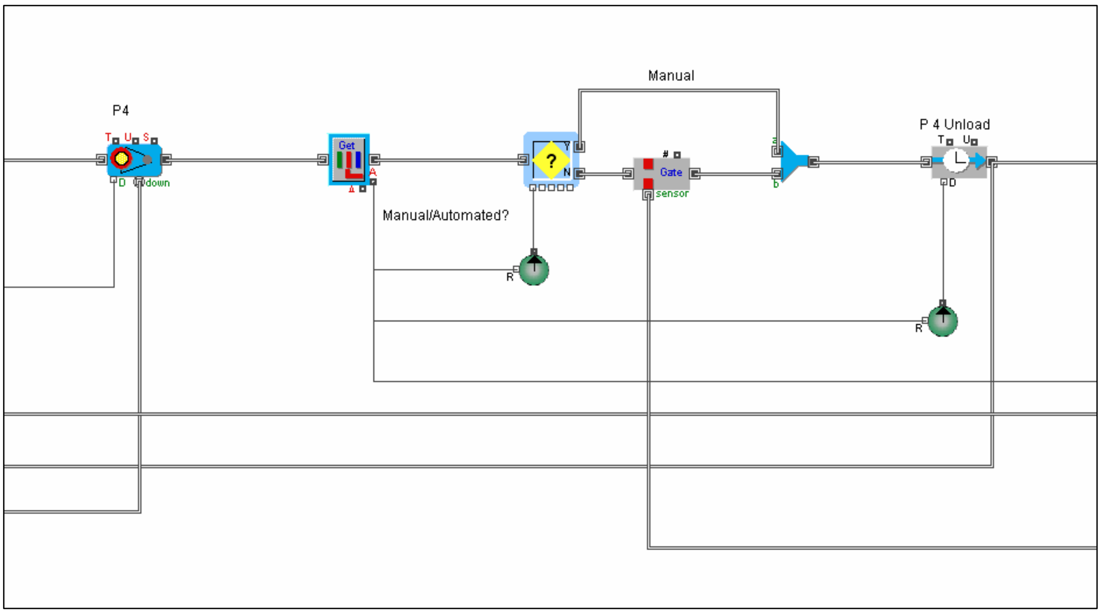


Figure A.5: Second Press 4 stage and Press 4 unload

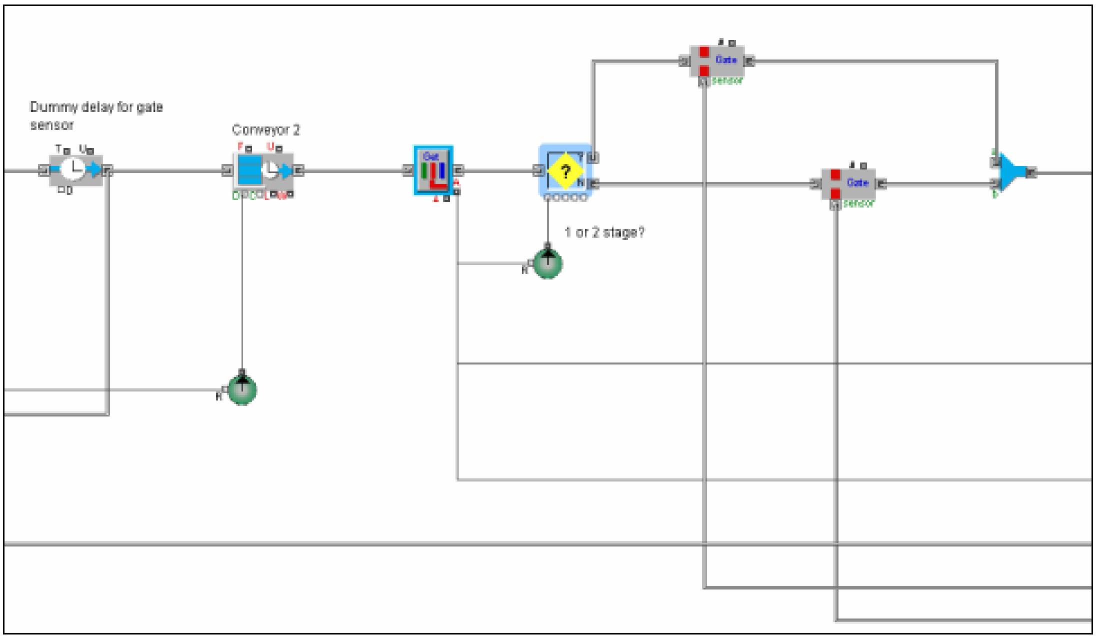


Figure A.6: Conveyor 2 and decision and gates for Press 5 stages.

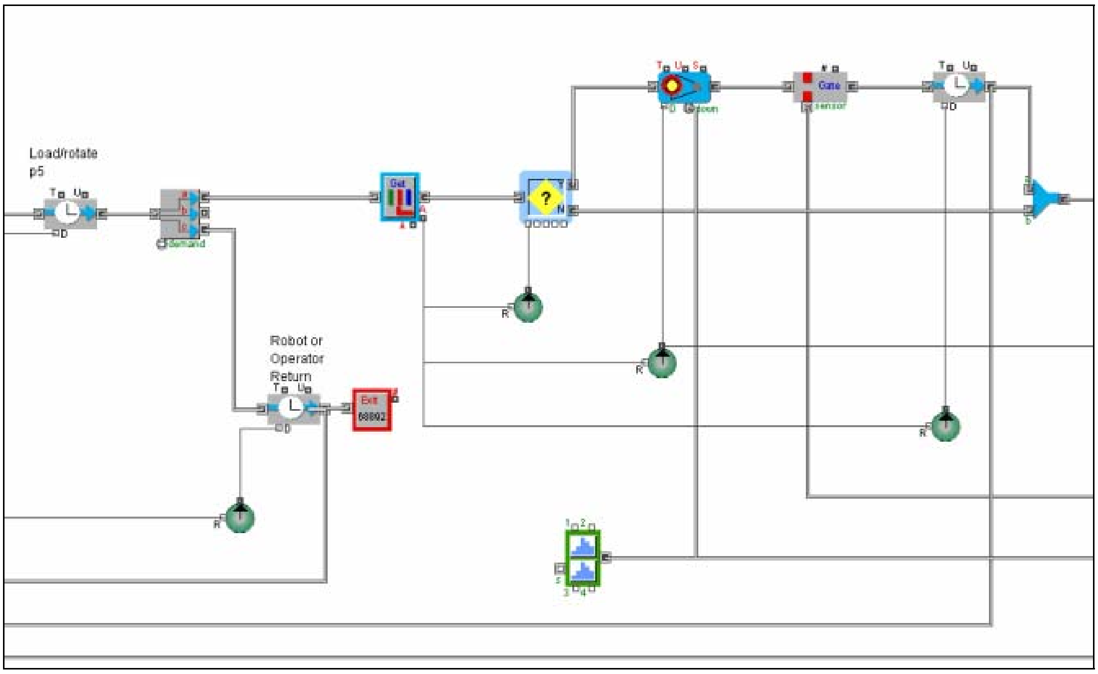


Figure A.7: Load Press 5 and first pressing stage.

