SIMULATION OF A FLEXIBLE MANUFACTURING SYSTEM: A PILOT IMPLEMENTATION

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ABSTRACT

SIMULATION OF A FLEXIBLE MANUFACTURING SYSTEM: A PILOT IMPLEMENTATION

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Manufacturing industry has made extensive use of simulation as a means of trying to model the impact of variability on manufacturing system behavior and to explore various ways of coping with change and uncertainty. Simulation helps find optimal solutions to a number of problems at both design and application stages of Flexible Manufacturing Systems (FMS's) serving to improve the "flexibility" level

The flexibility requirement of FMS necessitates the dissemination of every activity that concerns production, throughout all the levels of a company forcing almost every level of employee face with simulation software, either in terms of preparing models, modifying runs or evaluating results. This problem of inadequate capability of personnel to utilize simulation effectively can be overcome through the design of custom interfaces and integration of simulation software with everyday-use programs.

This research mainly focuses on realizing the modeling and simulation of FMS's by the use of the existing system in Middle East Technical University, Mechanical Engineering Department, Computer Integrated Manufacturing Laboratory as a test-bed. Additionally, the means of integration of simulation with auxiliary programs is demonstrated. The models developed throughout the study using ARENA$^{®}$ are used to come up with different scenarios of production. Sample results and decisions about production issues that can be attained through the use of simulation are provided. The described model creation procedures, the generated models, and result assessments are expected to act as a guideline for other simulations regarding FMS's.

Keywords: Simulation, Modeling, Flexible Manufacturing Systems, Integration of Simulation, ARENA$^{®}$

ÖZ

ESNEK İMALAT SİSTEMLERİNİN SİMÜLASYONU: PİLOT UYGULAMA

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Üretim endüstrisi, simülasyonu değişkenliğin üretim sistemi davranışları üzerindeki etkisini modelleyebilme aracı olarak ve değişim ve belirsizliklerle başa çıkmak için çeşitli yollar araştırmak amaçlarıyla kapsamlı bir şekilde kullanmıştır. Simülasyon, Esnek İmalat Sistemlerinin tasarım ve uygulama aşamalarında karşılaşılabilecek bir çok problemin optimum çözümlerinin bulunmasına yardımcı olurken "esneklik" düzeyinin arttırılmasına hizmet eder.

Esnek imalat sistemlerinin esneklik gereksinimleri, üretimi ilgilendiren her etkinliğin işletmenin her seviyesine yayılmasını gerektirmekte, her kademeden çalışanın model hazırlama, yürütüm değiştirme ya da sonuç değerlendirme gibi durumlarda simülasyon yazılımlarıyla karşı karşıya gelmesine sebep olmaktadır. Simülasyondan çalışanların yetenek yetersizliği sebebiyle etkin bir şekilde yararlanılamaması probleminin üstesinden, özel arayüz tasarımları ve simülasyon yazılımlarının her gün kullanılan programlarla bütünleştirilmesi yolu ile gelinebilir

Bu çalışma ile, Ortadoğu Teknik Üniversitesi Makina Mühendisliği Bölümü Bilgisayar Tümleşik Üretim Laboratuvarı'ndaki sistem pilot çalışma ortamı olarak kullanılarak esnek imalat sistemlerinin modellenmesi ve simülasyonunun yapılması hedeflenmektedir. Buna ilaveten, simülasyonun çevresel programlarla tümleştirilme metotları örneklerle gösterilmiştir. Çalışma süresince ARENA® kullanılarak geliştirilen modeller, farklı üretim senaryoları ileri sürmek için kullanılmış; simülasyon kullanılarak, üretimi ilgilendiren konulara dair elde edilebilecek sonuç ve karar örnekleri sunulmuştur. Anlatılan model oluşturma süreçlerinin, geliştirilen modellerin, ve sonuç değerlendirmelerinin esnek imalat sistemlerini ilgilendiren diğer simülasyon çalışmalarında yol gösterici olması beklenmektedir.

Anahtar Kelimeler: Simülasyon, Modelleme, Esnek İmalat Sistemleri, Simülasyon Tümleştirme, ARENA®

To My Lovely Family

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CHAPTER 1

INTRODUCTION

The business of manufacturing and production has evolved to a system dependent activity from a “process only” activity through history. This evolution has brought up dramatic improvements in systems, for manufacturing to excel. Accordingly, manufacturing systems have developed from job-shop manufacturing into flow-shop manufacturing, arriving at the most advanced expression; the Flexible Manufacturing System (FMS).

The first applications of flexible manufacturing systems in early 1960’s have introduced the philosophy of flexibility in manufacturing; the key term to attain a cost effective production, with emphasis on quality and customer oriented production with shorter product delivery times.

Actually, the need for flexible processes is to permit rapid low cost switching from one product line to another. This is possible with flexible workers whose multiple skills would develop the ability to switch easily from one kind of task to another. As main resources, flexible processes and flexible workers would create flexible plants which can adapt to changes in real time, using movable equipment, knockdown walls and easily accessible and re-routable utilities.

The process of constructing an FMS is costly as it requires heavy capital investment in machinery and equipment. Because of that, the design of FMS’s requires an intensive work on planning an efficient and effective system. Simulation shows up at this stage providing managers with a tool that helps to evaluate the results of different configurations of hardware and software for the production of a variety of available products. Simulation helps find optimal solutions to a number of problems at both design and application stages serving to improve the “flexibility” of FMS’s.

Since 1970’s, manufacturing industry has made extensive use of discrete event simulation as a means of trying to model the impact of variability on manufacturing system behavior and to explore various ways of coping with change and uncertainty. Simulation has provided means to support longer term decisions involving resource requirements, equipment needs and sensitivities to a variety of product demand as well as to shorter term decisions such as shop order releases, and shop floor control decisions.

Although the application of simulation into FMS’s is inevitable due to its benefits, it is not an easy one. The stages of modeling can be considered as art rather than science and therefore it is the task of experienced modelers. However, the flexibility requirement of FMS necessitates the dissemination of every activity that concerns production throughout the levels of a company. Due to this fact simulation models are in interaction with almost every level of employee starting from workers and craftsmen, up to higher levels in the management, either in terms of preparing models or evaluating results. This problem of enterprises can be overcome through the use of custom interfaces and integration of simulation software with everyday-use programs.

1.1 Motivation and Scope

Manufacturing management needs to be equipped with new and effective tools due to the rapidly changing and highly competitive nature of today’s global markets. New generation hardware and software, tailored into specific applications are being developed each and everyday, however a success in reducing costs, increasing efficiency and improving quality is not easy until an application based integration of these components is attained. A modern Flexible Manufacturing System (FMS) with a concrete system model design and the use of information technologies answers these requirements (Yücel, 2004).

In this study, the computer simulation study performed in a pilot Flexible Manufacturing Cell to investigate the application of simulation into Flexible Manufacturing Systems is presented. The complete integration of the existing system with the developed simulation models is not currently realized however it is proposed as a future development. The concentration is devoted to the integration with auxiliary programs to ensure usability of the developed models by inexperienced users. The feasibility of integration at this stage is demonstrated by designing, developing, and implementing and showing that it can be customized to be used for simulation in FMS. The simulation part is realized by using SIMAN and ARENA 7.0 and the integration is carried out using Visual Basic 6.0.

In addition to those, the performance of the existing flexible manufacturing system under different dispatching rules is discussed, providing a means to apply these dispatching rules into computer simulation models of flexible manufacturing systems.

1.2 Outline

Chapter 2 is dedicated to a sound literature survey to provide information about simulation basics and past and current application areas. The modeling and simulation tool used in the study, namely ARENA®, is introduced and finally the Flexible Manufacturing Systems and their relation with simulation is given.

In Chapter 3, the modeling and simulation efforts realized are discussed. The context starts with the actual system to be modeled. The simulation and modeling parameters follow.

Chapter 4 includes the programming efforts for the integration of simulation with auxiliary software. In this chapter, the means of interacting simulation models with users is discussed.

In Chapter 5, the preparation of sample simulation runs regarding different production philosophies and their results are given with comments on these results about production issues.

A discussion with concluding remarks and recommendations for future studies completes the thesis in Chapter 6.

CHAPTER 2

LITERATURE SURVEY

In this chapter the related literature and the historical background for simulation will be presented with an emphasis on the applications in scientific and industrial areas. The tool used in the study, namely ARENA® of Systems Modeling Corporation will be examined, providing the features of the software briefly. The final part of the literature survey will be dedicated to the manufacturing systems, especially to the flexible manufacturing systems considering the applications of simulation.

2.1 Simulation

One of the gurus of simulation Robert E. Shannon (1975) historically defined simulation as "the process of designing a model of a real or imaginary system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system." This primitive definition highlights the general framework of simulation principles and gives a clue of the roadmap that simulation has gone through within the last century. Each and every word and phrase in the definition should be further emphasized for exact comprehension of the term simulation.

The first sentence of the definition mentions the types of systems that simulation studies can be conducted on. The systems can be "real" or "imaginary", which means that there can exist a physical facility or a process to be modeled, or the model can be a modification of the existing system or it can be totally imaginary. The imaginary systems refer to the ones that are planned as alternatives to existing systems and entirely original systems.

2.1.1 Simulation Process

As Shannon states simulation is a continuous “process” rather than a one time create-and-use application. Especially computer simulation is an iterative method that includes several stages as Kelton et al (2004) identifies. A simulation study starts with efforts on understanding the system in addition with the identification of the goals of the study. The next step is creating the formulation of the model representation usually in terms of mathematical models or flowcharts. Subsequently, the created formulation needs to be transferred into modeling software using programming languages or with specific software tailored into the needs of a simulation study. Once a program is created, it is necessary to verify the program, in the sense that right things occur with expected inputs. The following stage is to validate the program with someone familiar to the represented system so that the program works in accordance with the conceptual model faithfully, supporting the validation work with statistical tests can be of critical importance at this stage. Experimentation on the developed model is the following phase, which includes designing experiments to identify the critical performance measures to be used with adequate confidence and running these designed experiments by using the computers effectively. The last stages take account of analyzing the results, getting insight of the results to evaluate the outcomes of the results and to assess the potential benefits. Finally, documentation is necessary for the inheritance of the work done for other simulation staff and also to clearly transfer the findings and recommendations to related management levels with precision and confidence.

The life cycle of a simulation study has also been identified in detail by Balci (1990). This life cycle has been divided into 10 processes, 10 phases and 13 credibility assessment stages. Figure 2.1 provides the details of those identifications and the precedence and succession relations between them. The author addresses that attention must be devoted to every credibility assessment stage for simulation study to be successful and sufficient effort must be dedicated to every process of the life cycle. In addition to the mentioned concepts of the cycle, it is recommended to consider the additional indicators that are specific to the area of application wherever possible.

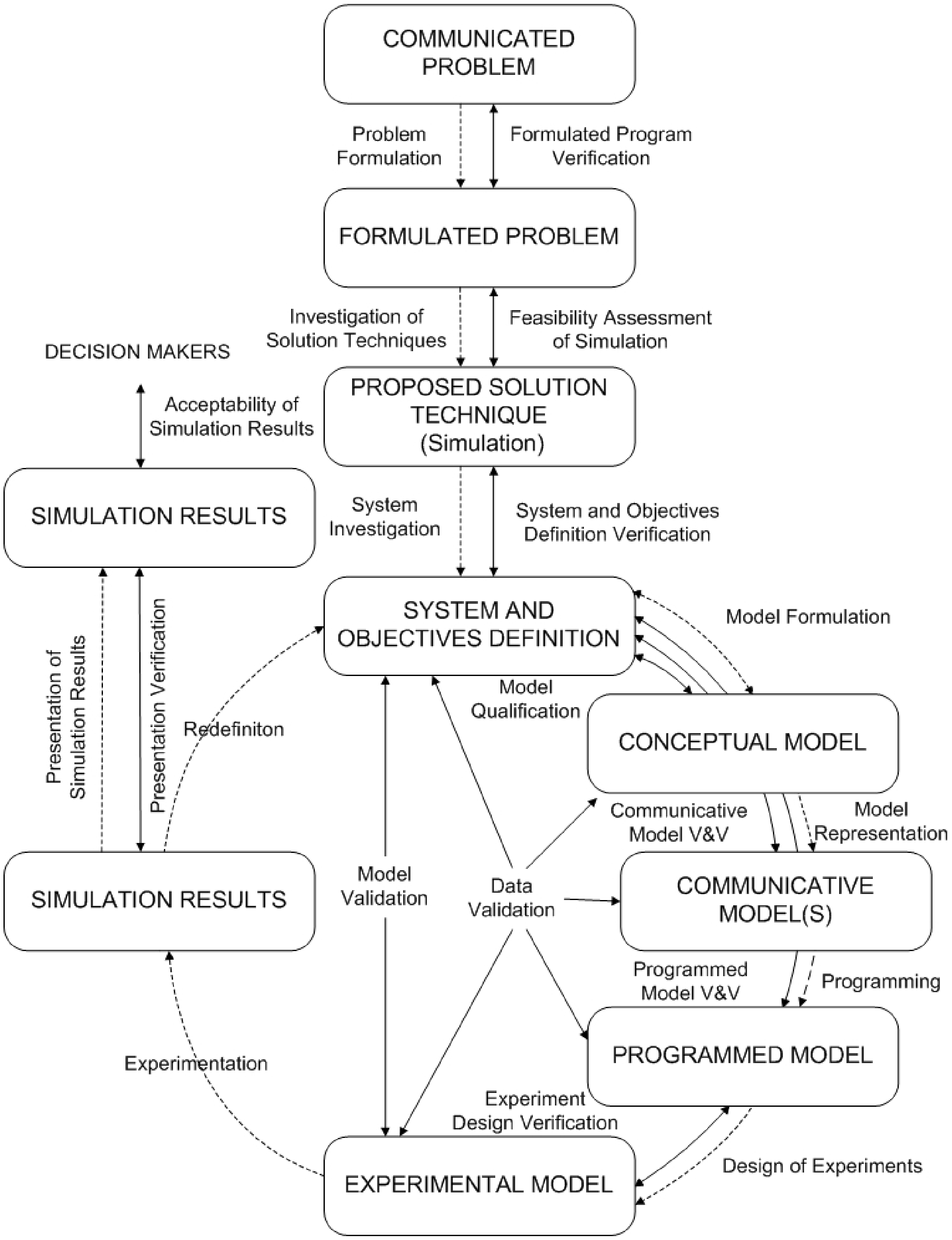


Figure 2.1 The life cycle of a simulation study by Balci (1990)

All those steps mentioned seem troublesome and time consuming, however success in simulation is difficult to attain without following these steps. It is necessary to identify what success is at this stage. According to (Sadowski 1999) a successful simulation project is the one that delivers useful information at the appropriate time to support a meaningful decision, which implies that there are three key elements of success in simulation; decision, timing and information.

2.1.2 Model Types

One deficiency of the definition provided by Shannon is that it does not provide a clue about the discrimination between the "real" and "imaginary" models, which addresses simulations done with different types of models. As outlined by Kelton et al (2004) the most realistic type of all, physical models include the tabletop models that act like the miniature versions of the actual facility or system, full scale versions of existing facilities used as mock-ups for experimentation, or flight or control room simulators used for training and emergency planning. On the other hand, the imaginary models comprise the mathematical and/or logical models that can also be transferred into analogous computer programs. These consequent programs resulting from the models come with a set of approximations and assumptions to represent the behavior of systems to be modeled.

2.1.3 Simulation Benefits

Simulation has many benefits for the users as outlined by J. Banks (2000). First of all, it lets users choose correctly among the possible alternatives, provides time compression and expansion according to the type of the simulated event, equips the managers with the tools to understand "why?" certain phenomena occur in a real system, allows the user to explore possibilities of new policies, operating procedures or methods. With simulation, one can diagnose problems of complex systems that are almost impossible to deal within the real environment, identify constraints that act as a bottleneck for operations, visualize the plan using the animation capabilities of the software used that results in a more presentable design. Simulation is also beneficial to build consensus among the members of the decision makers and to prepare for changes by considering the possible “what if” scenarios. Virtual Reality (VR) support creates training environments for production team, it can also be used to specify requirements for capabilities of equipment and carry out wise investments using all those properties.

In accordance with this definition and benefits, simulation has been extensively used as an off-line decision making tool for helping the management with production planning issues such as efficient capacity utilization, sequencing and scheduling and allocation of resources in manufacturing and production.

2.1.4 Disadvantages of Simulation

As outlined in the previous section simulation has many benefits and advantages, however despite these advantages, there are things one should consider carefully on carrying out simulation studies. It is a probability that simulation may not be the perfect tool for all types of system analysis.

Banks (2000) underlines four main disadvantages of simulation. The first disadvantage is that model building requires special training and it is highly unlikely that models generated by different modelers about the same system will be the same. The second disadvantage is about the simulation results’ being difficult to interpret. As most simulation outputs are essentially random variables based on random inputs, it may be hard to determine whether an observation is a result of system interrelationships or randomness. The third disadvantage is that simulation modeling and analysis can be time consuming and expensive especially when enough resource is not allocated for modeling and analysis, resulting in a simulation model and/or analysis that is not sufficient to the task. A final disadvantage is that simulation may be used inappropriately, especially in some cases when an analytical solution is possible or even preferable.

2.1.5 Future of Simulation

The future of simulation is believed to be different from the past. According to J. Carson and D. Brunner (2000) there will be an increase in simulation becoming embedded in other larger software applications and simulation will be more widely used for real-time decision making rather than the traditional off-line methods.

The general literature suggests that the interoperability of simulation software with other software is crucial. The data formats of the simulation software used to model and predict the behavior of manufacturing systems and the applications about design, manufacturing engineering, and production management need to be the same. Neutral interface specifications that would permit quick and easy integration of commercial off-the-shelf software should be developed.

One other important prediction about the future of the simulation is about the development of new simulation interface standards that would help the deployment of simulation technology. Currently, the simulation model development process is labor intensive, perhaps more of an art than science, an approach that leaves considerable work and creative responsibility to the simulation analyst.

One of the promising ideas for expanding simulation to a broader set of users is the concept of having pre-built models or model components that can be plugged together to form a model of the system to be modeled. The idea is to select the components from a library and use them directly. The goal is to build each model component once, verify its operation, and the make it available in a library to be used in many different applications.

2.1.6 Application Areas

Simulation has found a great deal of application areas both in the academic and industrial fields of work. The field of application of simulation includes but is not limited to manufacturing facilities, bank or similar other personal-service operations, transportation, logistics and distribution operation, hospital facilities, computer network, freeway system, business process, criminal justice system, chemical plants, fast-food restaurants, supermarkets, theme parks, emergency response systems, etc.

The following sections give examples from the literature about several applications of simulation. The topic is studied under two main headings, dividing the applications as manufacturing and production and others. Although this study is in the field of manufacturing and production, other applications in different fields provide insight for different aspects of simulation

2.1.6.1 Production and Manufacturing

One of the largest application areas for simulation modeling is that of manufacturing systems, with the first uses dating back to at least the early 1960’s. Since then, it has been used effectively in the design and analysis of manufacturing systems. Law (1999) has identified specific issues that simulation is used to address in manufacturing as follows:

The need for and the quantity of equipment and personnel

- Number, type, and layout of machines for a particular objective
- Requirements for transporters, conveyors, and other support equipment (e.g., pallets and fixtures)
- Location and size of inventory buffers
- Evaluation of a change in product volume or mix
- Evaluation of the effect of a new piece of equipment on an existing manufacturing system
- Evaluation of capital investments
- Labor-requirements planning
- Number of shifts

Performance evaluation

- Throughput analysis
- Time-in-system analysis
- Bottleneck analysis

Evaluation of operational procedures

- Production scheduling
- Inventory policies
- Control strategies [e.g., for an automated guided vehicle system (AGVS)]
- Reliability analysis (e.g., effect of preventive maintenance)
- Quality-control policies

As seen from the above discussion, manufacturing and production offers a huge number of issues to deal with. Some of the recent applications of simulation and modeling in this area are given below. It should be noted that there are thousands of studies in this field, but the following are important as they mostly make examples of using ARENA® in simulation.

The work of Williams (2002) is important as it presents the usefulness of simulation in studying the impacts of system failures and delays on the output and cycle time of finished parts. Also, the similarity of the robotic work cell used as the modeling medium to our environment is worth mentioning. The case study illustrates a modeling approach with system verification and validation revealing fundamental system design flaws.

Patel et al (2002) have used discrete event simulation for analyzing the issues of first time success rate, repair and service routing logic, process layout, operator staffing, capacity of testing equipment and random equipment breakdown in automobile manufacturing processes. They offer concepts and methods for discrete manufacturing processes especially for the Final Process System for optimizing resources and identifying constraints.

The studies in literature include the auxiliary programs for simulation, as well. Rogers (2002) has used OptQuest for ARENA® for applying optimum-seeking simulation tools to manufacturing system design and control problems. The author describes the software as a tool that can be broadly applied to find optimal values of controllable parameters for systems being analyzed via simulation.

Altinkilic (2004) has presented a use of simulation to improve shop floor performance. The performance of the existing system is evaluated by using ARENA®. Due to the motivation for redesigning the shop flow, manufacturing cells are performed and the performance of the new system is evaluated and compared with that of the current system. As a result, based on a simulation analysis, several recommendations are made to the management of the mentioned job shop production system.

The literature about the use of simulation extends back for about two decades comprising different aspects of manufacturing and production, considering scheduling, capacity and production planning, warehousing and storing, sales and after sale services, etc.

2.1.6.2 Other Areas

The example studies given below provide a reflection of the usage areas of simulation apart from manufacturing and production, and of typical results those can be attained. It is known for sure that both the number and range of the point at issue is almost unlimited, but these studies are important to provide a basic understanding of simulation applications.

Chen (2002) has used simulation to come up with an application to provide a critical decision support tool in a chemical plant for logistics activities. Using the simulation model, the authors have determined capital equipment requirements and assessed alternative strategies for logistics operations, such as the number and size of storage silos for the chemical plant. Although the authors do not propose a new concept, the object oriented approach they have used and their discrete event model to simulate continuous production flow is worth mentioning.

One of the mentioned application areas was policy. Simulation has been widely used to help public policy makers evaluate decisions on subjects such as traffic, emergency planning and health management. An application of simulation involves the discussion of traffic management for İstanbul district and advises on the future of the city taking marine traffic into consideration (Köse 2003). Land traffic and air traffic has also been subject to individual symposiums and editorials in several journals.

In their studies Hill (2001) and Standridge (1999) have studied the applications of simulation in the fields of military problems and health care applications, respectively. Both studies address wide ranging issues in their respective areas with sample applications to come up with invaluable comments and results about simulation studies in general. Graves and Higgins (2002) has combined logistics and military requirements in a single simulation study. With the applications described in the study, the potential impact that simulation can have on army logistical systems have been illustrated in the fields of supply, transportation and maintenance.

Business processes in service industries have also been comprised in simulation applications (Dennis et al 2000). Customer service of a telecommunication company was subject to a simulation study to define the service vision, operating principles, processes and other enablers that formed the business architecture. Using the developed simulation model it was possible to predict what effects the proposed solutions would have on things such as resourcing, quality of service, cost and process efficiency. In addition to those, simulation has also been used for testing several future scenarios.

The work of Nsakanda and Turcotte (2004) illustrates the use of simulation for evaluating and analyzing air cargo operations at one of the new state-of-the-art cargo facilities at Toronto Pearson Airport. A brief description of the airline's cargo operations has been described as well as the simulation modeling approach. They have showed that the simulation-based tool they have proposed could be effectively used in its current level of development to quantitatively evaluate and compare different policies, business practices and procedures within a given set of operational and business constraints.

2.1.7 Simulation Tools

There are several methods to create simulation models on computer. General programming languages such as FORTRAN, Basic, or C/C++ can be used with some routines to be found from the literature (Law and Kelton 1991) or one of the several commercially available simulation tools can be utilized.

These tools can be divided into three basic classes as follows: general-purpose simulation languages, simulation front-ends and simulation packages. The general-purpose simulation languages require the user to be a proficient programmer as well as a competent simulationist. The simulation front-ends are essentially interface programs between the user and the simulation language being used. The most advanced of all, the simulation packages of today utilize constructs and terminology common to the manufacturing community, and offer graphical presentation and animation.

Information about some major simulation software can be found from the following web addresses on Table 2.1, however it should be noted that there are also other software or simulation languages on the market. The programs provided in this table are chosen among the software that has a considerable share in the market.

Table 2.1 Simulation software on the market

Name of The Simulation Tool	Web Address for Further Information
Automod	http://www.autosim.com
Promodel	http://www.promodel.com
Arena	http://www.arenasimulation.com
AweSim	http://www.pritsker.com/
Witness	http://www.lanner.com/
Flexsim	http://www.flexsim.com/
Extend	http://www.imaginethatinc.com/
GoldSim	http://www.goldsim.com/
Mast	http://www.cmsres.com/
SimCad	http://www.createasoft.com/

2.2 ARENA®

The ARENA® modeling system from Systems Modeling Corporation is a flexible and powerful tool that allows analysts to create animated simulation models that accurately represent virtually any system. First released in 1993, ARENA® employs an object-oriented design for entirely graphical model development. Simulation analysts place graphical objects, called modules, on a layout in order to define system components such as machines, operators, and material handling devices. ARENA® is built on the SIMAN simulation language. After creating a simulation model graphically, ARENA® automatically generates the underlying SIMAN model used to perform simulation runs (Takus, 1997). This brief description provided by a senior software developer of the program owning company, emphasizes the graphical interface, and ease of programming that arises as a result.

The ARENA® product suite is designed for use throughout an enterprise, from strategic business decisions, such as locating capacity in a supply chain planning initiative, down to operational planning improvements, such as establishing production line operating rates (Bapat, 2000). To achieve enterprise wide top-down scalability and ease of use by all levels of an enterprise, ARENA® has many unique properties, which are described in brief below.

ARENA® has a natural and consistent modeling methodology due to its flowchart style model building regardless of detail or complexity. Even the flowcharts of systems created by Microsoft Visio® can be imported and used directly. It is extendable and customizable, which results in a re-creatable, reusable and distributable templates tailored to specific applications. The scalable architecture of ARENA® provides a modeling medium that is easy enough to suit the needs of the beginner, and powerful enough to satisfy the demands of the most advanced users. This makes it a perfect tool for continuously improving modeling studies as the modeler's capability and experience increase as the study progresses. One other advantage of ARENA® is that it is open to interaction with many applications such as Microsoft Access and Excel with its built-in spreadsheet data interface. Furthermore, with Visual Basic for Applications (VBA®) support there is virtually no limit on creating interfaces and programs. With those mentioned advantages ARENA® has become the academic standard, which is thought in most Industrial Engineering schools worldwide, which also encouraged the Integrated Manufacturing Technologies Research Group to obtain an academic license of the program.

2.2.1 ARENA® Tools and Features

ARENA® provides an integrated framework for building simulation models in a wide variety of applications. An entire simulation project may be completed within the ARENA® system, whereby integrated support is provided for all of the functions necessary to complete a successful simulation (including input data analysis, model building, interactive execution, animation, execution tracing, model verification, and output analysis) (Hammann, 1995).

ARENA® Input Analyzer can be used to process and classify the obtained data for input data analysis. Appropriate probability distributions can be obtained to for being used in the models. The model building window of ARENA lets the users easily convert flowcharts into functional models due to its natural modeling methodology. For execution tracing and verification of models, ARENA lets the user use breakpoints in the developed program code and tracing variables to inquire on the validity of the programs developed. Similar to input Analysis, Output Analyzer lets the user carry out statistical analysis on the results obtained. And finally, the Process Analyzer helps to examine the selected outcomes of several different alternatives dependent on selected controls on the system.

The most attractive feature of a simulation study is the animation that accompanies the model. Most people are interested in watching animated actions and graphs rather than straight numbers and texts. ARENA® has a powerful animation tool to help the user to pass his/her ideas, studies and results to the audience easily.

ARENA® animations can be run concurrently with the executing simulation model. Animations can be created in several ways: they can be created entirely using Arena's graphics drawing tools, they can be created from AutoCAD® or other .DXF file formats, they can be created in other tools and imported to ARENA® via Active X (formerly known as OLE), they can be created by using other Windows®-compliant drawing systems that can be pasted into Arena layouts, or any combination of the above. Arena includes various animation options for real time display of model statistics. The user can place dynamic plots, histograms, levels, and time clocks directly within a simulation in order to illustrate system status as the model performs. This information is displayed on a real-time basis as well as on a post-process basis in the Arena statistical summary report (Takus, 1997).

2.2.2 ARENA® Integration and Customization

The power afforded by Arena extends to its ability to integrate with other technologies, such as databases, drawing/modeling products, or spreadsheets.

ActiveX™ and Visual Basic® for Applications (VBA), Microsoft's key technology backbone for desktop application integration, are fully implemented in all ARENA® products, enabling ARENA® to utilize existing enterprise models and data hosted in applications such as Microsoft Office, Visio®, Oracle®, etc. (Swets, 2001).

ActiveX™ and VBA are Microsoft's strategic technologies for desktop application integration. This standard, open architecture provides insurance against future change in corporate information resources. VBA further enables the creation of custom interfaces and applications using a widely adopted programming engine.

2.2.2.1 ActiveX ™ Automation

ActiveX™ Automation is a loosely defined set of technologies developed by Microsoft® for sharing information among different applications. ActiveX™ allows applications to control each other and themselves via a programming interface. It is an outgrowth of two other Microsoft® technologies called OLE (Object Linking and Embedding) and COM (Component Object Model). ActiveX™ Automation is a "hidden" framework provided by Windows®, accessible through a programming language (such as Visual Basic®) that has been designed to use the ActiveX™ capabilities.

The types of actions that an application supports are defined by what's called an object model. The designers of an application build this object model to provide and interface so that programming languages can cause the application to do what a user would do interactively with a mouse and keyboard. The object model includes the following.

- a list of application *objects* that can be controlled (e.g., Excel worksheet, ARENA® modules);
- the *properties* of these objects that can be examined or modified (e.g., the name of a worksheet, the value of a variable in an assign block)

- the *methods* (or actions) that can be performed on the objects or that they can perform (e.g. delete a worksheet, remove a module)

When an application that contains an object model is installed, its setup process registers the object model via the operating system. Then, if the application's functionality is desired to be utilized through a programming language, a reference to its object model can be established and its objects can be programmed directly. Many desktop applications can be automated (i.e. controlled by another application), including Microsoft Office, AutoCAD®, Visio® and ARENA®. Many programming languages like C++, Visual Basic, or Java can be used to create the program that controls the application.

2.2.2.2 Visual Basic for Applications® (VBA)

Visual Basic for Applications® is an implementation of Microsoft's Visual Basic which is built into all Microsoft Office® applications, some other Microsoft applications such as Visio and is at least partially implemented in some other applications such as AutoCAD® and MSWord®. It supersedes and expands on the capabilities of earlier application-specific macro programming languages such as Word's WordBasic, and can be used to control almost all aspects of the host application.

Visual Basic for Applications® provides a complete integrated development environment (IDE) that features the same elements familiar to developers using Microsoft Visual Basic, including a project window, a properties window, and debugging tools. VBA also includes support for Microsoft forms, for creating custom dialog boxes, and ActiveX Controls, for rapidly building user interfaces. Integrated directly into a host application, VBA offers the advantages of fast, in-process performance, tight integration with the host application (code behind documents, cells, and so forth), and the ability to build solutions without the use of additional tools.

As its name suggests, VBA is closely related to Visual Basic, but it can normally only run code from within a host application rather than as a standalone application. It can however be used to control one application from another.

2.3 Flexible Manufacturing Systems

Increasing expectations of today's customers involving the quality and variety of produced goods are becoming more and more critical on the market. The fast changing tendencies on the market results in a shortened life cycle for products and a competitive market that forces the manufacturers to explore new markets to sell the goods. The requirements of the market necessitate the introduction of changes in the organization of production processes, through the launch of automation, computer aided design and manufacturing works and management, and the development of modern multi-stand machining systems, such as Flexible Manufacturing Systems (FMS).

FMS is defined as a computer-controlled configuration of semi-dependent workstations and material-handling systems designed to efficiently manufacture various part types with low to medium volume (Luggen 1991). It is an integrated production system composed by a set of independent machining centers. An automatic part handling system interconnects the machining centers to a group of part-storage locations such as loading/unloading positions and input/output buffers. An automatic tool handling system interconnects the machining centers to a group of tool-storage locations as tool magazines, tool rooms, exchangers and spindles. Either the part handling system or tool handling system mechanisms consist of one or more automated guided vehicles (AGVs) or transporters. A central supervisor (the FMS control software) monitors and manages the whole system (Anglani et al, 2002).

Operator interdiction is discouraged by FMS. As jobs are changed, the computer is reprogrammed to handle new requirements. The workpieces in FMS are usually complex, and can require complicated manufacturing steps. Production of the various parts requires processing by different combinations of manufacturing, but FMS is versatile and can perform different operations on a variety of products. Often an FMS machine can perform many processing steps. The process begins with a robot or operator loading or unloading a Computer Numeric Controlled (CNC) machine in the FMS. After processing in FMS, the robot returns the semifinished or finished part to the conveyor.

FMS is integrated with computer-aided design (CAD) and manufacturing (CAM). CAM, for example, limits the number of tools to a preset number, such that the factory does not store more than a specific number. Another approach finds the number of tools and then reduces that number by cost control methods. Standardization of tools, their kind and quantity, and specifications are a natural development of FMS (Ostwald and Muñoz 1997).

2.3.1 IMTRG and FMS

Integrated Manufacturing Research Group has been interested in Flexible Manufacturing Systems since the first day of its foundation. To start with, an FMS control software was developed as an M.Sc. thesis, which forms the main structure of the control software that currently runs in the pilot FMS system of Middle East Technical University (METU) Mechanical Engineering (ME) Department Computer Integrated Manufacturing (METUCIM) laboratory (Ünver, 1996). A Ph.D. thesis was completed based on a new planning and scheduling software, which can be integrated to the pilot FMS control software (Ünver, 2000). One other implementation is developing a computer aided quality control software to integrate coordinate measuring machine (CMM) with the FMS (Başıbüyük, 1999). In July 2000, a M.Sc. thesis was completed related to Agent Based Shop Floor Control System using Distributed Internet Applications (DNA) technology (Cangar, 2000). This was a web-based cell controller, which gives the full control of METUCIM equipment to manufacture parts and manage the enterprise over the web.

As seen from the above paragraph the IMTRG of METU has especially dealt with providing non-traditional ways to manage FMS. The test-bed used as an FMS cell to realize all these mentioned work will be described in Chapter 3.

2.3.2 FMS Simulation

Simulation has found a great deal of concern in FMSs. Usually the need of simulation arises with the questions to be answered when planning an FMS. Some of these problems concern the design of the system, while others relate to its operation. It is important, especially when building simulation models of systems, to recognize that different types of problems necessitate different types of models. Consequently, a framework within which the various problems can be placed so that similar problems can be addressed with similar types of model is needed. One of the most appropriate in the present context is that by Van Looveren et al. (1986) who identify six problems and three levels of planning.

Strategic Planning:

- ➢ The screening problem, a preliminary economic evaluation of alternatives to eliminate inefficient designs.
- ➢ The selection problem, to identify the alternative with the highest net savings, considering both technical and economic factors.

Tactical Planning:

- ➢ The batching problem, organizing production so that orders are completed on time, taking into account the limited numbers of pallets and fixtures.
- ➢ The loading problem, determining which operations will be performed in which machines and with what tools.

Operational Planning:

- ➢ The release problem, controlling the flow of work into the system taking the overall allocation of resources to part types, and the current status of the system, into account

- The dispatching problem, concerning the routing of the parts through the system, taking advantage of any alternatives which exist.

The different levels of planning are concerned with different time scales, dealing with long-term prospects, medium-term sales forecasts and current system status respectively. However, it is difficult to draw a clear division between the levels of planning. They are bound to overlap.