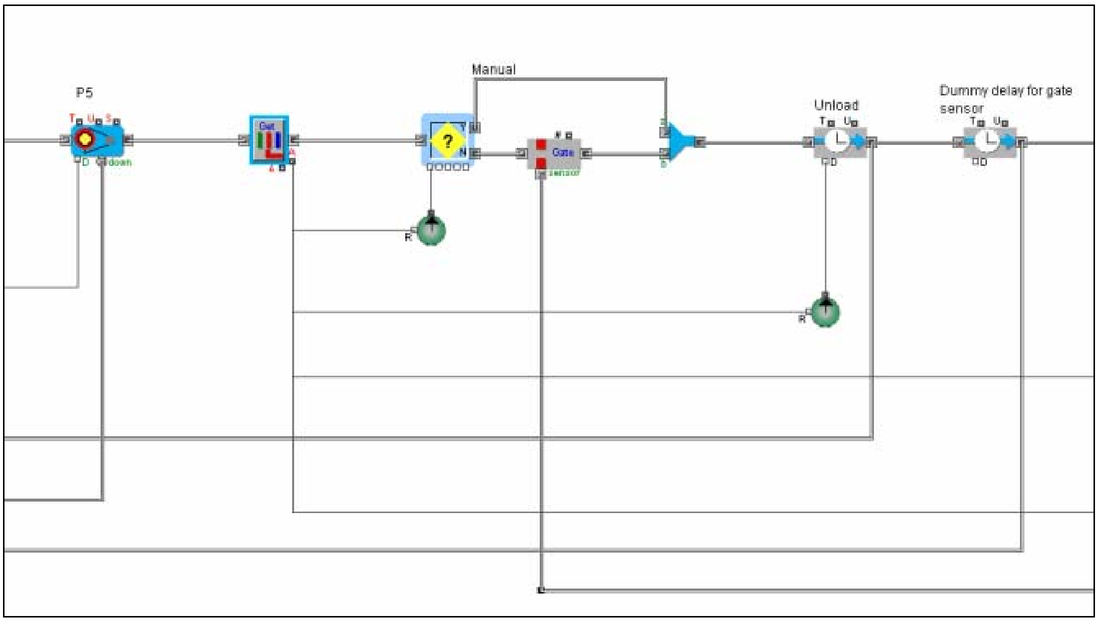


Figure A.8: Press 5 and Press 5 unload.

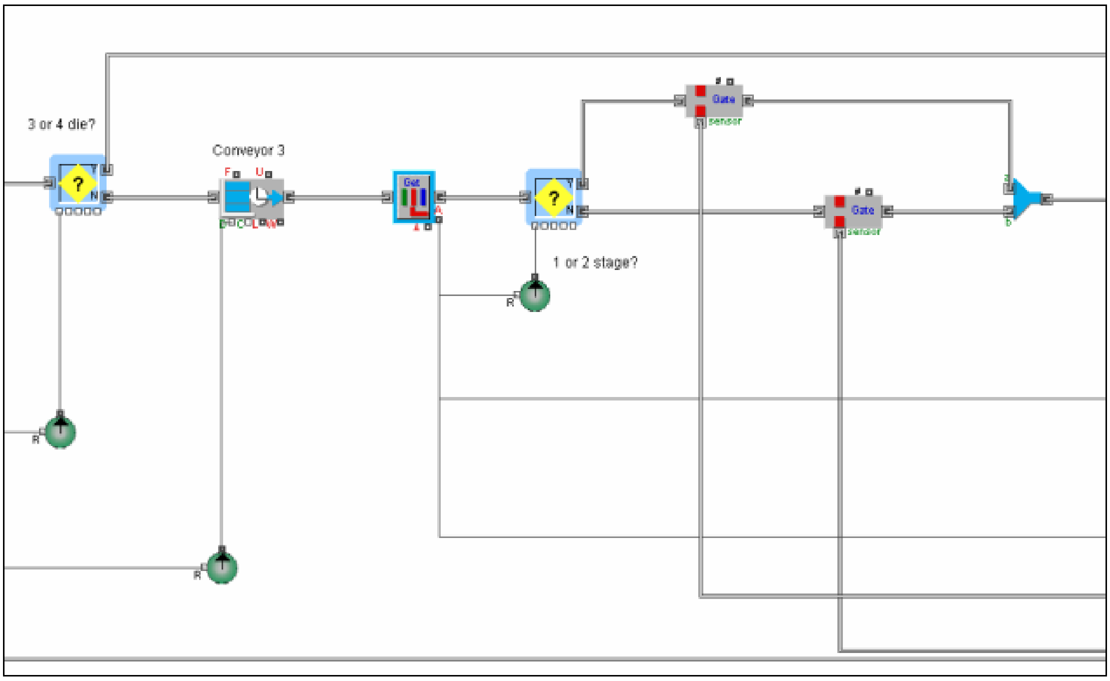


Figure A.9: 3 or 4 die decision block and routing and conveyor 3.