At the strategic planning level, a simulation model will have to use approximate estimates of production requirements, routings and operation times. As the lower levels are tackled, the simulation model will have to become more detailed and the knowledge of operating practices gets much more specific. In building a simulation model of a system one should be explicit about the decision rules which are used, even although no clear information to base them exists. The rules can be altered and refined as the project proceeds to more detailed planning levels. Strictly, it is not until the strategic plans have been made that simulation has a major contribution to play, because until a system design has been suggested it cannot be modeled. Simulation can help to evaluate the alternative designs, but the model builder will often have to make assumptions about the decision rules, which are really in the realm of tactical planning.

The main contribution of simulation will be in the area of tactical planning, for it is at this level of planning that the decision rules are decided. There are several contributions to the literature dealing with tactical planning of FMS. For example, Stecke (1981) gave a hierarchy of five planning problems:

1: The Part Type Selection Problem: From the set of part types that have production requirements, determine a subset for immediate and simultaneous processing.
2: The Machine Grouping Problem: Partition the machines into machine groups in such a way that each machine in a particular group is able to perform the same set of operations.

3: The Production Ratio Problem: Determine the relative ratios at which the selected part types will be produced.
4: The Resource Allocation Problem: Allocate the limited number of pallets and fixtures of each type among the selected part types.
5: The Loading Problem: Allocate the operations and required tools of the selected part types among the machine groups, subject to technological and capacity constraints of the FMS.

Among the outputs of the tactical planning process there is the basic data concerning the organization of the FMS. This will include a list of the operations needed on each part, the machine group where each operation is to be done, its duration, the list of the tools required and the cutting time of each cutting tool.

At the operational level, the system manager is concerned with the release of parts onto the system, and the relative properties of parts in buffers, vehicle scheduling and so on. Simulation may have reduced role to play at this level, since it deals with the current status of the system. Few simulation models are able to access the current status of a system. Therefore, setting up the initial conditions in the model may be highly time-consuming for personnel managing the system to make much use of simulation. Instead, operating procedures which these personnel should adapt may be established by off-line simulation modeling, usually as a part of the tactical planning process. Indeed, since rules of this type will normally be built into the system control software, it is essential that they are established in advance of building the system. An important question is the extent to which the system software provides facilities for the manager to override the system's normal logic. The recent studies and application of simulations show that, it is possible for simulation tools to take part as a part of the real-time software for controlling the FMS. (Ruiz-Torrez, 1998; Versteegt, 2002; Yalcin, 2005)

In practice the role of simulation lies at two levels, which support Von Looveren's hierarchy:

System Design: Addressing the system design problems, and ensuring that the system has sufficient capacity to meet its production targets. Simulation modeling at this stage aims to assist in the strategic planning problems, but most consider the decision rules to be used at the tactical level.

System Operation: At this stage the design of the system has been determined, and simulation can assist in determining the best operating procedures for machine grouping, sequencing rules and so on. Thus, simulation is concerned with the interface between tactical decisions and operating procedures (Carrie, 1988).

CHAPTER 3

MODELED SYSTEM AND MODEL STRUCTURE

This chapter includes the modeling efforts performed for carrying out simulation on Flexible Manufacturing Cell in hand. The first sections describe the present system as a Flexible Manufacturing System and the following sections give the details of the simulation structure and the models developed with and emphasis on Flexible Manufacturing System concepts.

3.1 Present System

Being a test-bed for many previous studies, the flexible manufacturing cell in Middle East Technical University (METU) Mechanical Engineering (ME) Department Computer Integrated Manufacturing (METUCIM) laboratory serves as the basis of the model in this study as well. Before emphasizing the modeled details of the FMS, it is necessary to mention the existing software and hardware capabilities of the system.

The present, agent based FMC control model has been implemented by Integrated Manufacturing Technologies Research Group (IMTRG) in METU, and it was developed using the three-tiered model of Windows DNA (Ünver et al., 2000). User, Business, and Data Services of the "Agent" has been mostly written under Visual Basic 6.0. For the communication and event driven messaging of agents, Microsoft Message Queue Server (MSMQ) has been used; stateless objects for database search and update has been deployed in Microsoft Transaction Server (MTS). The common database of the "Agent" has been constructed using SQL Server 7.0. Internet Information Server (IIS) has been used to grant access to the web sites as ASP and

HTML pages, which are designed in Visual InterDev 6.0, a product of Microsoft Visual Studio.

Additional information about the working principles, control model, hardware and software components and database architecture can be obtained from Cangar et al (2000) and METU ME Integrated Manufacturing Technologies Research Group Agent web site (www.imtrg.me.metu.edu.tr). Using this web site, real-time manufacturing orders can be given for being realized by the Flexible Manufacturing Cell

3.1.1 METUCIM Test-bed

In order to discuss the models developed for the FMS in hand, it is necessary to identify the system in advance. To start with, a sketch that shows the positions of the components of the system is given in Figure 3.1. As demonstrated in the figure, the FMS basically consists of a single manufacturing cell. The main material handling system utilized in the system is composed of a closed loop buffer and a 6 axis robot. The conveyor which has 14 cups for placement of parts is used as an intermediate storage and for intercell movements between Computer Numerical Controlled (CNC) Turning-Milling Machines and the static buffer. The static buffer is used for loading and unloading parts to the system. It offers different places for accepted and rejected parts. The movement of the robot between the CNC Turning- and CNC Milling Machine is accomplished by a Pneumatic Linear Robot Drive (PLRD). PLRD lets the robot move linearly between Part load-unload and CNC Turning and CNC Milling Stations. CNC Turning and Milling Machines are loaded and unloaded using the robot. A Coordinate Measuring Machine (CMM) whose complete integration to the system is not realized is omitted during the design of the simulation system.

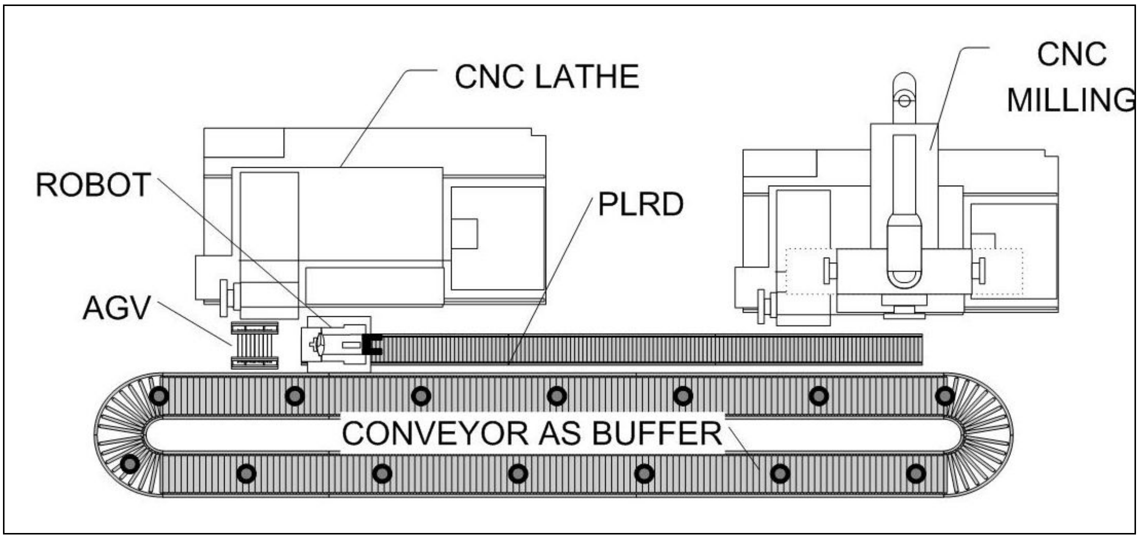


Figure 3.1 Layout of FMS

After naming the components of the FMS one by one, these manufacturing and transport elements are described in detail in terms of functionality, properties and capabilities. The emphasis is given on the properties that are directly used in the models developed.

1. CNC Turning Machine: The machine's model is Mirac/Denford/UK and it is a PC based, medium duty lathe having 2 simultaneously controlled axes. It is equipped with a turret having 8 stations. The door and the chuck of the machine are pneumatically powered. It can handle typically bars up to 50 mm in diameter and 150 mm in length and increase spindle speeds up to 2500 rpm. It has a user-friendly built-in interface to visualize and debug part programs. The control is via standard RS 232 serial communication port and I/O card at a single sensor channel. Times parts spend in the CNC Turning Machine depend on the G codes assigned.

2. CNC Milling Machine: The machine's model is Triac/Denford/UK. It is a PC based, medium duty milling machine having 3 simultaneously controlled axes and equipped with an automatic tool magazine with 6 stations. The door, chuck and tool magazine are pneumatically powered. It can handle parts up to 200 mm in width and

500 mm in length and the spindle speeds can be increased up to 2500 rpm. It also has a user friendly built-in interface to visualize and debug part programs. The control is via standard RS 232 serial communication port and I/O card at a single sensor channel. Times parts spend in the CNC Milling Machine depend on the G codes assigned.

3. Closed Loop Buffer: The model of the conveyor is SKF/UK. It is a unidirectional, constant speed, closed loop buffer having 14 cups. Typically, it can handle cylindrical parts up to 50 mm in diameter. It is driven by a motor with gearbox. The control is via 48 channel I/O card. The conveyor has one operate channel and one counter channel. When the operate channel is ON, it starts to rotate and stops when the channel is OFF, the counter channel is used to count the cups passed. The conveyor has a speed of 87 mm/sec and a total length of about 7100 mm's. As a consequence it makes a full rotation in about 82 seconds.

4. Robot: The robot is a Movemaster EX/Mitsubishi/Japan. It is a 6 axis controlled material handling robot. The robot is capable of handling bars of 50 mm in diameter and has a weight of approximately 3 kg's. The control of the robot is realized by storing positions taught by the user in its EPROM and these programmed positions can be executed by external triggering of program commands through RS232 connection from the computer. ADSR (data set ready) signal from the serial port indicates that there is no active program running or the task is finished. Each operation carried out by the robot such as loading or unloading of machines and conveyor lasts approximately 30 seconds.

5. Pneumatic Linear Robot Drive (PLRD): The PLRD is a product of FESTO/Germany. It acts as a pneumatically powered linear drive for the robot and has a movement range of 2 meters. The only stop positions of the PLRD are at both ends only. In METUCIM configuration it is used to move the robot from CNC Turning to CNC Milling neighborhood. The control is via 48 channel I/O card. The PLRD has two operate- and two sensor channels. When the first operate channel is

triggered and immediately released it moves to right and vice versa for the second. Sensor channels on the left- and right positions indicate ON when the robot is at left and right ends of its range respectively. The traversing speed of the robot is not constant during the 2 meter movement as it accelerates during starting and stopping, keeping this fact in mind an assumption is made taking an average time for the robot motion on PLRD, the motion is assumed to last a constant time of 5 seconds.

6. Static Buffer (AGV): The stationary buffer is used to import parts to the cell and export the finished parts. It has 3 input and 3 output stations which can handle bars of 70-90-100 millimeters. Actually, the buffer is not physically connected or driven by a computer and it has no control or moving capabilities, however it is modeled as an AGV in the system.

Figures B.2-B.5 in Appendix B are dedicated to the photographs of the components of the system that show these components one by one. In addition to those photographs, a photograph that shows the entire system when it is in operation is provided as well in Figure B.1.

3.2 Simulation Structure

Systems to be simulated are quite diverse in terms of size and complexity. However, regardless of how complex a discrete-event system may be, it is likely to contain some basic components that are also common to flexible manufacturing systems. The structural components of a discrete-event simulation include entities, activities and events, resources, global variables, a random number generator, a calendar, statistics collectors and animation (Ingalls 2001). These structural elements and their relations with flexible manufacturing systems are described in the following sections. The models generated throughout the study are used as examples to demonstrate the methods of application for modeling and simulation.

3.2.1 Entities

The most essential elements of a simulation are the entities that move around dynamically and cause changes in the state of the simulation. The changes are generated through altering the resources, affecting or being affected by other entities or by entering or leaving the system. Without entities, nothing would happen in a simulation.

There are two possible types of entities, referred to as external entities and internal entities (Schriber 2001). External entities are those whose creation and movement is explicitly arranged for by the modeler. This type of entities usually has a “real” equivalent in the system to be simulated. In our case, examples to this type of entities are the parts to be processed. There exist several types of parts, explained in detail in Appendix E requiring different processing and routing, which have different properties assigned to them. In FMS, the most common external entities are those that correspond to parts to be entered into the system.

In contrast to the external entities, internal entities are created and manipulated implicitly by the simulation software itself or designed by the modeler to take care of certain modeling operations. They may be used to account for logic operations within the system such as changing the state of a resource at some certain time (e.g. a machine failure, a capacity increase due to a shift). In our study an internal dummy entity is created in the file reading and writing module to create a continuous loop to keep on reading entity arrival times and properties from a text file.

Most of the programming effort required to account for logic operations using internal entities in simulation, has been transferred to simulation packages with the use of advanced simulation tools. Specially tailored built-in modeling constructs used in ARENA® such as the modules named Failure and Schedule are examples to internal entity creating modules.

3.2.2 Attributes

Entities retrieve their unique identities with the attached attributes to them. Perfect analogous objects in literature to attributes are the adjectives. An attribute is a common characteristic of the same type of entities, but with different values assigned, they can differ from one entity to another, distinguishing one entity of a type from another. These assigned values of attributes provide the basis to calculate statistics and also offer programming flexibilities for the modeler.

The most important thing to remember about attributes is that their values are tied to specific entities. These values can be assigned to entities at the beginning of a run or, they can be assigned at special times during model run. The assigned values for attributes are subject to change as the simulation run progresses and these values can be used at any time during the run or even after the simulation run is complete.

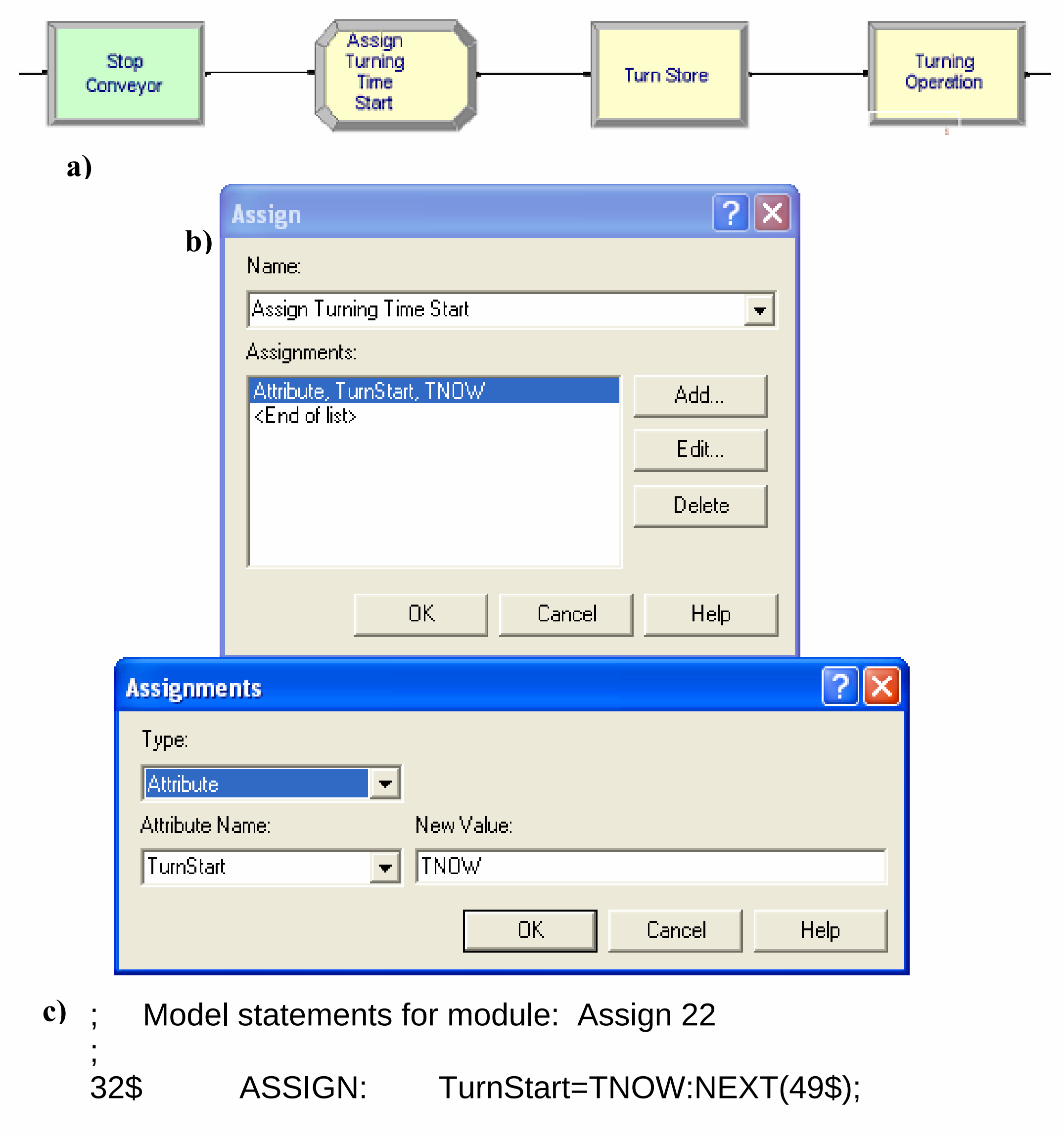
The list of attributes used in simulation of the pilot FMS and their brief purpose of usage in the developed models is given in Table 3.1. This table gives an essential idea on the use of attributes and provides the modeler with a list to start with for modeling a FMS. It should be noted that several other attributes may exist depending on the complexity and specialty of the FMS to be modeled and depending on the modeler and his/her programming skills..

The last column of the table is reserved to the type of the attribute used. The attributes, although they belong to the same group in terms of simulation structure, can have different application areas according to the purpose of assignment. In this study attributes are collected under four main types as statistical, program, animation and fundamental attributes. These attribute types are described in detail, in the following paragraphs.

Table 3.1 The attributes used in the system, their brief descriptions and types. (Anim stands for Animation, Fund for fundamental, Pro for Program and Stat for Statistical)

Name of Attribute	**Description**	**Type**
Check Operation	Traces the completion of individual machining operations	Pro
DueDate	The parts due date is assigned to this attribute	Fund
Entity.Picture	The pictures used in the animation are assigned to this attribute	Anim
Entity.Sequence	The entity follows the sequence defined in this attribute	Fund
JOBFINISHED	Traces the completion of all operations of the part within the system	Pro
Milling Time	The Value of Milling Time is assigned to this attribute	Fund
MilStart	Marks the starting time of milling operation	Stat
Part Index	Part Type is assigned to this attribute	Fund
Timein	Marks the entities entry time into the system	Stat
Turning Time	The Value of Turning Time is assigned to this attribute	Fund
TurnStart	Marks the starting time of turning operation	Stat

Statistical attributes are the ones that constitute the elementary basis for statistics collection. Statistics such as average machining times or time in system are calculated using each entity's corresponding values. These values are assigned in the following way. Before an entity is on the verge of a specific action in simulation (entering a queue, start being conveyed, being grabbed by a transporter, or at the initiation of machining, etc.), the entry time is marked to an attribute. ARENA® has a built-in variable called TNOW, which returns the current simulation time. A sample assignment code and the idea behind are demonstrated in Figure 3.2.



Name:
Assign Turning Time Start

Assignments:
Attribute, TurnStart, TNOW
<End of list>

Type:
Attribute

Attribute Name: TurnStart

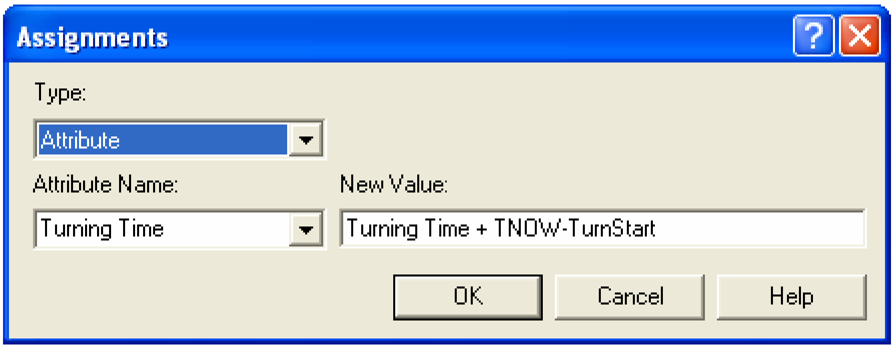
New Value: TNOW

```
;     Model statements for module:  Assign 22
;
32$         ASSIGN:       TurnStart=TNOW:NEXT(49$);
```

Figure 3.2 Attribute assignment for statistical purposes a) assign block before turning operation b) assignment of the current time to the attribute TurnStart c) corresponding SIMAN code.

Upon completion of the related task, the time is recorded and using the previously attached attribute, a new attribute is assigned that has the information of the required action, which will be used at the end of the run for statistics collection. Figure 3.3 shows the assignment code at this stage.

a)



Type: Attribute

Attribute Name: Turning Time

New Value: Turning Time + TNOW-TurnStart

b)

```
; Model statements for module: Assign 20
;
30$ ASSIGN: Turning Time=Turning Time + TNOW-TurnStart:
```

Figure 3.3 Attribute assignment after completion of a task a) Assignment of Turning time using current simulation time and the previously assigned attribute TurnStart b) corresponding SIMAN code.

Fundamental attributes offer the means to attach basic information to the entities. The information that is carried by this type of entities is known beforehand and is not usually subject to change during the simulation run. Attributes that store the information of machining times, part types, colors, features and other production planning related predefined data such as sequences, costs, priorities, due dates and part machine relations are in this group. The assignments on this type of entities are generally done at the beginning of the run, as soon as the newly created entity enters the simulation model.

Program entities are used in simulation to offer some modeling flexibilities to the modeler. It is not always easy to mimic the unique properties of the real system with a simulation and modeling language as it is with general programming languages. Usually the modeler is forced to use branches to compensate for the entity related If-Then structures and the variable used within the structure is either a program or a fundamental attribute. An application of branching in the simulation by the use of a program entity is shown in Figure 3.4. An entity that arrives in the Robot Exit

Station is first assigned a global variable, and afterwards it is either sent to the conveyor to seize a place or the conveyor is stopped for the entity to leave according to the value of the program attribute JOBFINISHED. This attribute has an initial value of "0" at the beginning of the simulation and after the completion of all manufacturing operations on the part the value is incremented to "1".

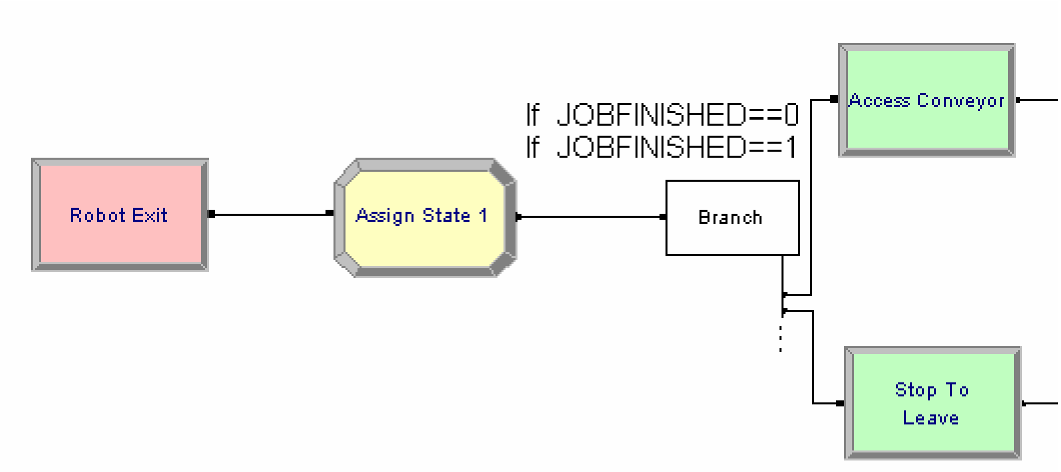


Figure 3.4 Functional usage of program attributes

The last group of attributes is the Animation Attributes. As the name implies, these entities are used to represent the pictures of the entities. These pictures are subject to change as the part gets machined within the system. In the pilot simulated system, Entity.Picture, the internal variable of ARENA®, is used to assign the pictures of the entities.

In addition to the ones listed above, ARENA® keeps track of some attributes automatically, to calculate its own statistics. Priorities and incurred costs to produce parts can also be taken into account in FMS and attributes about them can also be assigned to entities.

3.2.3 Activities and Events

Activities are the processes and logic that are defined in the simulated system. Entities that interact with the activities constitute events and cause changes in the state of the system. There are mainly three types of activities defined for simulation; delays, queues and logic.

Delays are due to the detaining of the entities for a definite amount of time in the systems. The length of this waiting time is either fixed or randomly generated by using statistical distributions. The events related to a delay occur at the beginning and the end of the delay, where the entity arrives at and leaves from the delay block. An entity that successfully seizes a resource undergoes a delay, so it can be told that every type of activity in an FMS that require a resource results in a delay. These delay activities include but are not limited to machining, storage, inspection, and transfers in FMS.

In the pilot application, delays are due to the processes defined in the system (turning and milling) and the transferring of entities from one station to another (robot loading and unloading). Robot loading and unloading delay is treated as a constant value as it does not change from one part type to another, whereas the machining times are taken from different triangular distributions for each type of part, considering a pessimistic, optimistic and most likely time. This approach can be modified considering fixed times for machining operations, as in FMS the uncertainty in machining times is lower when compared to conventional machining systems.

Queues also make the entities wait but the main difference from delays is that the waiting period is unknown in advance. Waitings in queues mainly occur in one of the following two conditions: Either waiting to seize for a resource, or waiting for a system condition to occur such as storing the parts to be taken out of the queue when the right conditions exist. Queues can have capacities representing a limited buffer capacity.

In FMS, queues have also an important role on determining the production philosophy. Queue selection rules are utilized to select parts from queues to determine the next part that will get service from the available resources. In the pilot FMS simulation queues that reflect the properties of both types of queues exist. The queue WAIT FOR BATCHING.Queue is an infinite hold type queue and the entities are forced to wait until a number of five finished parts in the queue exist. This type of operation does not really exist in the existing FMS but added for demonstration purposes for packaging applications and condition type queues.

Considering the queues that occur because of competing parts for resources, there are many examples in the pilot FMS system. However, due to the nature of the conveyor utilized in the system, queues that have capacities larger than 1 arise either to seize a space in the conveyor or to be grabbed by the robot to enter the system. So, the only real queue is the WAIT FOR SYSTEM.Queue that is for the entrance of the parts to the system. For the other queues, the conveyor itself works as a buffer that has a capacity of 14 and each part that is able to ask for being machined by the turning or milling machines have no competing rivals waiting in the same queue as the capacity of the conveyor at turning and milling stations is only 1.

Finally, logic activities allow the entities to help carry out decisions in order to follow specific routes in the system. By interacting with the system state variables and user defined variables and attributes, several logic operations can be realized. The decision stages in the flowcharts can be directly transferred into simulation models once the flowchart of the operations within the flexible manufacturing system is determined. In addition to the logic operations that originate from the flowcharts, logic activities can arise due to modeling necessities such as statistics collection and attribute assignment.

In our pilot implementation, several examples to logic activities exist in every sample model. Figure 3.4 in the previous section shows a logic activity in addition to the functional application of attributes. Another equally important application of logic activities is considering the system state variables. In the logic activity demonstrated in Figure 3.5 the number of entities in WAIT FOR BATCHING.Queue is used to collect a number of five entities for batching. The parts that arrive in the Branch block are transferred in to WAIT FOR BATCHING.Queue until the number of parts in the queue is 4. The next entity that arrives in the queue is used to remove the entities in the queue in order to let the parts proceed within the model for batching purposes.

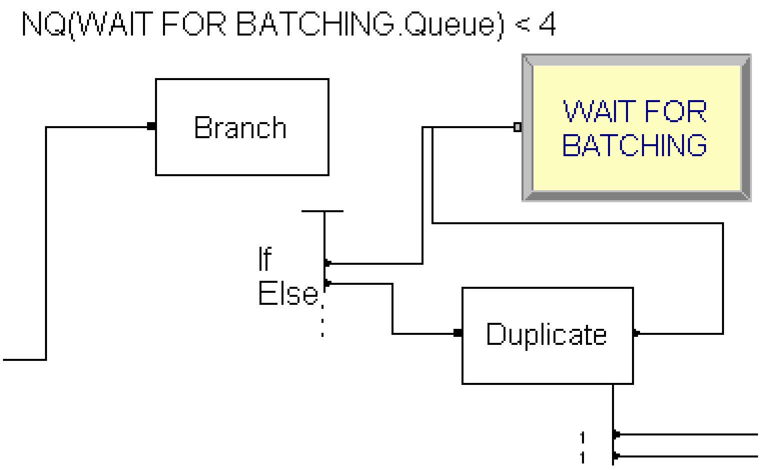


Figure 3.5 Logic activities using system state variables

Similarly, branching operations in models due to assignments of specific attributes to parts and statistics collection are also present in models. Picture assignment according to part type and type of manufacturing process completed is realized by branching and also statistics collection that is consistent with the type of completed operations makes use of this logic approach.

3.2.4 Resources

In simulation, resources represent service providers with restricted capacity for whom the entities compete with each other. Considering FMS's, the extent of the things that the term represents, contract to mainly machinery and equipment, personnel or space in a storage area of a limited size. The resources are allocated to entities when an entity successfully seizes that resource and released when the required operations are finished.

An entity can seize more than one resource at the same time and also a single resource can represent a group of several individual servers and can serve many entities. An example to the first case is a part that seizes both a machine and an operator at the same time. A machine or an area that has a capacity of more than one is an example to the latter case. In addition to machines and operators, material handling devices act like resources in the simulation of FMS. Conveyors, automated guided vehicles (AGV) and other transporters are among the complex resources that generally exist in FMS.

Several resources are used in the pilot simulation considering the real system and possible alternatives to the existing configuration. Evidently, the main resources simulated in the study are the existing CNC turning and milling machines. They have a fixed capacity of one part for servicing and assumed to work without problems except randomly determined breakdowns. The machining times of the parts are determined considering the part types and the idle/busy times of the machines are animated and discriminated with changing color of the lights above them.

One other resource in the system is the conveyor. It is modeled considering its original speed, its 14 spaces for part storage and transport. The segments of the conveyor are defined according to the distances between loading, unloading and machining stations. The other resource is the robot that is modeled as a transporter. This mobile robot is analogous to many AGV's that possibly exist in any FMS. It is modeled considering the distance it moves between the two loading stations and the loading and unloading actions from the stationary buffer to the conveyor, from conveyor to the machines, from machines to conveyor and from the conveyor to the buffer.

3.2.5 Global Variables

Variables are the means to store information that reflects some characteristic of the simulated system. They are used to track just about anything that is of interest to the entire simulation. Coarsely, three usage areas can be defined for variables. The modeler can define system state variables to control the entity flow and guide simulation (Control variables) as well as to collect information on addressing certain areas (Information variables). Besides, values that are subject to change during a simulation run can be assigned to variables and this provides ease of access and manipulation (Access Variables).

In addition to the user defined variables regarding the state of the system, the simulation software itself usually keeps track of various variables. Average, maximum and minimum values of attributes, numbers in queues and simulation clock are examples to the variables internally kept by ARENA®. Considering such similarities between attributes and variables, one question may arise at this stage, about the difference of attributes from variables. The main difference is that variables return the values, which pertain to the system as a whole, whereas attributes carry entity specific information.

Once FMS are considered, there is no distinctive difference from other simulation environments about the use of global variables. Variables used in the pilot study will give a basic idea for advanced applications. Table 3.2 shows examples to each type of variables used and brief descriptions. These variables are selected from different models generated to provide an idea on application methods.

Table 3.2 Variables used in the system, their brief descriptions and types. (Acc stands for Access, Con for Control, Inf for Information)

Name of Variable	Description	Type
Robot Transfer	The time that loading and unloading action takes place is assigned to this variable	Acc
STATESYS	It is a control variable that indicates that there is at least one entity in the system. The variable is used to accept entities when there is no part being processed in the system.	Con
Number in AGV	Traces the number of waiting entities in the stationary buffer.	Inf
Scancontrol	Traces whether there is an active entity seizing for a free space in the conveyor and robot	Con
Max Conveyor	Traces the position of the parts on the conveyor	Inf
Station2,10,11,15 …	Traces whether there exists an entity in the associated station or not	Con
removed	The value assigned to this variable determines the entity to be removed from the conveyor animation	Con
i	Incremental counter	Con

Variables are usually just numbers, however according to the requirements of the modelers, vectors or even matrices can be assigned as variables.

3.2.6 Random Number Generator

A simulation study usually depends on random variables rather than pre-defined well known events. Most of the processing times, entity arrivals and transfer times are taken from statistical distributions and also machine failures are assumed to occur randomly. In order to carry out these statistical procedures, each simulation package has an internal software routine that generates a random number between 0 and 1 that is used in sampling random distributions, which is called a random number generator. Everything that is random in a simulation uses the random number generator as an input to determine values.

Today’s simulation packages have their own random number generators. ARENA® has its own random number generator as well. The program has 10 built in random number streams and lets the user use any of them or define his/her own.

3.2.7 Event Calendar

The calendar keeps a list of the events that are scheduled to occur in the future. The detail of the event calendar’s data structure is of no interest when this thesis is concerned, but it should be noted that when the logic of simulation calls for it, a record of information for a future event is placed in the event calendar. One other importance of event calendar is that the simulation clock is updated according to the events at the calendar, rather than flowing continuously. Finally, it is worth mentioning that it is an ending condition for a simulation run when there are no events remaining in the event calendar and event calendar is kept internally by ARENA®.

3.2.8 Statistics Collectors

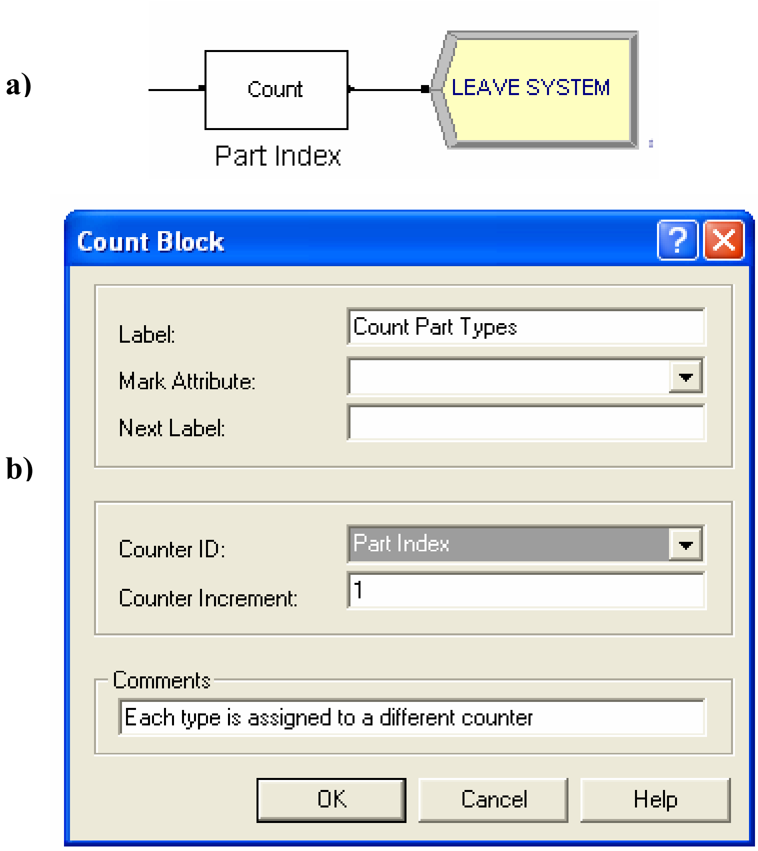
The most tangible outputs of a simulation study are the statistical outputs as output performance measures. A modeler should keep track of several statistical-collector variables as the simulation progresses to come up with the necessary outputs at the end. There are three different types of statistics, namely counters, time-persistent statistics and tallies. Table 3.3 as a list addresses the statistic collectors defined within the models, their brief descriptions and types. It should be noted that ARENA® itself keeps track of almost any statistics available in the model; however it is burdensome to select the required statistics among thousands of available ones in a middle sized model.