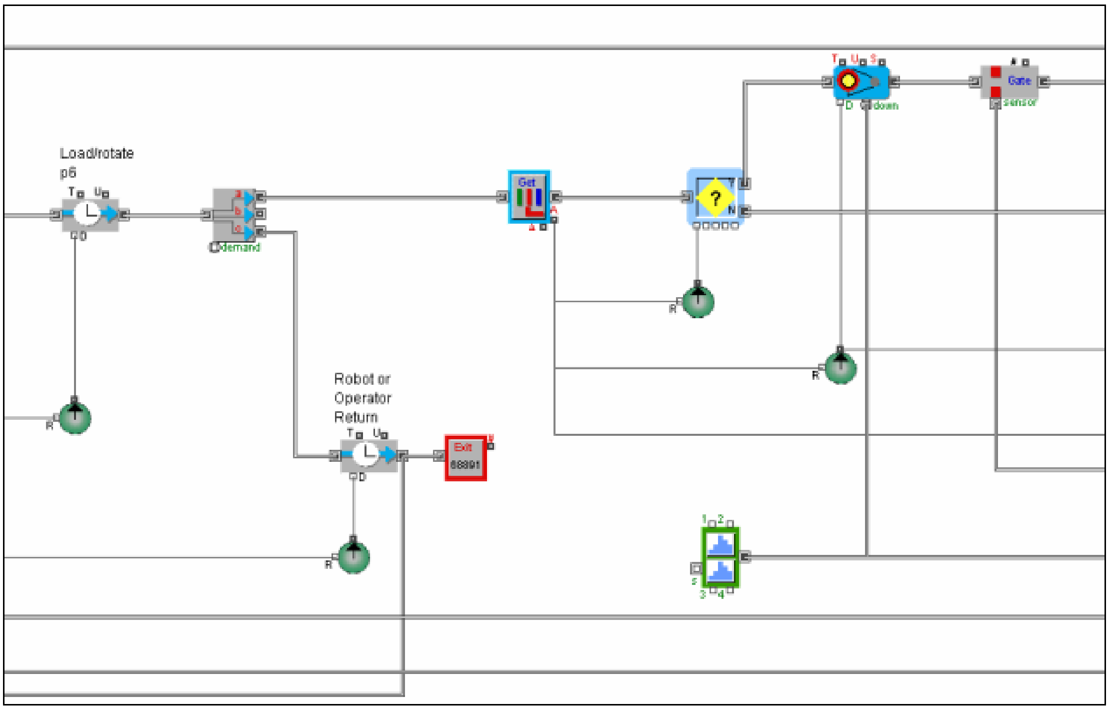


Figure A.10: Load Press 6 and first pressing stage.

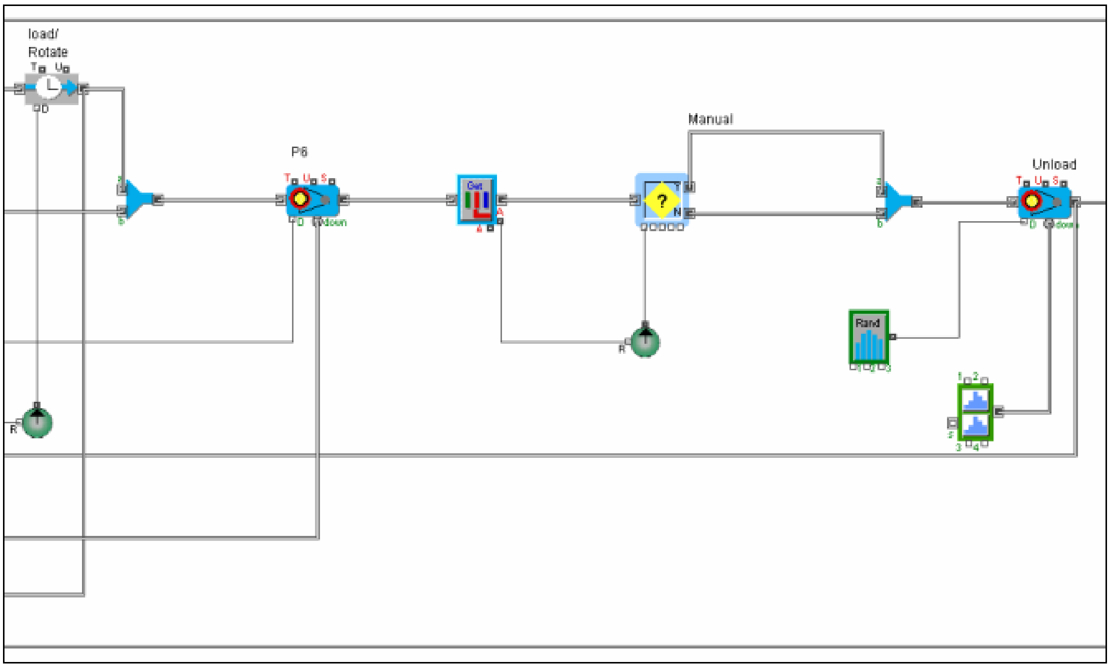


Figure A.11: Press 6 and Press 6 unload.

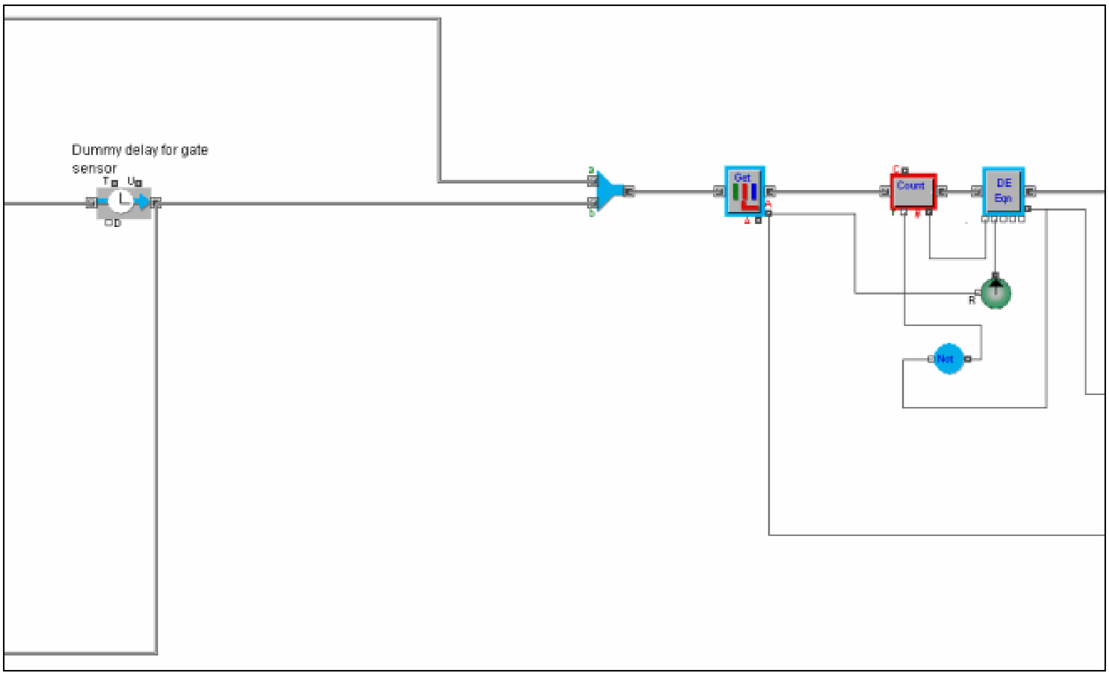


Figure A.12: Combine block for 3 die line output and logic setup for panel count for filling stillages.