Table 3.3 The list of the statistics collected, their brief descriptions and types (Cnt stands for Counters, Per for Time-persistent statistics and Tal for Tallies)

Name of Statistics	**Description**	**Type**
NumberOut1..4	Counts the number of parts of each type	Cnt
Turning Scheduled	Counts the number of times the turning machine is scheduled.	Cnt
Milling Scheduled	Counts the number of times the milling machine is scheduled.	Cnt
Robot Scheduled	Counts the number of times the robot is scheduled.	Cnt
No of Batches	Counts the number of batches produced	Cnt
Timeinsystem	Traces the time parts spend in system	Tal
Lateness	Traces the lateness of parts	Tal
Earliness	Traces the earliness of parts	Tal
Turning Times	Traces durations of turning operations	Tal
Milling Times	Traces durations of milling operations	Tal
Machining Times	Traces durations of total machining operations	Tal
Turning Utilization	Measures the utilization of turning machine	Per
Milling Utilization	Measures the utilization of milling machine	Per
Conveyor Utilization	Measures the utilization of the conveyor	Per
Robot Utilization	Measures the utilization of the robot	Per
Number in AGV	Measures the number of waiting entities in the AGV	Per

Counters, as the name implies, are used to count occasions of a specific event. In FMS, number of parts produced in a given time period and/or at a given cell is usually of interest. The number of occurrence of specific events such as failures of machinery or number of schedules of equipment also needs attention. Initially the counters are set to 0 and these counters are updated on relevant occasions.

Figure 3.6 demonstrates the use of counters. A counter block is placed at the desired point of counting in the model, before the disposal of entities to count part types at this case. The specified counter ID is incremented according to the specified value. As seen in the figure, Part Index is assigned to counter ID. Actually Part Index is an attribute that takes values from 1 to 4 according to the part type. The counter corresponding to the Part Index is incremented, which corresponds to counting each part separately under different counters.



Label: Count Part Types

Mark Attribute:

Next Label:

Counter ID: Part Index

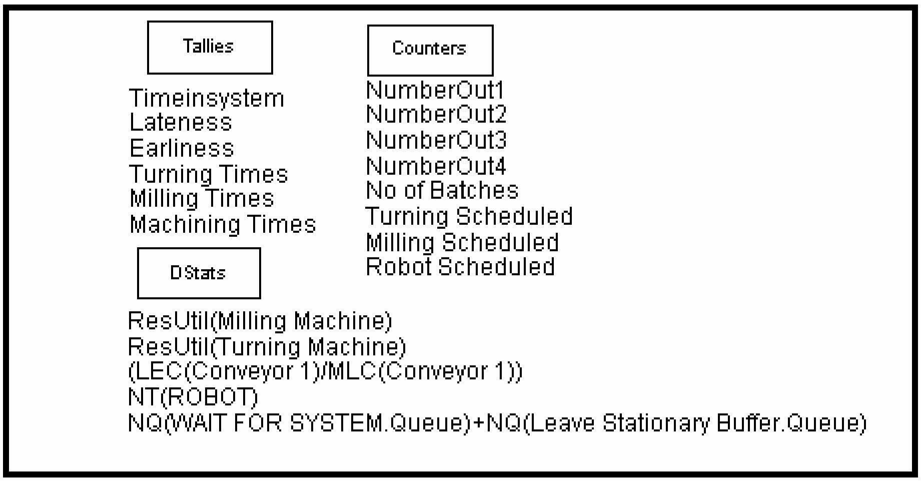
Counter Increment: 1

Comments: Each type is assigned to a different counter

Figure 3.6 Statistics collection using counters. a) Count block in the model b) Details of count block

Time persistent statistics are those that give the time weighted values of some variables in the simulation. The representation of these statistics involves the area under a plotted curve, time being on the x axis, which is an integral representation. In FMS utilizations of machinery and workers and also the number of entities waiting in queues are included under this type of statistics.

Time persistent statistics are kept externally in the model using DStats element of ARENA®. The simulation software has built in operands to calculate variables regarding resources and queues. In Figure 3.7 the full list of the statistics kept is given. The operands that calculate the time persistent statistics can be seen under the DStats Element.



Tallies

Timeinsystem
Lateness
Earliness
Turning Times
Milling Times
Machining Times

Counters

NumberOut1
NumberOut2
NumberOut3
NumberOut4
No of Batches
Turning Scheduled
Milling Scheduled
Robot Scheduled

DStats

ResUtil(Milling Machine)
ResUtil(Turning Machine)
(LEC(Conveyor 1)/MLC(Conveyor 1))
NT(ROBOT)
NQ(WAIT FOR SYSTEM.Queue)+NQ(Leave Stationary Buffer.Queue)

Figure 3.7 Statistics calculated in the simulated system with the addition of the operands of DStats Element

The first four address the utilizations of milling and turning machines, conveyor and the robot respectively. The last line under the DStats element is for the number in queue for two queues, which in reality refers to the number of parts on AGV.

Tally statistics are created using the values collected at single occasions from taking the average, minimum or maximum of a list of numbers (usually attributes) without regard to the time between the observations. The statistics are usually the times spent during various events such as time spent in system, on machinery and material handling devices or waiting in a specific queue. Other time related statistics such as earliness and lateness are also of concern.

3.2.9 Animation

Animation in simulation of FMS is excellent for communication and adding realization to models and it can also be used to debug the simulation program. Validation of simulation models usually require a well set up animation component for the modeler to observe the responses of the model to extreme conditions. Animation can be divided into two main headings as animation of processes and animation of statistics. Both are important in terms of helping the decision makers grab the necessary outcomes out of the simulation study.

The amount of time and effort decided to invest on animation depends on the level of detail required. However, FMS necessitate a sounder animation component when compared to other systems because of the autonomy they involve. In ARENA, animations can be created by several methods. ARENA has its own graphic tools, and built in pictures to be assigned to entities and resources and also, animation medium of ARENA accepts exported pictures and drawings to be used as background images.

In Figure 3.8 a screenshot from the animation of one of the models is given. The states of the robot, conveyor and the machines can be traced from the instant. Also the positions of the existing parts in the system are clearly defined. There are 4 parts of 2 different types in the stationary buffer waiting for station 10 to be emptied to be able to enter the conveyor. There is a part being machined on the milling machine and a finished part in the AGV in addition to one positioned on the conveyor. The robot and the conveyor are stationary at the moment the capture is taken. A green light on the machine indicates that it is busy whereas a red light indicates that it is idle. Simulation clock is also added to the animation for ease of tracing time.

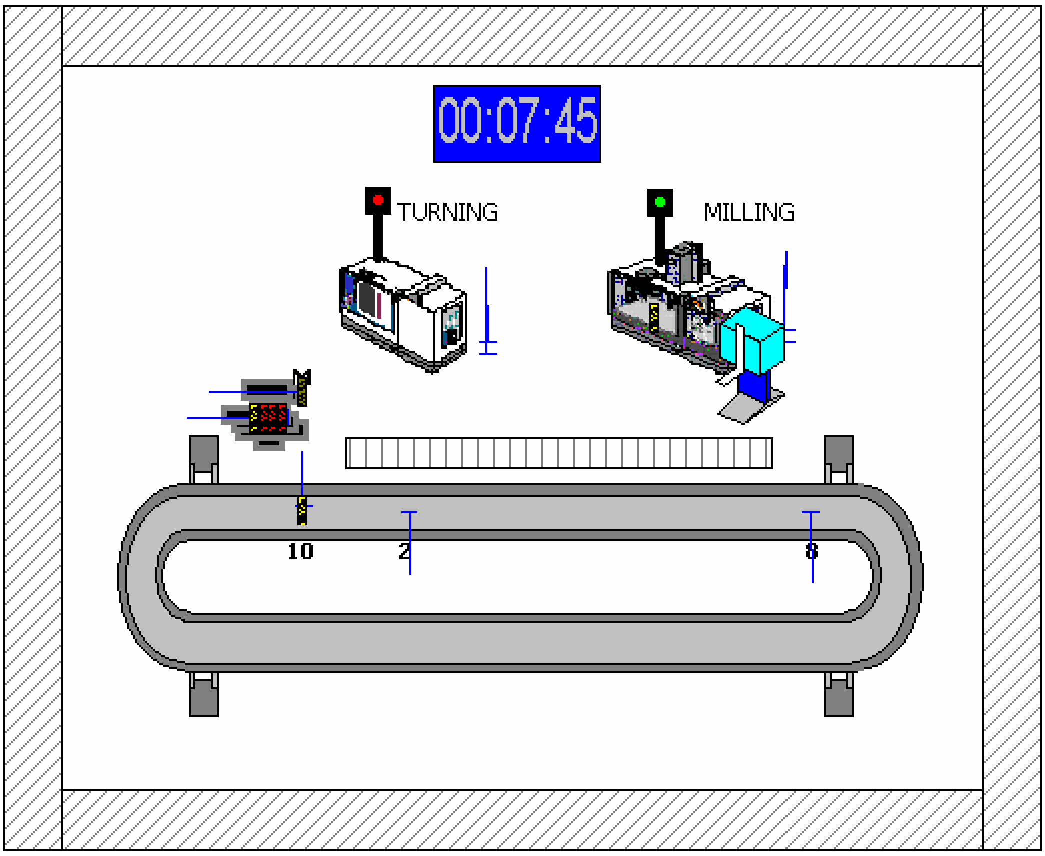


Figure 3.8 A screenshot from the animation

The significance of the collection of statistics was well discussed before in Section 3.2.8. In addition to the acquisition of statistics at the end of runs, the tracing of the intermediate values of these statistics is of equal importance to identify the exact characteristics of the system. ARENA® provides various animation options for concurrent display of model statistics as the simulation run progresses.

In the pilot study, each model has an animation component that shows mentioned statistics dynamically. Dynamic plots are used to show time-persistent statistics such as number in queues, time being in the x axis. Utilizations are demonstrated with levels. Histograms are applied to tallies and counters are visualized. Sample results on the animation screen of statistics are demonstrated on Appendix A on Figures A-1 and A-2 with other simulation results.

3.3 Model development

In this study, ARENA$^{®}$ Simulation Tool is used to develop models. The capabilities of the software, discussed in Chapter 2, are utilized effectively to come up with models that are as realistic as possible. The flowchart of events given in Appendix F is used as a guide for model preparation. During model verification stage, each step of the execution has been traced extensively using both the ARENA$^{®}$'s and Visual Basic$^{®}$'s interactive debuggers and the detected errors in the models and modeling logic have been removed.

The generated models are different in terms of queuing methodologies however the structures of the developed models are common up to some extent. The submodels developed to construct the entire model are part creation, routing and assignment, AGV loading/unloading, selection rule, machining operations, stations, part disposal and data. Each submodel is discussed in the following sections and the modules and blocks of ARENA that are used to develop these sub models are provided as screenshot views in Appendix C.

3.3.1 Part Creation Submodel

The Part Creation submodel is responsible for the introduction of the parts to the models. The nature of this submodel is arranged so that it allows the selection of part arrivals either from a statistical distribution or from a Microsoft EXCEL$^{®}$ file. The selection procedure will be discussed in detail in Section 4.2 when describing the import data module.

In the first option the parts are generated from an exponential distribution of with a mean value of 5 minutes. This value may seem unrealistic when the nature of the FMS in hand is considered as it is not used intermittently; however if it were to be used continuously with work orders following one another, the parts that arrive in this time intervals would result in a steady state system. A creation limit of 180 parts is used, limiting the number of parts to arrive at the system for a day. The ASSIGN block next to the CREATE block is used to assign the attributes such as due dates and part indexes, to identify the created part.

The second option at this stage is letting the user use the values entered to an EXCEL® file as part arrival data. A single control entity is generated at the beginning of the simulation if this option is selected. This entity is responsible for reading the values of part arrival times, the associated part indexes, due dates and priorities. The duplicated entity enters the system with attached data and the control entity keeps on looping until the last part data. Once the last line of data is input from the file, the control entity is disposed. Figure C.1 shows the submodel's blocks and modules.

3.3.2 Routing and Assignment Submodel

As the name implies, routing submodel is responsible for routing the parts that arrive or that are expected to arrive at the AGV station. Firstly, the assignments are made providing the part with some values necessary for simulation. Next, it is decided whether the part is a new part that is trying to leave the AGV or whether it is a part trying to reach AGV. According to the decision, if the part has just entered the system, the position of the furthermost entity on the conveyor is checked and if there is a free space in the conveyor the status of the conveyor is set to available and the part is transferred to a queue where the selection from the queue depends on the utilized selection rule. The duplicated entity leaves the submodel to trigger the selection rule submodel. The part that returns through selection submodel seizes the robot and is sent to loading and unloading AGV submodel.

The other possibility for a part to enter the routing submodel is a part that is to leave the system to be stored in the AGV. After realizing that the part is to leave the conveyor for AGV, the part is removed from the conveyor and sent for part disposal submodel.

3.3.3 Selection Rule Submodel

For most of the models, there is a selection rule submodel that is used to pick up parts from the waiting queue according to the desired production philosophy. The duplicated entity in routing module is used to search within the queue. The part that satisfies the search condition (i.e. earliest due date, longest processing time, etc.) is sent back to the routing module and initially duplicated entity is disposed. Figure C.3 demonstrates the submodel.

3.3.4 AGV Loading and Unloading Submodel

This submodel shown in Figure C.7 corresponds to the station 10 of the actual FMS which is used for loading and unloading the AGV. A part can reach this submodel in three occasions. A part that has recently entered the system that is sent through the routing submodel, a part that has completed its operations and waiting to leave for AGV or a part that has first entered the milling station and passing through the unloading station to be delivered to the turning station.

In the case of a finished part, the action to be taken is straightforward. Using the Branch block, an entity whose JOBFINISHED attribute is set to 1 is sent to the routing submodel. That part will further be sent to the job disposal submodel for being removed from the system.

For the case of a new part, the part is allowed to seize a place on the conveyor. The robot is freed after the part is allocated a place on the conveyor. The procedure after is the same for the remaining case also. After making the assignments for station numbers that determine the position of the parts, the availability of the robot and the turning machine is scanned and when appropriate conditions exist, the part is sent to the station depending on the sequence determined in Sequences element of ARENA$^{®}$ as the part process plan.

3.3.5 Stations Submodels

The flow of the parts on the conveyor is controlled through effective usage of stations. There are three station submodels controlling the positions of the parts on the conveyor two of which are between turning and milling stations and one before the loading / unloading station. At each station, the assignment regarding the position of the part is made initially and when the appropriate conditions exist, the part is conveyed to the station in sequence. Figures C. 4-5-6 show the associated modules and blocks to model these stations.

3.3.6 Machining Operations Submodel

Machining submodels that comprise the turning and milling operations in the system form the core of the developed models. The parts are delivered to this submodel through other submodels and the sequence of the turning and milling operations depend on the production plan of the part. Once all the operations are finished the parts are directed to AGV loading and unloading submodel.

A part that arrives at the Turning Station in Machining operations submodel is checked, considering the production plan and the completed operations after the assignment of station numbers. The parts with a turning operation to be realized initially request the robot, then they are delayed for unloading time. Next, they leave the conveyor and access to the Turning Machine. The robot is freed and after the operation that lasts according to the part type the assignment of work in process pictures is done. After the seizing of the robot, the turning machine is released and the part gains access to the conveyor. Finally, the robot is freed and the part is conveyed for the operation in sequence.

In the developed models, milling station operations are similar to turning station operations. The parts that arrive from the station submodels reach the milling station and the parts that require milling are sent to milling routines. These routines are almost the same as the turning routines, the only difference being the allocation of milling machine instead of the turning machine. The parts that do not require milling are sent to the stations in sequence in their production plan.

The routines of a part accessing and leaving the conveyor are included in the submodel where necessary, to trace the parts on the conveyor and their locations. Also counters are utilized in the submodel to count the number of schedules for the machines and the robot.

3.3.7 Part Disposal Submodel

Once the parts complete operations in the machining operations submodel, and leave the routing submodel to be disposed, part disposal submodel is in action. Firstly, the statistics are collected according to part types, milling times are collected for only milled parts, turning times are collected for only turned parts. Machining times are collected for every part. Once the parts reach the Exit system station, time spent in system for every part is calculated in addition to the lateness / earliness values. Counters are utilized for counting the parts by part type and VBA codes are executed to transfer these values into environmental applications, which is the subject of Chapter 4.

The last operation done in the model is collecting the parts in to batches of 5 pieces and disposing all the entities that represent the parts after counting them. Figure C.8 of Appendix C shows the submodel in modules and blocks.

3.3.8 Data Submodel

Data modules define the characteristics of various process elements, like entities, resources, and queues. They can also set up variables and other types of numerical values and expressions that pertain to the whole model. Icons for data modules in the Project Bar look like little spreadsheets. The Basic Process panel's data modules are Entity, Queue, Resource, Variable, Schedule, and Set; the Advanced Transfer panel includes Sequence, Conveyor, Segment, Transporter and Distance. Entities don't flow through data modules, and data modules aren't dragged into the model window; rather, data modules exist "behind the scenes" in a model to define different kinds of values, expressions, and conditions.

The modules on the Advanced Transfer Panel are used to define the part process sequences, conveyor and transporter properties such as the conveyor type, velocity and cell and segment distances. The modules of the Basic Process Panel are used to define entity types, queues and queue types, resources and capacities, initial values of variables and part picture sets.

CHAPTER 4

INTEGRATION OF SIMULATION MODELS

As described in Chapter 2, the future of simulation is believed to comprise solutions about interoperability and interface of the simulation software. Models that work integrated with other software are favored to deploy the use of simulation to a large number of users and simple and neat interfaces are proposed not to discourage these users and confuse them.