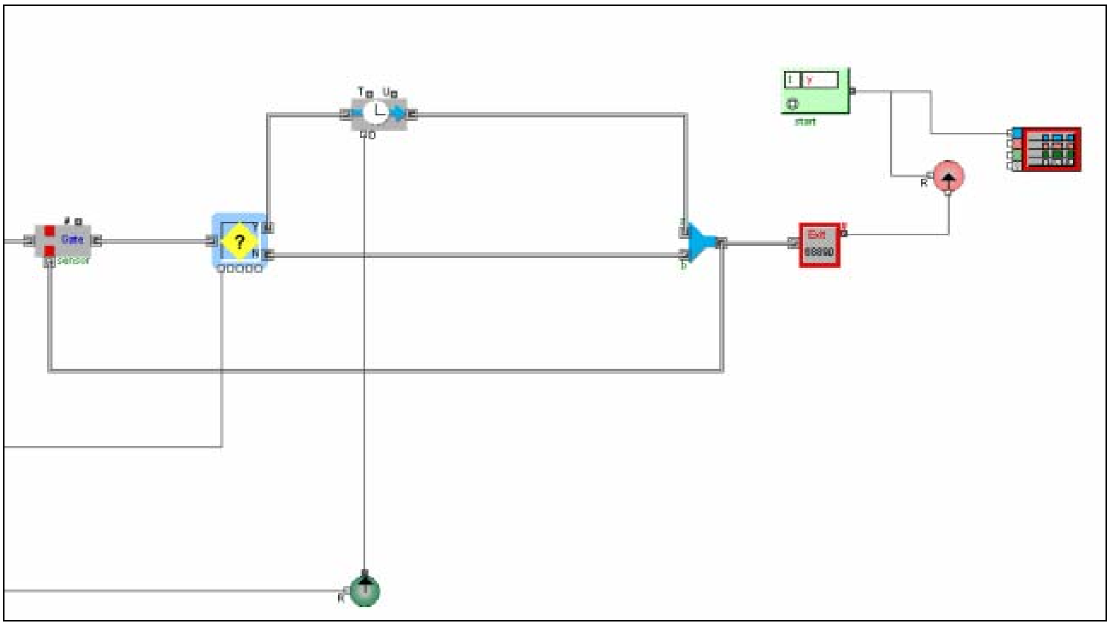
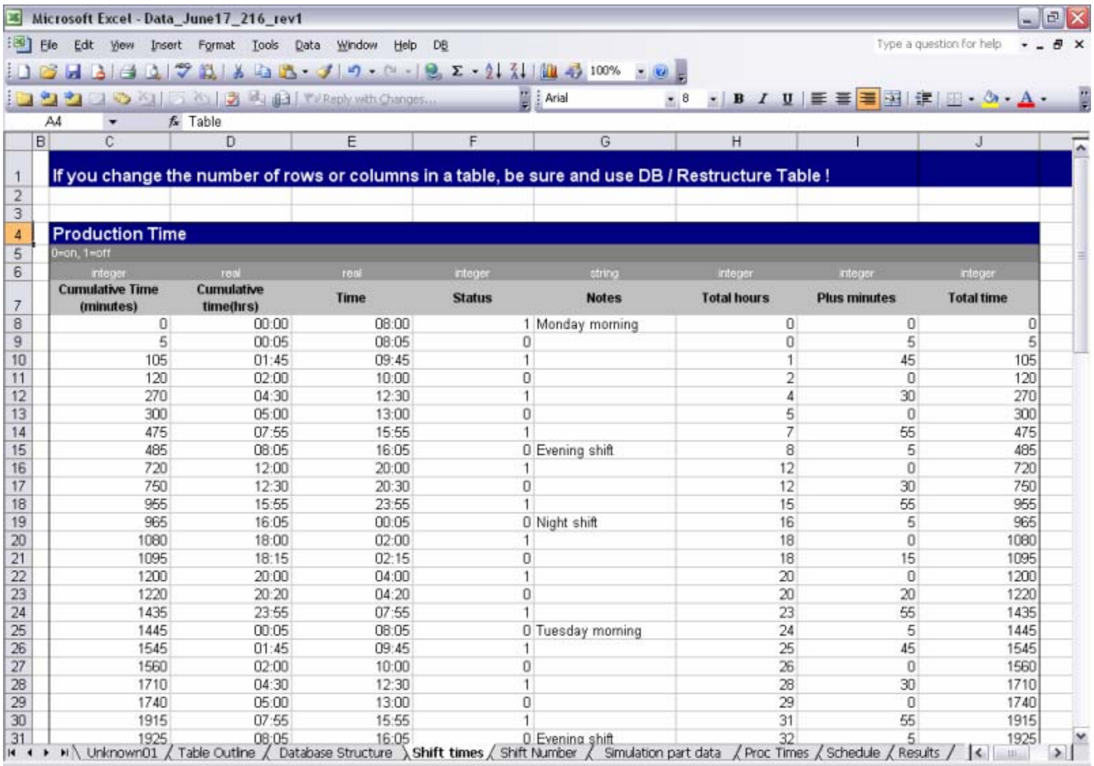


Figure A.13: Stillage change delay and end of line with shift counter.

Appendix B – Sample Model Database



Production Time

0=on, 1=off

Cumulative Time (minutes)	Cumulative time(hrs)	Time	Status	Notes	Total hours	Plus minutes	Total time
integer	real	real	integer	string	integer	integer	integer
0	00:00	08:00	1	Monday morning	0	0	0
5	00:05	08:05	0		0	5	5
105	01:45	09:45	1		1	45	105
120	02:00	10:00	0		2	0	120
270	04:30	12:30	1		4	30	270
300	05:00	13:00	0		5	0	300
475	07:55	15:55	1		7	55	475
485	08:05	16:05	0	Evening shift	8	5	485
720	12:00	20:00	1		12	0	720
750	12:30	20:30	0		12	30	750
955	15:55	23:55	1		15	55	955
965	16:05	00:05	0	Night shift	16	5	965
1080	18:00	02:00	1		18	0	1080
1095	18:15	02:15	0		18	15	1095
1200	20:00	04:00	1		20	0	1200
1220	20:20	04:20	0		20	20	1220
1435	23:55	07:55	1		23	55	1435
1445	00:05	08:05	0	Tuesday morning	24	5	1445
1545	01:45	09:45	1		25	45	1545
1560	02:00	10:00	0		26	0	1560
1710	04:30	12:30	1		28	30	1710
1740	05:00	13:00	0		29	0	1740
1915	07:55	15:55	1		31	55	1915
1925	08:05	16:05	0	Evening shift	32	5	1925

Figure B.1: Screenshot of model database showing different worksheets for different types of data