With these ideas in mind, during the study, it is noted that the preparation of input values and the interpretation of the simulation results require expertise and experience. Besides, it is a burdensome and time consuming activity to pick the necessary information from the pages of reports generated. Considering that the value-added from a simulation study will be elevated through the dissemination of the use of simulation to different levels in a company and the need of today's manufacturing world to reach the required information as soon as possible, custom programs and interfaces familiar to an everyday computer user is targeted. However the capabilities and standard operating principles of the simulation software is far from reaching these objectives without external modifications. Following sections represent the effort and methods for attaining a level of integration with auxiliary programs and development of custom interfaces.

4.1 Overview

The topics of integrating ARENA models with other applications and building customized ARENA interfaces are introduced in this section. The illustration of these concepts is realized with the models generated for the FMS system. Sample code developed for this realization is given in Appendix D.

The import data module presents a module in which scheduled arrival times, part types, due dates and priorities are read from an external file. The set-up of the file, communication means and data imports are discussed.

Export data module is for the formation of a report file in which several statistics are presented in terms of charts and tables. The following context is dedicated to setting up of the file, creation of the charts, modifications on the format of the files and data exportation means.

Interface module presents the preparation and usage of custom interfaces to edit, modify and change several parameters of models created. The discussions are about the creation of forms and execution of controls on these forms.

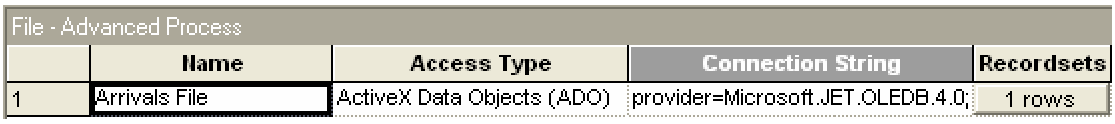
VBA modules present the collection of statistics and exportation of these data to files. The discussion about VBA modules is about the placing of these modules inside the models created and the codes generated to achieve the collection of required statistics.

All those mentioned modules are realized through two Microsoft® Windows® operating system technologies that ARENA® exploits for integrating directly with other programs, ActiveX® Automation and Visual Basic® for Applications (VBA). For data access to a variety of data stores, as in the case of the import data module, ActiveX® Data Objects (ADO), which is also a Microsoft technology, is used.

4.2 Import Data Module

The successful operation of an FMS starts with the work orders. There are several methods to model these working orders, such as taking samples to determine the statistical distribution behind and use random arrival times according to this distribution, or letting the user of the model to input the required values. The models developed throughout the study let the user select from these two options. The selection procedure will be explained in detail in the following sections, but initially the development of a user friendly import module is discussed.

The file reading operation in ARENA starts with the definition of the file to be accessed in *File Element* in the *Advanced Process Panel* of ARENA. The name, Access Type, Connection String and the Recordsets that the file possesses are defined here as shown in Figure 4.1. Two different methods are proposed for reading arrival data. First, data are read in from a text file that contains the Part Type, Time of Arrival, Due Date and Priority information in rows separated by tabs. However, considering the difficulty of preparing a file directly in the above format another alternative is proposed.

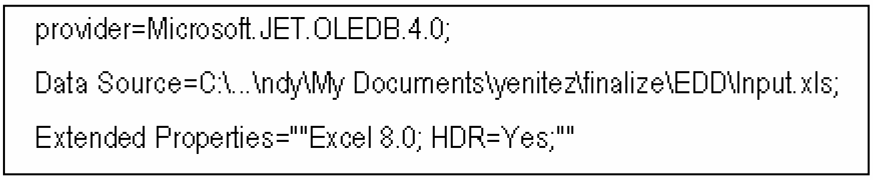


File - Advanced Process

	Name	Access Type	Connection String	Recordsets
1	Arrivals File	ActiveX Data Objects (ADO)	provider=Microsoft.JET.OLEDB.4.0;	1 rows

Figure 4.1 The details of File element in advanced process panel

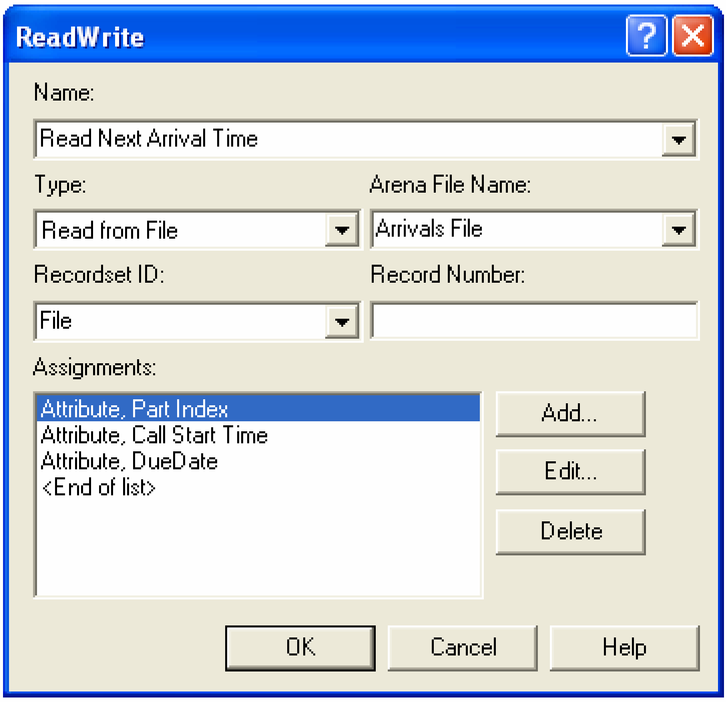
The same information is kept in an Excel® file with headings above each type of information. The field that stores the data is kept as a Recordset and a Connection String that allows data transfer between the file and the ARENA model. Figure 4.2 gives the ActiveX Data Objects (ADO) Connection String that allows the use of Excel with the support of headings used in the developed models.



```
provider=Microsoft.JET.OLEDB.4.0;
Data Source=C:\...\ndy\My Documents\yenitez\finalize\EDD\Input.xls;
Extended Properties=""Excel 8.0; HDR=Yes;""
```

Figure 4.2 Connection string for Excel with headings using ADO

After the arrangement of the files element, it is necessary to adapt the file reading and writing module into the developed model, which is a modeling concept rather than integration. It should be noted that the Recordset ID specified in ReadWrite module should be the same with the Recordset Name in the File element. Once an entity passes from this module data in the Excel file under the headings will be assigned to this entity's specified attributes. Figure 4.3 shows the ReadWrite module.



ReadWrite

Name: Read Next Arrival Time

Type: Read from File

Arena File Name: Arrivals File

Recordset ID: File

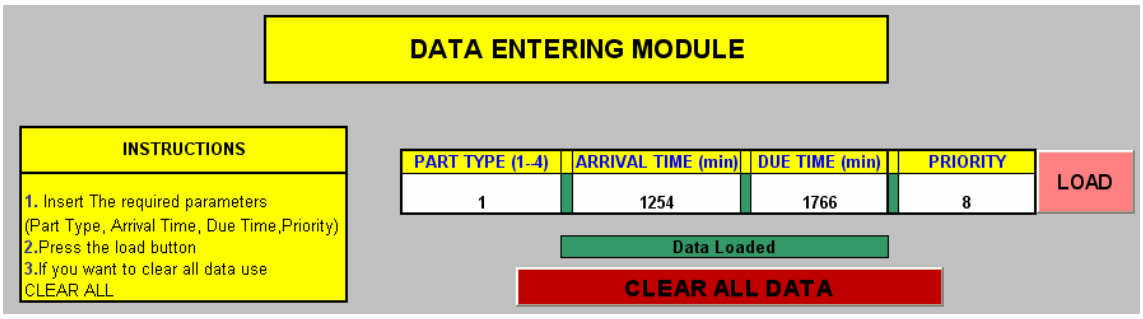
Record Number:

Assignments:

Attribute, Part Index
Attribute, Call Start Time
Attribute, DueDate
<End of list>

Figure 4.3 The ReadWrite module to access the Import Data file

So far, the methods to communicate the model with the prepared Excel file are discussed. In addition to the integration of ARENA and Excel, a program with an interface that will help the user to submit work orders is prepared. This interface shown in Figure 4.4 helps to create the necessary worksheet to be used directly by ARENA® as a data source. The user can easily add new work orders using this program or directly manipulate on the previously defined work orders by opening the work sheet that stores the accompanying data.



INSTRUCTIONS

1. Insert The required parameters
(Part Type, Arrival Time, Due Time,Priority)
2.Press the load button
3.If you want to clear all data use
CLEAR ALL

PART TYPE (1--4)	ARRIVAL TIME (min)	DUE TIME (min)	PRIORITY
1	1254	1766	8

Data Loaded

Figure 4.4 Developed interface for worksheet preparation

The working principle of the program is as follows. The user enters the part type, arrival time, due time and priority of the part to be entered to the model as a work order following the instructions. Upon pressing the load button, entered data is taken into the worksheet and a sorting operation is realized to sort the work orders in the order of increasing arrival time. Clear all data button is used to clear all previous work orders. The space above this button is reserved for messages. If any erroneous data is entered in the cells, data cannot be loaded to the work sheet and an error message of "Erroneous Data" appears. On the case of a successful loading of work order data, "Data Loaded" message appears. The code developed for the realization of above tasks is given in Appendix D

4.3 Export Data Module

Upon completion of simulation runs, ARENA® itself creates reports about almost every component of the model, including resources, queues, attributes and variables transporters, conveyors, etc. However, these reports are of hundreds of pages long and although being classified under main headings by ARENA®, it is a tough task to reach the required information in a small amount of time. The reports created by ARENA® have deliverability, but it is not possible for the end users to manipulate on those reports to make the necessary changes.

Creating customized outputs require programming efforts. For this purpose, the export data module is created by Visual Basic applications with the utilization of ARENA® Objects and ARENA®'s built-in VBA events. ARENA®'s built in VBA events fall into three broad categories as pre-run events, ARENA-initiated run events and model/user-initiated run events. However, most of the programming effort is concentrated about the simulation run. Figure 4.5 shows the sequence of ARENA actions and VBA events that occur with the start of a simulation run. This figure also points out to an important aspect, regarding the type of data that are available for VBA codes. According to these timing options components of the module are placed as seen in the same figure.

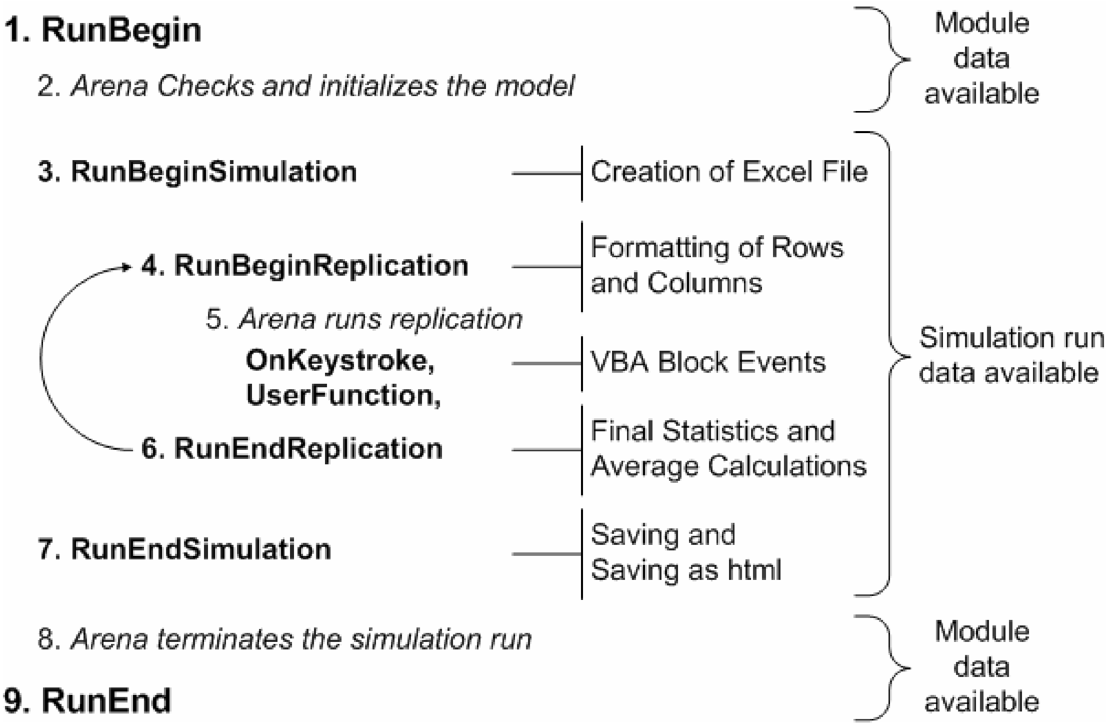

1. RunBegin
2. Arena Checks and initializes the model
Module data available
3. RunBeginSimulation
Creation of Excel File
4. RunBeginReplication
Formatting of Rows and Columns
5. Arena runs replication
OnKeystroke, UserFunction,
VBA Block Events
Simulation run data available
6. RunEndReplication
Final Statistics and Average Calculations
7. RunEndSimulation
Saving and Saving as html
8. Arena terminates the simulation run
9. RunEnd
Module data available

Figure 4.5 Simulation-Run VBA events

The functioning of the data export module starts with the creation of an Excel file in the *ModelLogic_RunBeginSimulation* event of ARENA. After the creation of the file, worksheets to be used for data submission are created and the headers of each page are prepared. Although the values for attributes are generated throughout a simulation run, each worksheet is expected to have standard text values specified for specific cells such as headers and identifiers. The assignments of these text values are done at this stage, preparing the general layout of worksheets.

ModelLogic_RunBeginReplication event is used to create replication dependent sheets to the previously created file. The formatting of these sheets is also done at this stage. By formatting, the creation of row headings and definition of fonts and number formats is meant.

As the simulation run progresses, the columns prepared beforehand, are filled with the values that are transferred from the simulation run via VBA blocks. The details of the VBA modules will be discussed in the following section.

After each replication run is completed, *ModelLogic_RunEndReplication* event is called. At this stage the averages of the replication dependent values in columns are calculated and charts are created that demonstrate the trends of the traced attributes. Statistics that count on the DSTATS module of the ARENA® template (time-persistent statistics) are also calculated at this stage and transferred into the prepared sheets. Figure 4.6 shows one of the output charts of the data export module.

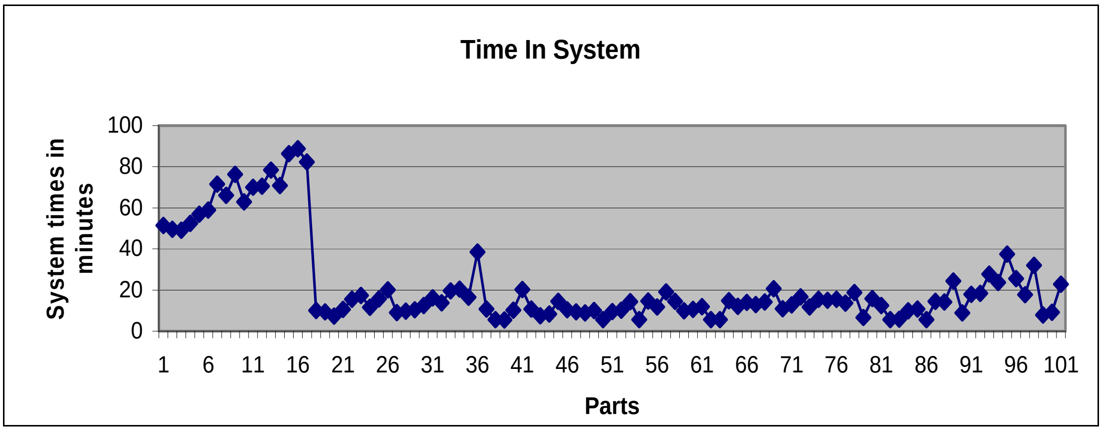
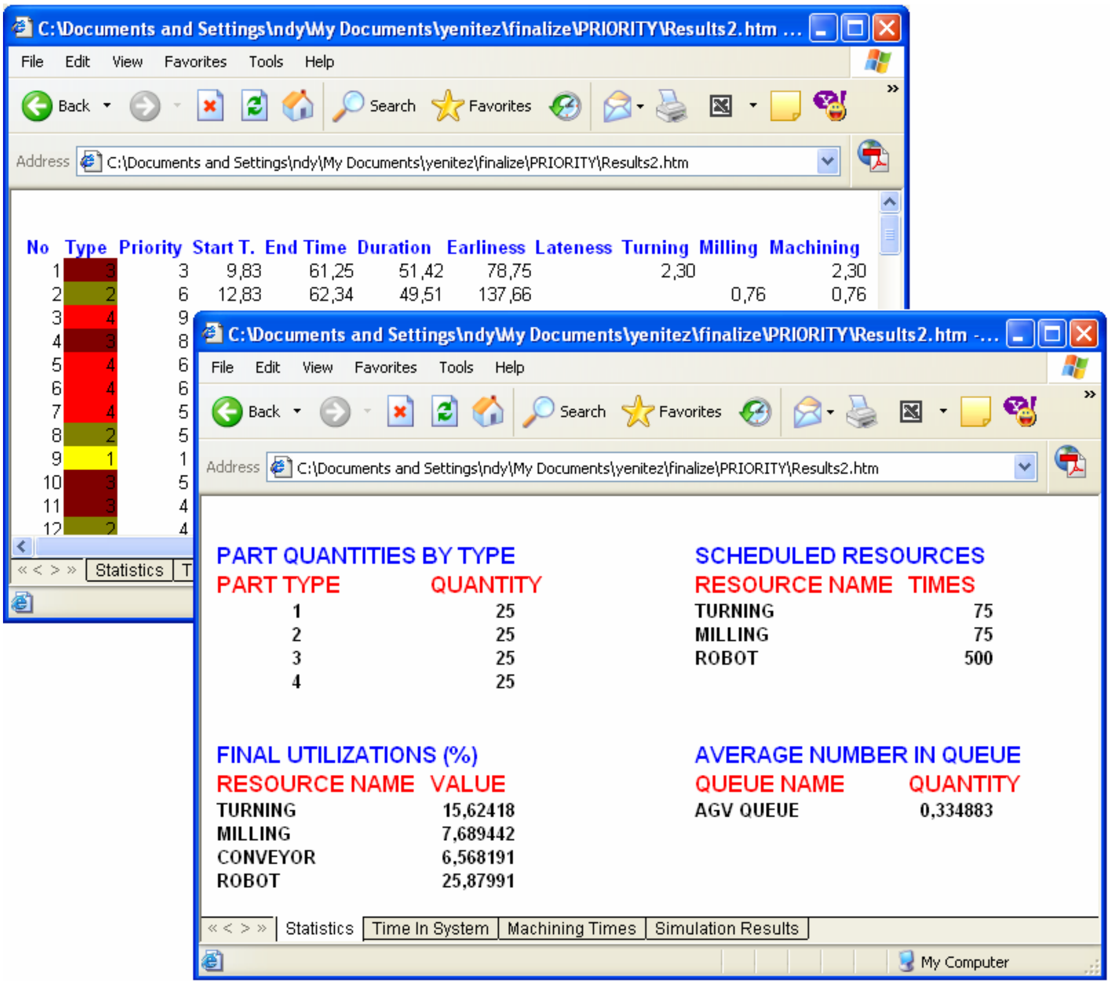


Figure 4.6 Sample chart prepared by the program for data export module

As seen in the developed web pages on Figure 4.7, the export data module prints the values of production related attributes of each part such as part type, priority, system entrance time, exit time, time spent in system, the earliness or lateness according to the due date, the individual turning and milling times and the total machining time. In another worksheet, counter based statistics are printed out, such as the number of parts produced, the number of schedules of turning and milling machines and the robot. Resource, conveyor and robot utilizations and the average number in queue for the AGV station are also provided in statistics worksheet. The other two worksheets seen in the tabs are the charts dedicated to the Time in System and Machining Times attribute values, similar to Figure 4.6.


C:\Documents and Settings\ndy\My Documents\yenitez\finalize\PRIORITY\Results2.htm ...
File
Edit
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Favorites
Address
C:\Documents and Settings\ndy\My Documents\yenitez\finalize\PRIORITY\Results2.htm
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T
C:\Documents and Settings\ndy\My Documents\yenitez\finalize\PRIORITY\Results2.htm -...
File
Edit
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Favorites
Tools
Help
Back
Search
Favorites
Address
C:\Documents and Settings\ndy\My Documents\yenitez\finalize\PRIORITY\Results2.htm
« < > »
Statistics
Time In System
Machining Times
Simulation Results
My Computer

No	Type	Priority	Start T.	End Time	Duration	Earliness	Lateness	Turning	Milling	Machining
1	3	3	9,83	61,25	51,42	78,75		2,30		2,30
2	2	6	12,83	62,34	49,51	137,66			0,76	0,76
3	4	9								
4	3	8								
5	4	6								
6	4	6								
7	4	5								
8	2	5								
9	1	1								
10	3	5								
11	3	4								
12	2	4								

PART QUANTITIES BY TYPE

PART TYPE	QUANTITY
1	25
2	25
3	25
4	25

SCHEDULED RESOURCES

RESOURCE NAME	TIMES
TURNING	75
MILLING	75
ROBOT	500

FINAL UTILIZATIONS (%)

RESOURCE NAME	VALUE
TURNING	15,62418
MILLING	7,689442
CONVEYOR	6,568191
ROBOT	25,87991

AVERAGE NUMBER IN QUEUE

QUEUE NAME	QUANTITY
AGV QUEUE	0,334883

Figure 4.7 The outputs from the Data Export Module

The idea presented here is that almost every statistics that is naturally kept by ARENA® can also be externally calculated and presented to the end user with the tools he/she is already familiar with. The modeler should specify the type and amount of necessary information considering the needs of the end user and customize the data export module accordingly.

4.4 VBA Modules

When a simulation run is started, ARENA® checks and initializes the model placing the model in a run state. During the run, the values of variables, resource states, statistics, etc. can be reached, examined and changed through ARENA®'s run controller and through VBA codes. VBA codes can be utilized before, after and during the run, according to the type of the tools used. As described before, the timing of the events on the data export module was determined according to the built-in events of ARENA®, however with the use of VBA modules the occurrence of events is synchronized with special events in the simulation.

The VBA module operations in ARENA® start with the placement of a VBA block inside the model on appropriate location. The place of the block determines the time of execution of the associated VBA code. There are three VBA blocks associated with each model in the developed simulation models. Figure 4.8 shows the placement of one of the VBA modules inside the model. The VBA block is placed as if it is one of the other modules or blocks with one enter and one exit point.

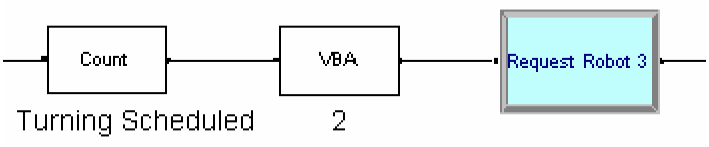


Figure 4.8 Placement of VBA blocks

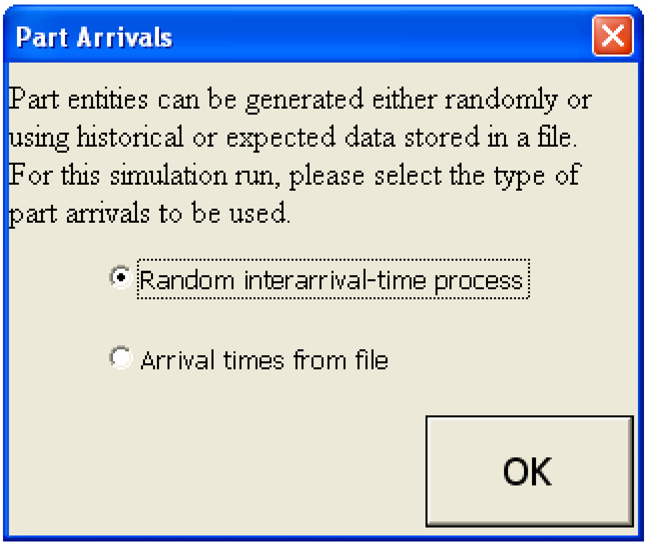
The three VBA blocks are placed within the model for the updating of fields in the excel worksheet created by the Data Export Module. The first VBA block is placed at the system exit, where the parts leave the system. At this point, the VBA_Block_1_Fire() procedure is called for each entity. This procedure is responsible for inputting the values of the attributes of the part that passes through the block to the corresponding fields on the Excel sheet named “Simulation Results”. In addition to that the part numbers in “Statistics” sheet is incremented accordingly.

The other two VBA blocks are placed after a part is machined on one of the machines to indicate the number of schedules of each machine. Whenever an entity passes through the VBA module, the counter values kept in the simulation run are transferred to the corresponding cells in the “Statistics” work sheet.

4.5 Interface Module

The necessity of development of custom interfaces for simulation was discussed on several occasions before. The purpose of the interface module is to interact with the users who are running ARENA® models, while allowing the user to make simple manipulations without delving into the details of the model. Several kinds of interfaces can be built providing the user with options to select from about the general parameters of the simulation run or about specific data regarding the model. Also, interfaces that let the user to interact with and modify the model on the occurrence of specific occasions can be developed.

An interface that allows a choice to be made to use either part arrivals generated from a random process or from a file when the model runs is developed to assess the feasibility of the concept. Figure 4.9 shows the pop up window that is displayed at the beginning of the run providing the options. The user selects the desired option by clicking on the appropriate option button, then clicks OK button to allow the simulation run to commence.



Part Arrivals

Part entities can be generated either randomly or using historical or expected data stored in a file. For this simulation run, please select the type of part arrivals to be used.

● Random interarrival-time process

○ Arrival times from file

Figure 4.9 Part arrival interface

The first step for preparing this kind of an interface is to set up the model so that it can perform all of the operations offered as options to the user. In other words, when the developed interface is considered the model should be modified to generate entities from both the random arrival process and the input file. The details of this operation were described in Chapter 3 on the development of sub-models. The VBA *Userform* is prepared as the second step, inserting the option and command buttons and labels. The next step is writing the Visual Basic® code that runs according to user's choices and makes the changes on the modules in the model.

The timing of the interface is arranged according to the placement of the show option for the form, *frmArrivalTypeSelection.Show*, for our case. The form can be associated with VBA blocks in the model or with built-in ARENA® events. Part Arrivals interface is functional at the start of a run so, it is displayed under the *ModelLogic_RunBegin* event of ARENA®.

The idea presented here is that by the development of custom interface, the modeling capabilities of an advanced modeler can be transferred to an average end user through the use of programming techniques.

CHAPTER 5

TEST RUNS

In order to check the credibility of the developed models several runs are realized under different scenarios. The results obtained after these runs provide a scientific basis to evaluate the optimal sequencing algorithm for parts to enter the system. The scenarios of the runs, run parameters used in the test runs, and the results of these runs are described in the following paragraphs.

5.1 Test Scenarios

One of the main objectives of this work is to create a system that enables making comparisons between different production philosophies. A specially tailored bidding algorithm or a well known and easy to apply heuristic, each philosophy come with its own advantages and disadvantages. Before being applied to the real system, possible outcomes of the changes in scheduling philosophy can be seen in advance of using the scenarios developed.

The agent based system in hand, as the name implies, uses agents to decide on the sequence of the jobs. The algorithm used in the system for realizing the tasks is called “bid preparation algorithm” and can be summarized as follows (Cangar 2000). The customer agent identifies and announces a task to be done and criteria for bids. The bidding server agents send bids for the announced task to the costumer agents. The bid, satisfying the given criteria is awarded and the task is given to the selected server.

The algorithm proposed is resource driven and operational if there are competing resources (servers in agent terminology). With this in mind, one can realize that the scheduling system do not take the properties of the work orders such as due dates or parts with different process plans into consideration, and these work orders are processed in the order of arrival.

An improved version of the algorithm contributed by Alataş (2003) can deal with urgent work orders and the concept of assigned priorities is introduced. In this method it is possible to reorder the compartments of the queue using these properties. The parts with same priorities are dealt with the simple First Come First Served (FCFS) rule.

The following sections are dedicated to the developed alternative scenarios for the realization of a given production plan. These philosophies are discussed briefly and application methods are discussed.

5.1.1 First Come Served

The simplest of all kinds, FCS (First Come Served), is considered as the first alternative to provide a basis for comparisons. The philosophy is simple and straightforward as the name implies; the first part to come to the system is served first and the other parts are delayed until the completion of the tasks, or in other words considering the purpose of our production system, FCS refers the one by one processing of parts in the order of arrival.

FCS is applied in the system in the following manner. The first work order that arrives in the Automated Guided Vehicle (AGV) triggers the system and the robot is utilized to transfer the part to a free cell in the conveyor. The part is then processed in the specified order according to the assigned process plan. The other parts that belong to other work plans are kept in the AGV until the work order that is currently processed is completed. After the completion of all the processes of the work order, the part is conveyed to unloading station and the robot is finally utilized once again to unload the part. The sequence is repeated until all the work orders waiting in the

AGV are processed. The first part to enter the system is decided according to the order of arrival by AGV.

5.1.2 First Come First Served

The next alternative methodology to consider is First Come First Served (FCFS). This philosophy differs from the previous one, from the point of allowance of multiple numbers of parts in the system simultaneously. It indicates the policy of a particular establishment to serve the parts in the order that they have arrived, without other biases or preferences.

The application of FCFS to the simulation system is similar to FCS. The first work order that arrives in the AGV triggers the system and the robot loads the part from the AGV to the conveyor. When a new part arrives to the system at this time, that part is also transferred considering the current state of the robot the conveyor and the machines. The selection of the entering part among the parts waiting in the AGV is realized by FCFS rule. The inherent properties of the Hold module of ARENA®, directly selects parts accordingly.

5.1.3 Earliest Due Date

As another alternative methodology, due dates of the parts are considered. Earliest Due Date (EDD) indicates the policy to accept the part with the earliest due date to the system, without considering any other property of the parts. In EDD, multiple numbers of parts are allowed in the system at the same time as in the case of FCFS.

The application of EDD to the simulation system is similar to FCFS. The first work order that arrives in the AGV is directly taken into the system and the other parts that arrive afterwards are temporarily kept in the AGV before being transferred to the conveyor. The selection of the entering part among the parts waiting in the AGV is realized by EDD rule. For this purpose a selection rule submodel is added to the developed model to search among the parts waiting in the AGV for the part with the earliest due date.

5.1.4 Longest and Shortest Process Times

Two other alternative methodologies consider the remaining process times of the parts. Longest Process Times (LPT) and Shortest Process Times (SPT) indicate the policy to accept parts according to the total time for turning and milling operations with longest process time first and shortest process time first, respectively. SPT is generally regarded as an efficient rule in that it tends to reduce average waiting time, and hence average flow time.

The applications of LPT and SPT to the simulation system is similar to the mentioned other methodologies. The parts waiting in the AGV are reordered as new parts arrive in the cell, moving the parts with longest or shortest process times to the front of the queue according to the selected rule. The submodel developed for EDD case has been modified to account for selection of the appropriate parts with the desired attribute.

5.1.5 Priority

Priority is a term that refers to precedence; that is the status established in order of importance or urgency. Each work order comes with a defined priority value. The work orders are queued according to their priority values so the part with higher priority can be manufactured before the others. The queuing list is dynamic that, it is updated by a decreasing priority, each time a new work order is added to the queuing list.

The application of priority to the models requires the assignment of priorities to the parts, before a part enters to the AGV. Then the work orders that are delayed in the AGV are accepted to the system considering these assigned priority values, being the part with the highest value the first. A modified version of the previously developed selection rule submodel is used for this case as well.

5.2 Run Parameters

For each simulation run, it is necessary to define some parameters beforehand. These parameters include, simulation dependent parameters such as run lengths, and model dependent parameters such as arrival schedules and due dates. Different values specified for these parameters can affect the outcomes from a study drastically.

5.2.1 Determination of Run Lengths

The system analyzed in this study is inherently a non-terminating system. In a non terminating system, there is no event that causes the system to return a fixed initial condition. Hence, there is no natural basis for selecting either the starting conditions or the length of the runs.

For the cases of input data reading from prepared files, the run length phenomenon is out of consideration as the simulation terminates when there are no existing entities in the system, which is completely based on the number of parts given in the input data files.

For the cases of input arrival times from statistical distributions a run length of 24 hours is specified, keeping the unmanned nature of FMS's in mind. This value is subject to change according to the modeling horizon and modeling objectives of another FMS.

5.2.2 Determination of Arrival Schedules

As stated before in the preceding chapters, the models can accept two types of data for part arrivals. Under operating conditions for the models, the data input for part arrivals is expected from the user through the input data module; however for sample runs a data input file is generated. The file includes 100 parts from different part types with associated arrival times, due dates and priorities which are all created randomly.

When part arrivals from statistical distributions case is concerned, one should carry out statistical data analysis and distribution fitting techniques to obtain statistical distributions to represent the patterns of part arrivals. However, when the working principles of the modeled FMS are concerned it should be noted that the system completely works on deterministic part arrival schemes under the consent of the system administrators. So the selection of part arrival statistical distributions is done considering the other model parameters taking into account the machining times of the parts, not to end up with a system that will extensively be populated with parts and contrarily, not to have a few parts traveling in the system. The exponential distribution is used to model inter arrival times in random arrivals of parts with a mean value of 10 minutes.

5.2.3 Determination of Due Dates

As in the case of part arrival times, due dates are also subject to two methods for being attached to the parts that enter the system. Under normal operating conditions the user inputs due date values together with the part arrival schedules using the data input module. In the case of our runs the due dates are arranged according to a Uniform distribution. A random number is selected between 0 and 100 and it is added to the system entrance time of a part to be used as a due date. This value is consistent with average times spent in systems and provides the basis for the calculation of lateness and earliness values.

In the case of selecting arrivals from random distributions, due dates are calculated in the same way as in the case of the sample test runs.

5.3 Run Results

Test runs are made by using the specified parameters in the preceding section. Part process plans used in the runs are given in Appendix E. The statistical results of the runs under 6 different scheduling algorithms are given on the following tables. Table 5.1 gives the average values for the selected performance measures. These values are taken from the Export Data Module's of the corresponding models. Further results can be examined in Appendix A.

Table 5.1 Averages of performance measures.

	FCS	**FCFS**	**EDD**	**SPT**	**LPT**	**PRI.**
(in minutes)	TALLY VARIABLES					
Lateness Value	66.261	48.517	34.492	36.571	56.545	39.800
Earliness Value	19.120	63.181	30.451	30.541	30.782	31.810
Turning Times	6.683	6.675	6.678	6.687	6.687	6.685
Milling Times	3.496	3.505	3.505	3.501	3.501	3.496
Machining Times	7.634	7.635	7.638	7.641	7.641	7.632
Time in System	102.830	56.814	57.897	57.094	75.363	63.518
Total Makespan	1236.55	1159.46	1157.99	1151.01	1155.15	1151.95
	DISCRETE-CHANGE VARIABLES					
Milling Utilization	0.212	0.255	0.253	0.256	0.254	0.254
Turning Utilization	0.405	0.442	0.445	0.447	0.449	0.448
Conveyor Utilization	0.020	0.227	0.237	0.236	0.258	0.223
Robot Utilization	0.243	0.331	0.324	0.333	0.333	0.334
Number in AGV	7.323	0.903	0.871	0.825	2.086	1.570

In addition to the average values of the performance measures, some of the statistics are important from the point of number of occurrences such as the number of late parts and early parts. Each delivers different costs to production, although it is out of scope of this study.

Table 5.2 Number of occurrences for important performance measures.

	FCS	FCFS	EDD	SPT	LPT	PRI.
	TALLY VARIABLES					
Lateness Value	85	41	60	57	65	57
Earliness Value	15	59	40	43	35	43

Additionally, the numbers of schedules for the robot and the turning and milling machines is important. The scheduling of the components can incur fixed costs and from maintenance point of view they need to be traced. As the number of parts and their respective plans are same for all the scenarios these values are also the same for all runs.

Table 5.3 Number of schedules for hardware components.