Part Data

Part	Man/Auto	No of Dies	Sheets/Bale	Slots/Stillage	No of Stillages on line	Total number of slots	Press 3 stages	Press 4 Stages
	Auto = 1 Man = 0							
string	integer	integer	integer	integer	integer	integer	integer	integer
changeover	0	0	1	0	0	0	0	0
1018.11	0	3	250	56	2	112	1	2
1018.224	1	3	190	80	1	80	1	1
1018.216	1	4	300	200	1	200	1	1
1018.111	0	3	250	56	2	112	1	2
1018.132	1	3	0	0	0	0	1	1

Figure B. 2: Sample extract from database showing model input data for different part types

Processing Times (Minutes)

Part	Attribute	Changeover Time	Bale Change Time	Press 3 Load	Press 3 Cycle	Press 3 unload	Conveyor 1	Press 4 Load	Return to P3	Press 4 Cycle	Press 4 Unload	Conveyor 2
string	integer	real	real	real	real	real	real	real	real	real	real	real
changeover	1	75.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1018.11	2	0.000	5.000	0.125	0.167	0.070	0.167	0.250	0.010	0.133	0.083	0.167
1018.224	3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1018.216	4	0.000	5.000	0.120	0.156	0.060	0.000	0.060	0.060	0.132	0.060	0.000
1018.111	5	0.000	5.000	0.083	0.167	0.077	0.167	0.250	0.000	0.133	0.108	0.167

Figure B. 3: Database extract showing processing times

Production Results		
0=on, 1=off		
integer	integer	integer
Shift Number	**Panels Produced**	**Per Shift**
1	1483	1483
2	2174	691
3	2929	755
4	3674	745
5	4326	652
6	5024	698
7	5702	678
8	6464	762
9	7179	715
10	7846	667
11	8449	603
12	9053	604
13	9740	687
14	10381	641
15	11063	682
16	11784	721
17	12459	675
18	13134	675
19	13810	676
20	14520	710
21	15234	714
22	15987	753
23	16767	780
24	17486	719

Figure B. 4: Production results list from database

Appendix C – Examples of Data Sources

- Production Analysis Report -

PressShop - Large Presses

FBK No	Panel No	Panel Name	Prod Mins	DT mins	Setup	Quantity	Partial Qty	Panel/Hour	Target
16838	P1018.145	FILLER FLOOR PAN	4.00	0.00	0.00	0.00	0.00	0.00	140.00
16886	P0250.131.40	MAIN COVER	0.00	0.00	45.00	0.00	0.00	0.00	140.00
16921	A1018.178.RH	D/CAB DOOR OPENING PANEL RH	0.00	0.00	73.00	1000.00	0.00	0.00	140.00
16922	P1018.111.LH	PILLAR REAR CORNER OUTER LH	1032.00	82.00	0.00	1075.00	0.00	62.50	140.00
16923	P1018.145	FILLER FLOOR PAN	1367.00	0.00	0.00	2100.00	20.00	93.05	140.00
16926	P1018.217	REINF FRONT SIDE MEMBER	532.00	0.00	85.00	900.00	0.00	101.50	140.00
16927	P1018.211A	HEATER PLENUM CHAMBER FRT	489.00	0.00	55.00	720.00	100.00	100.61	180.00
16928	A1018.224	STORAGE TRAY	875.00	33.00	97.00	240.00	36.00	18.93	140.00
16930	A4209.001.20	STAINLESS BELLYBANDS	201.00	0.00	0.00	112.00	0.00	33.43	140.00
16931	A4209.001.10	STAINLESS BELLYBANDS	1150.00	0.00	0.00	250.00	0.00	13.04	140.00
16932	A4209.005.20	GALFAN BELLYBANDS	660.00	0.00	0.00	180.00	0.00	16.36	140.00
16933	A4209.005.10	GALFAN BELLYBANDS	0.00	0.00	0.00	45.00	0.00	0.00	140.00
16934	P1018.106	PANEL ROOF (SGN CAB)	363.00	0.00	47.00	553.00	0.00	91.40	80.00
16935	P1018.107	ROOF (SGN CAB) LESS HOLES EVE	142.00	0.00	102.00	214.00	0.00	90.42	80.00
16936	P1018.110.RH	PILLAR REAR CORNER OUTER RH	638.00	0.00	0.00	235.00	0.00	22.10	140.00
16937	P1018.216	HEATER PLENUM	0.00	0.00	425.00	0.00	0.00	0.00	140.00
16941	P1018.211A	HEATER PLENUM CHAMBER FRT	0.00	0.00	62.00	757.00	0.00	0.00	180.00
16943	P1018.209.RL	EXT FRONT FENDER APRON RL	123.00	0.00	204.00	575.00	0.00	280.49	140.00
16949	A1018.139.LH	DOOR INNER PANEL LH	624.00	0.00	182.00	275.00	0.00	26.44	140.00
16951	A1018.166.RL	PANEL BDY REAR CORNER UPPER R	156.00	77.00	117.00	362.00	0.00	139.23	140.00
16954	P1018.211A	HEATER PLENUM CHAMBER FRT	336.00	0.00	94.00	862.00	0.00	153.93	180.00
16955	A1018.138.RH	DOOR INNER PANEL RH	351.00	0.00	15.00	604.00	0.00	103.25	140.00
16956	P1018.211B	HEATER PLENUM CHAMBER FRT	759.00	0.00	83.00	0.00	0.00	0.00	180.00
16957	P1018.106	PANEL ROOF (SGN CAB)	712.00	89.00	523.00	826.00	0.00	69.61	80.00
16958	P1018.107	ROOF (SGN CAB) LESS HOLES EVE	228.00	0.00	100.00	463.00	0.00	121.84	80.00
16961	P1018.208.LH	REINF PANEL COWL SIDE	570.00	94.00	137.00	1650.00	0.00	173.68	140.00
16962	P1018.105.30	PANEL ROOF	189.00	0.00	433.00	277.00	0.00	87.94	80.00
16963	P1018.105.20	PANEL ROOF	329.00	99.00	118.00	281.00	0.00	51.25	80.00
16964	P1018.111.LH	PILLAR REAR CORNER OUTER LH	222.00	0.00	529.00	1088.00	5.00	295.41	140.00
16970	P0250.131.40	MAIN COVER	434.00	0.00	1.00	484.00	0.00	66.91	140.00
16971	P0250.131.20	MAIN COVER	246.00	0.00	113.00	365.00	0.00	89.02	140.00
16972	P1018.145	FILLER FLOOR PAN	2392.00	0.00	472.00	3900.00	0.00	97.83	140.00
16973	P1018.106	PANEL ROOF (SGN CAB)	548.00	0.00	112.00	1081.00	0.00	118.36	80.00
16974	P1018.107	ROOF (SGN CAB) LESS HOLES EVE	310.00	0.00	0.00	510.00	0.00	98.71	80.00
16976	P1018.217	REINF FRONT SIDE MEMBER	853.00	68.00	105.00	1756.00	0.00	123.52	140.00
16977	P1018.207.RH	REINF PANEL COWL SIDE	581.00	0.00	18.00	1331.00	0.00	137.45	140.00
16978	P1018.211B	HEATER PLENUM CHAMBER FRT	165.00	0.00	78.00	0.00	0.00	0.00	180.00
16979	P1018.211B	HEATER PLENUM CHAMBER FRT	618.00	0.00	52.00	287.00	0.00	27.86	180.00
16980	A1018.201	ASSY LOWER CHANNEL	1480.00	0.00	196.00	1887.00	0.00	76.50	140.00
16981	A1018.202	ASSY BRACKET RETRACTOR	335.00	0.00	0.00	0.00	0.00	0.00	140.00
17065	A1018.139.LH	DOOR INNER PANEL LH	117.00	48.00	0.00	200.00	0.00	102.56	140.00
17067	P1018.209.RL	EXT FRONT FENDER APRON RL	636.00	0.00	179.00	1715.00	0.00	161.79	140.00
17072	A1018.166.RL	PANEL BDY REAR CORNER UPPER R	702.00	0.00	0.00	685.00	0.00	58.55	140.00
17075	P1018.208.LH	REINF PANEL COWL SIDE	521.00	0.00	0.00	2000.00	0.00	230.33	140.00
17076	P1018.105.30	PANEL ROOF	185.00	80.00	64.00	215.00	0.00	69.73	80.00
17080	A1018.137.LH	DOOR OUTER GLAZED LH	294.00	0.00	46.00	200.00	0.00	40.82	140.00
17081	A1018.136.RH	DOOR OUTER GLAZED RH	330.00	0.00	0.00	0.00	0.00	0.00	140.00
17082	P1018.217	REINF FRONT SIDE MEMBER	982.00	0.00	118.00	2227.00	0.00	136.07	140.00
17085	P1018.211B	HEATER PLENUM CHAMBER FRT	478.00	0.00	32.00	0.00	0.00	0.00	180.00
		TOTALS	**24259.00**	**670.00**	**5112.00**	**34487.00**	**161.00**	**85.70**	

Figure C.1: Sample Production Analysis Report (truncated)

Production Analysis Report/ Large Presses

Week No.	Shift		Down Time	Set Up Time	Panels Actual	Panels Target	Prod. Hours Actual	Prod. Hours Target
19	A	1	0.5	0.5	720	910	5.5	6.5
	B	2	7.15	3.2	587	1242	4.67	4.9
	C	0						
	Total		*7.65*	*3.7*	*1307*	*2152*	*10.17*	*11.4*
20	A	5	7.41	5.83	3837	3285	23.32	25.66
	B	6	2.93	6	4259	4442	28.12	34.83
	C	4	4.7	0.6	3312	3645	24.95	29.54
	Total		*15.04*	*12.43*	*11408*	*11372*	*76.39*	*90.03*
21	A	7	4.5	5.32	5131	6678	37.57	44.41
	B	6	8.98	2.92	5437	6754	35.25	42.24
	C	6	3.16	8.43	5713	6296	54.35	50.66
	Total		*16.64*	*16.67*	*16281*	*19728*	*127.17*	*137.31*
22	A	7	12.24	2.09	5002	6980	36.3	49.75
	B	7	8.84	9.75	4801	6718	35.98	48.18
	C	5	5.25	9	5379	5835	52.00	55.25
	Total		*26.33*	*20.84*	*15182*	*19533*	*124.28*	*153.18*
23	A	6	6.08	1	4563	5888	32.74	39.66
	B	6	10.49	8.61	3728	6442	29.03	39.95
	C	5	2.91	8.91	7421	7405	64.25	66.50
	Total		*19.48*	*18.52*	*15712*	*19735*	*126.02*	*146.11*

Figure C.2: Sample Prod, Analysis Report, Overall Type

LAPPLE IRELAND LTD CARLOW

PRODUCTION REPORT

POS NO: 1018/216 OP NO's: 20/50 JOB NO: 17003

DATE	SHIFT	HOURS WORKED ON JOB	TOTAL PANELS	DESPATCH PANELS	ASSEMBLY PANELS	PANELS IN PROGRESS	REWORK	DEFECT BLANKS	SCRAP	OP NO.	CHECKED	BALE/CAST NO.	SEQ NO.	ISSUED QTY
15/6/06	12-8		842	841	–	–	–	–	1 op 50	20/50	JS	921513		203
												921515		203
15/6/06	8-4		820	820	–	–	–		–	20/50		921510		227
												921509		227
												921516		203
												889021		314
												911084		208
TOTALS														

Figure C.3: QC Report Sample

Appendix D – Additional Experimental Results

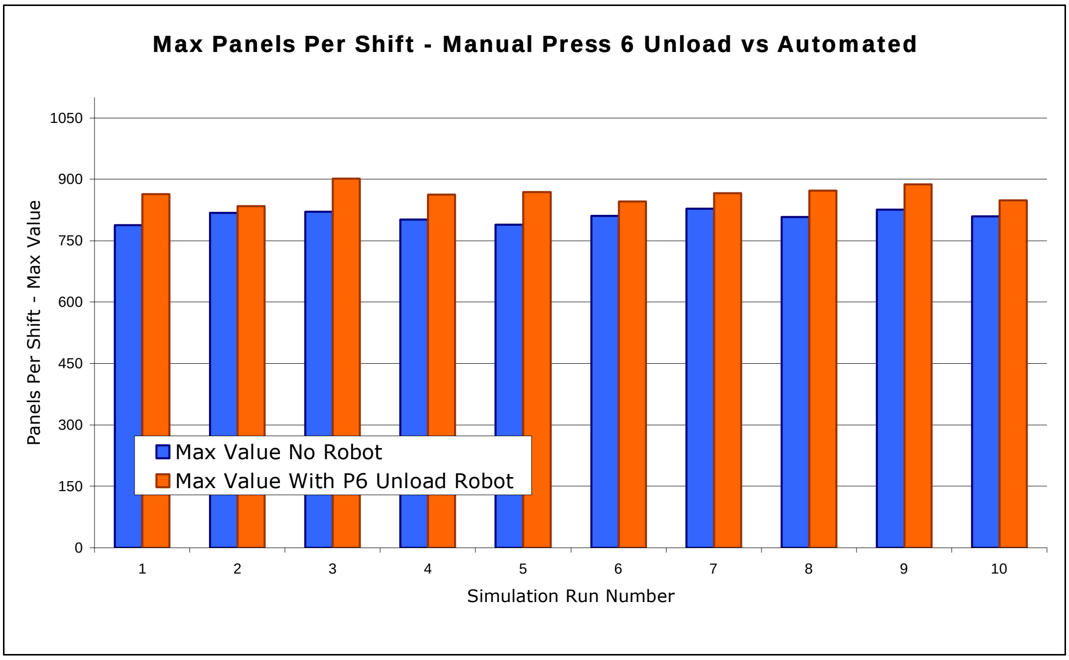


Figure D.1: Max panels produced per shift comparison, experiment 1

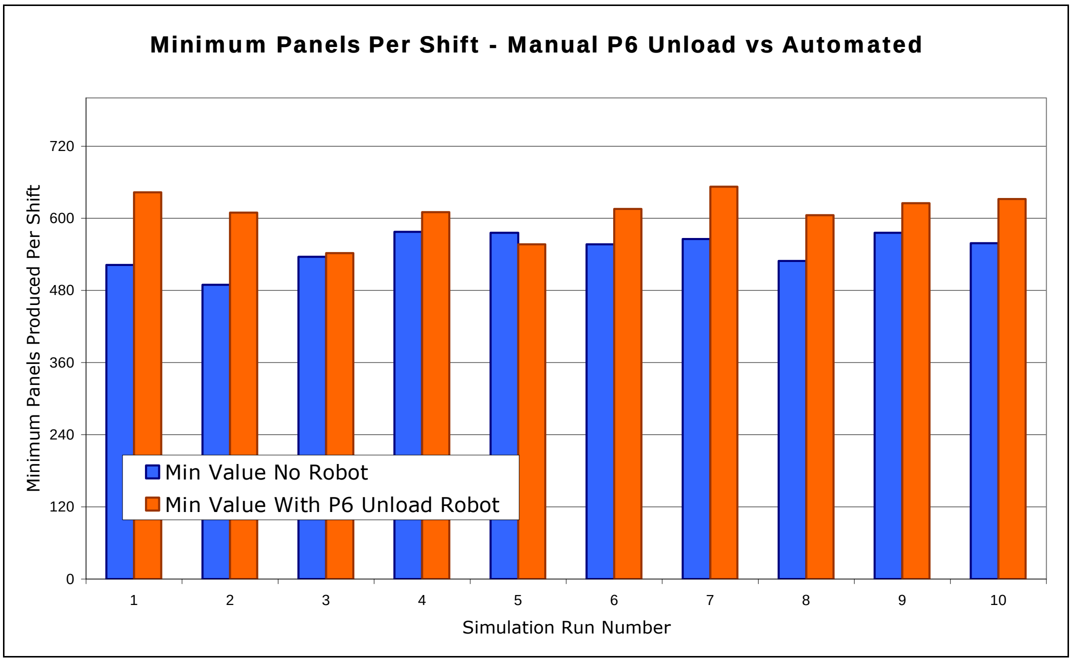


Figure D.2: Minimum panels per shift comparison, experiment 1

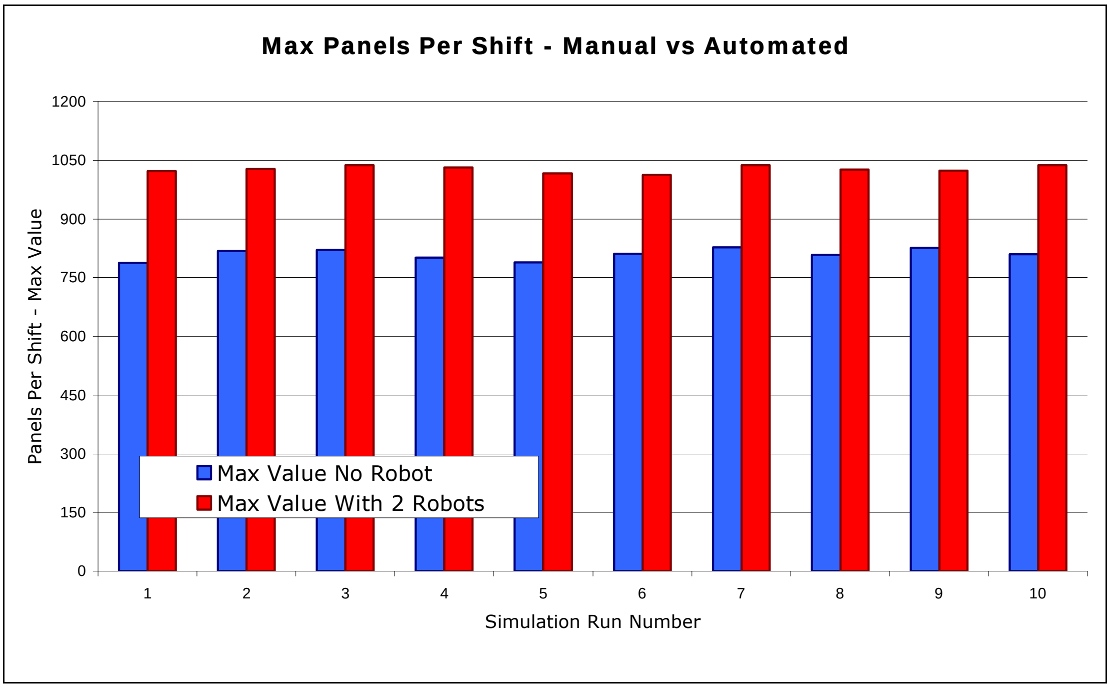


Figure D.3: Max panels produced per shift comparison, experiment 3

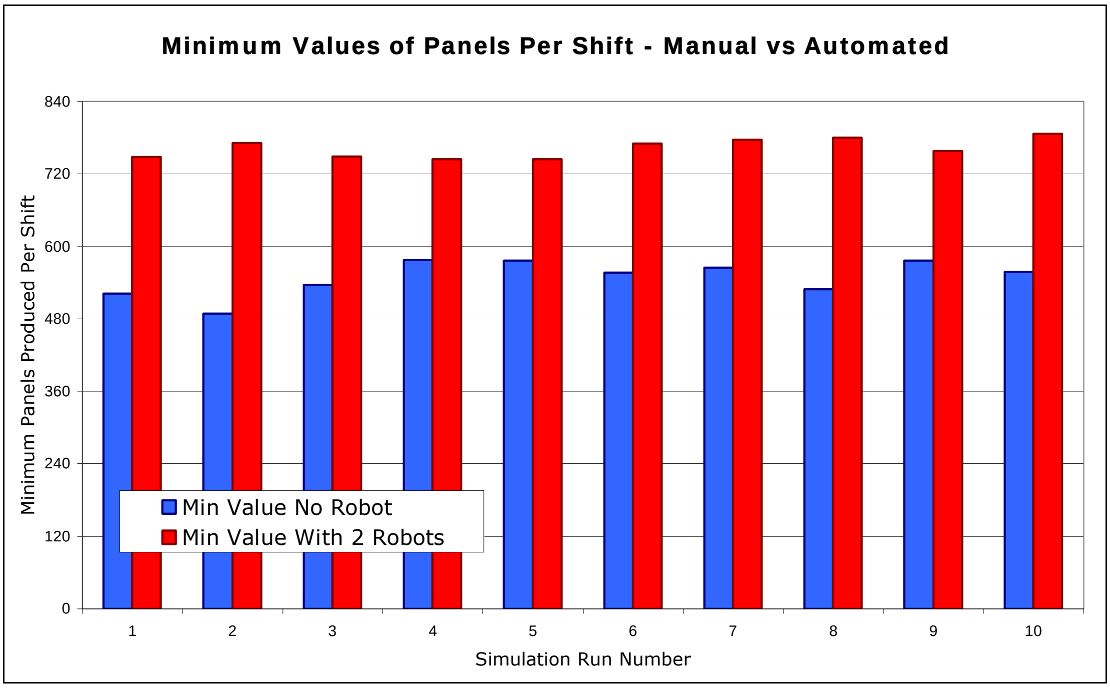


Figure D.4: Min panels produced per shift comparison, experiment 3

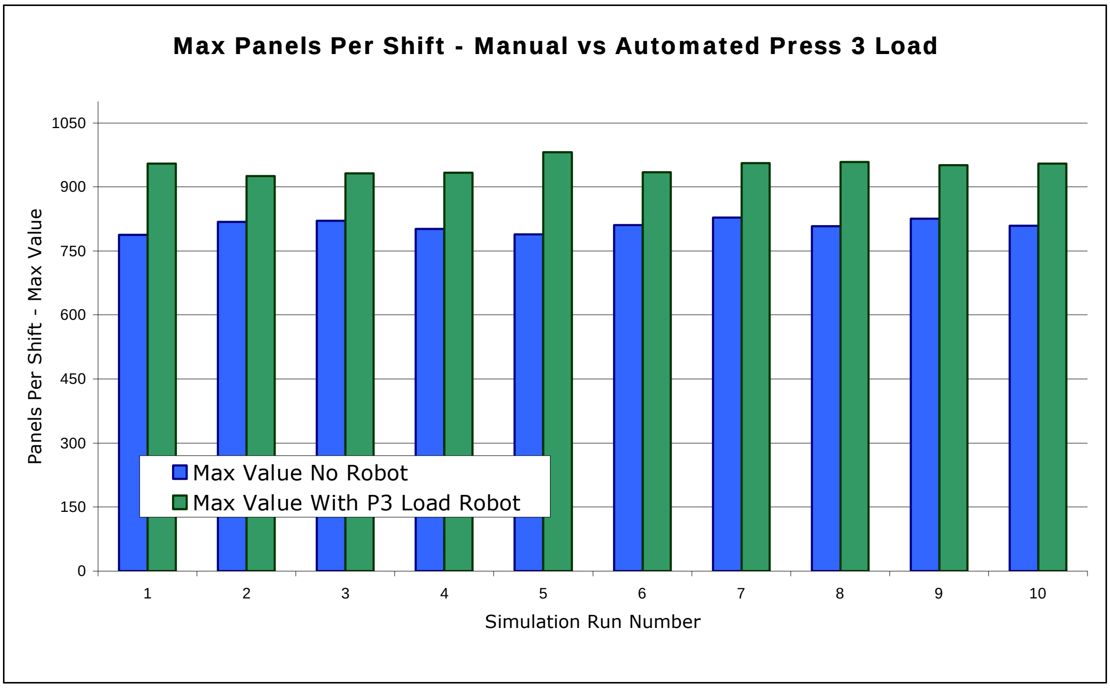


Figure D.5: Max panels per shift comparison, experiment 2

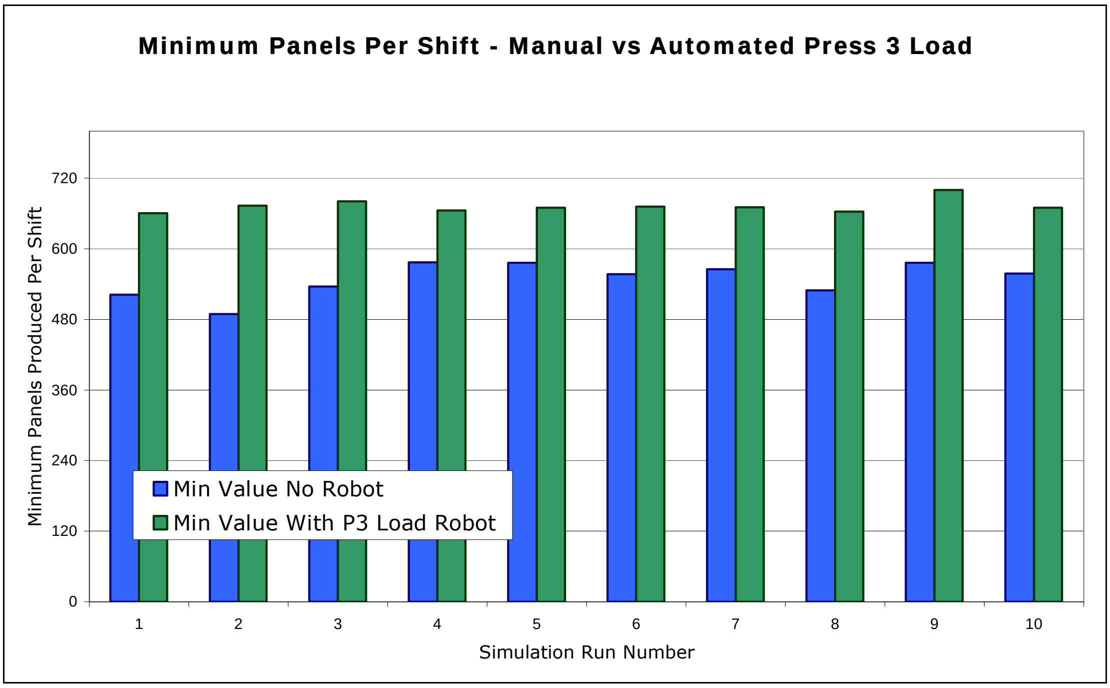


Figure D.6 Min panels produced per shift comparison, experiment 2