	Turning Machine	Milling Machine	Robot.
Number Scheduled	75	75	500

Some statistics are important considering the resulting maximum values. The maximum time parts spend in system and the maximum lateness values are important for tracing the system performance and the maximum number of parts on the AGV is important to define the incoming part capacity for the static buffer.

Table 5.4 Maximum values for important performance measures.

	FCS	FCFS	EDD	SPT	LPT	PRI.
(in minutes)	TALLY VARIABLES					
Lateness Value	138.52	138.39	109.79	168.14	285.37	153.00
Time in System	154.28	163.71	170.12	225.33	297.06	246.53
	DISCRETE-CHANGE VARIABLES					
Number in AGV	12	6	6	5	10	13

More of the results obtained are provided in Appendix A as they are prepared in export data module. In these demonstrative test runs of the developed models it is observed that the results obtained can be used effectively to decide on the parameters of the FMS both in terms of hardware components and production philosophies. Sample comments depending on these results are as follows:

When the tardiness values are concerned it is observed that the EDD principle provides the minimum average for lateness values, which is an expected result. The long waiting times in SPT and LPT algorithms increase the time in system values for specific part types, which in turn increases the lateness values. The “only one part in system” principle of FCS results in elevated values for all time dependent statistics except earliness values. The use of EDD does not guarantee the minimum number of tardy jobs. This fact is seen on Table 5.2 as the minimum number of tardy jobs is attained in the FCFS rule. This is not a surprising result as the due dates are dependent on the system entrance time.

Turning, milling and consequently the machining times are almost equal for all sample runs as the part numbers and types used in all the runs are the same. The importance of this statistics arises when the total manufacturing times are compared with makespans of the parts. In the best configuration that minimizes the time in system of the parts, FCFS rule, the average manufacturing time is about 14% of the average makespan of the parts. In the most unfortunate case this value drops to about 7.5 %. The effect of this fact demonstrates itself through low utilizations of machines.

The utilization of turning and milling machines are about 45% and 25% respectively and do not differ in significant amounts from one scenario to another. This is also an expected result, as the scenarios directly affect the system entrance sequences for parts and there is no machine dependent sequencing. Another fact identified through these utilization and machining times values is that the system is highly transportation and storage means dependent as most of the time parts spend in the system are due to waiting on the conveyor.

The number in AGV statistic is important to identify the AGV capacity. As expected, The FCS scenario results in the most number of both average and maximum parts on the AGV as only one part is accepted into the system. The LPT and priority scenarios also cause elevated number of parts waiting on AGV as less prior parts or, parts with short processing times are forced to stay on the AGV for long times. The maximum number of parts on AGV is also important as the capacity is directly dependent on this value. The SPT scenario results in the least number of both maximum and average entities on AGV.

It is obvious that the results obtained are production order dependent and are subject to change. Considering all those results, an objective function can be determined according to the requirements of the management of the FMS. Before realizing the production orders on the actual FMS, these orders can be processed on the models and according to the results of the runs a production scheme can be figured out.

CHAPTER 6

CONCLUSION AND FUTURE WORKS

This research on Computer Integrated Manufacturing is mainly focused on the implementation of a flexible, re-configurable simulation and modeling system. It focuses on realizing the modeling and simulation of Flexible Manufacturing Systems by the use of the hardware in Middle East Technical University, Mechanical Engineering Department, Computer Integrated Manufacturing Laboratory (METUCIM), Ankara, Turkey as a test-bed. In addition to that, the means of integration of simulation with auxiliary programs is demonstrated. The models developed throughout the study are used to come up with different scenarios of production and sample results and decisions about production issues that can be attained through the use of simulation are provided.

Simulation has historically found a great deal of applications in FMS's. The need of simulation arises with the questions to be answered when planning of an FMS at the design or operation stages. As it can be seen in the outline of the thesis; the first part of this study deals with the identification and implementation of structural simulation components on FMS. These components are defined and explained in detail by the use of examples taken from the developed models. Subsequently, the model development procedure is explained with the introduction of sub-models. These concepts are important to provide a guideline for the development of simulation models for other FMS's.

Simulation is expected to increase its strength and area of application through integration with other tools. These other tools will include spreadsheets, statistical analysis software, mathematical optimizers, programmable logic designers, robotic software, or process flow layout and analysis tools. With this motivation in mind, the scope of the work is extended to comprise the development of methods and applications to be used for linking a simulation package, ARENA®, to less advanced programs such as text editors and Microsoft Office® programs with the development of custom interfaces to provide a fast and effective decision support tool for every level of a company. This combination provides the users with a tool that is fast to use and easy to maintain for the assessment of performance measures for FMS.

The actual aim to be expected from a simulation study is its supplying a scientific basis for making decisions about the modeled system. The developed software provides the infrastructure and it is the management's task to analyze the results and respond to the facts of the system. As the final component of the study, sample simulation runs under different scenarios of production are presented. The preparation procedure of the runs and the interpretation of the results obtained through the developed software are important to provide an idea on the effective use of simulation in manufacturing systems.

The scope of the thesis comprises both a modeling and application approach. It provides guidelines on the determination of modeling parameters for FMS and integration of the models with other programs. Although attentive work is employed on the subject, the approach has certain limitations and drawbacks. These can be summarized as:

- The results of the models can not be directly verified with the existing agent based system as the system is limited considering the number of work orders that can be processed at the same time. The verification is done by comparing the responses of the system with the responses of the models.

- The bidding times those contribute to the overall systems times in the actual FMS are neglected through the modeling approaches. Actually the response of the system under heavy work loads is unpredictable due to computer crash problems. So bidding times that contribute to less than %1 of task makespans is neglected during modeling.

- The animation component of the models can be improved so that the accompanying graphic quality of the simulation is enhanced. Currently, only a 2-D animation is present

As the scope of the thesis is widespread through the topics of both application and methodology, the presented study offers strong prospects for future research integrated with other ongoing research topics in the Integrated Manufacturing Technologies Research Group (IMTRG). By the work done in the current research, following possible future improvements can be deducted:

- The models can be used to provide a basis for the application of bid preparation algorithms to the existing FMS. The performance of several different algorithms can be first examined on the models and then be implemented to the FMS.

- Developed models can be improved and extended to account for extended scenarios beyond the current capabilities of the existing system, to provide a basis for the improvement of the FMS.

- The concept of integrating simulation models with other manufacturing software, such as Computer Aided Manufacturing and production planning programs can be investigated to disseminate the use of simulation into other application areas.

- A level of integration can be attained for driving the models in interaction with the existing agent based software. The states of the components of the FMS can be fed into the developed models and the models can be run simultaneously with the system.

- A second level of integration that can be attained on the shop floor of FMS is on the control of the “Agent” system. Once a two way interaction between the simulation models and the existing hardware is established simulation can be directly used to control the ongoing manufacturing operations to get the desired outputs on performance variables. The advantage of fast computing times of today’s computers can be utilized to give manufacturing orders according to the result of the simulation model.

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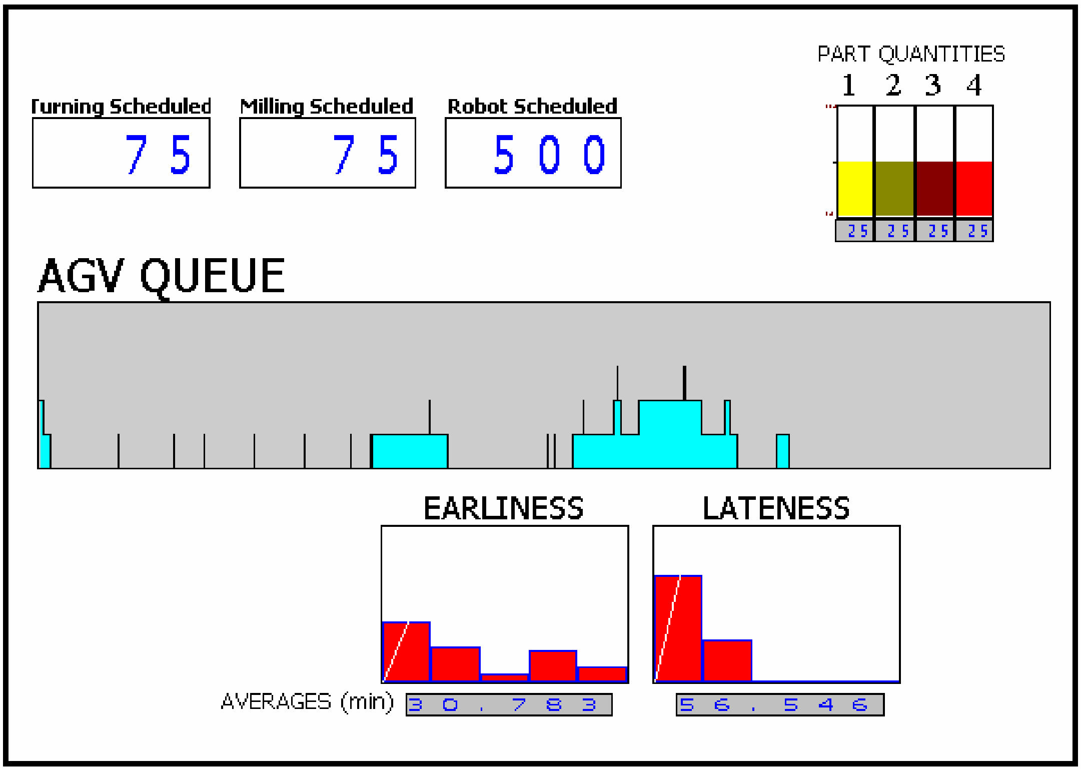
APPENDIX A

RUN RESULTS

ARENA® itself provides the user with the opportunity to view several reports, comprising a great number of statistics kept within the system. However, the classification and interpretation of these is a time consuming and burdensome activity for the potential users that are not interested in details of the simulation models. The following results are taken from the models' export data modules. The results of LPT scenario are supplied for demonstrative purposes. Figures A.1 and A.2 are from the animation submodel and show the results in a graphical form.



Turning Scheduled 75

Milling Scheduled 75

Robot Scheduled 500

AVERAGES (min) 30.783 56.546

Figure A.1 Graphical results for LPT scenario

Figure A.1 shows the final counter values, the time dependent change of the number of parts on the AGV Queue, and histograms of earliness and lateness values. Figure A-2 shows the final utilizations of machines conveyor and the robot. The times parts spend in system and machining times are supplied as histograms. The production plan parameters can be clearly seen in the figures.

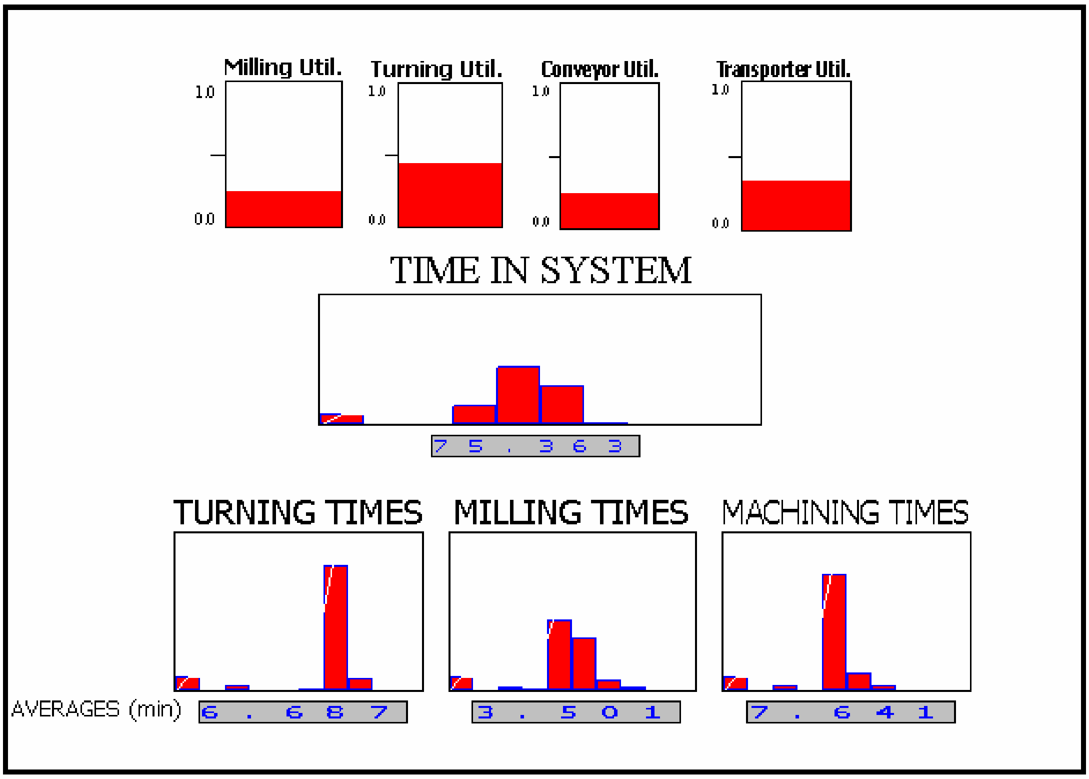


Figure A.2 Additional graphical results for LPT scenario

The data export modules supply the same information in a more formal and structured way, in terms of sheets and charts. Figures A.3 and A.4 are the charts that are prepared automatically in Excel® to show the individual times for times part spend in system and the machining times. The machining times are grouped under 4 main values, each corresponding to a specific part type. The time in system values reach a peak value of about 300 minutes. It is not a surprising fact that the corresponding machining time for that part is only about 3 minutes which is one of the shortest values. The LPT rule forces that part to wait in the queue for a long time.

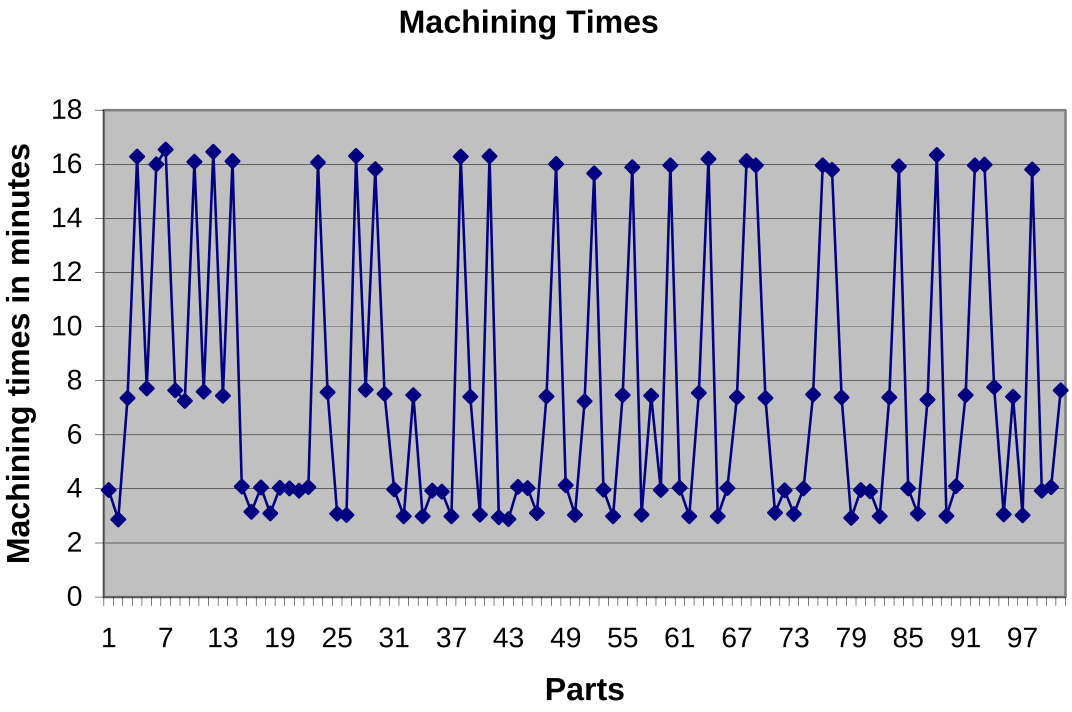


Figure A.3 Machining times of parts under the LPT scenario

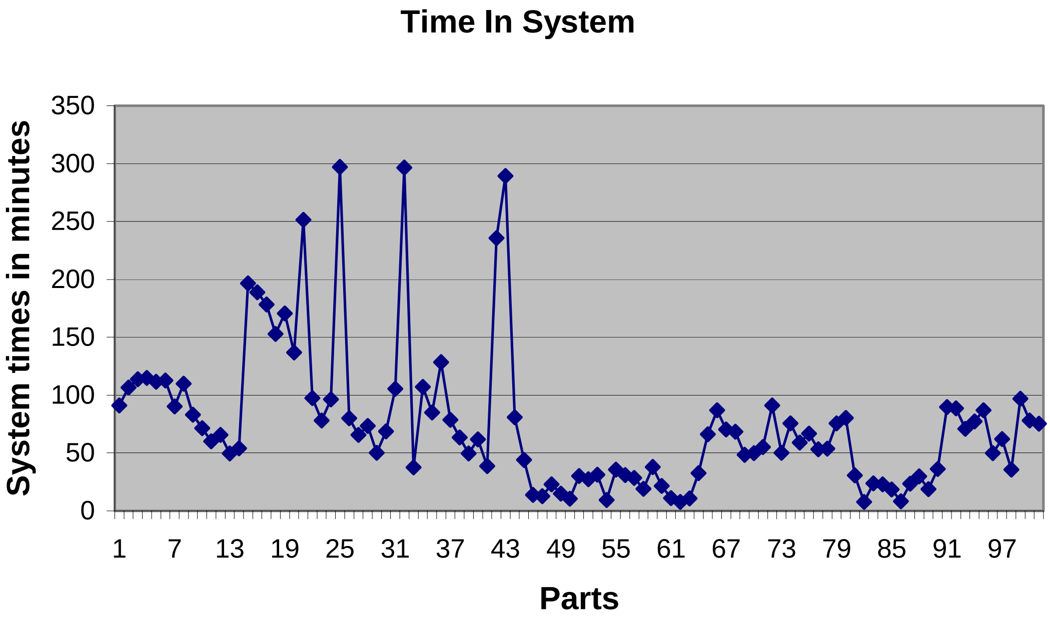
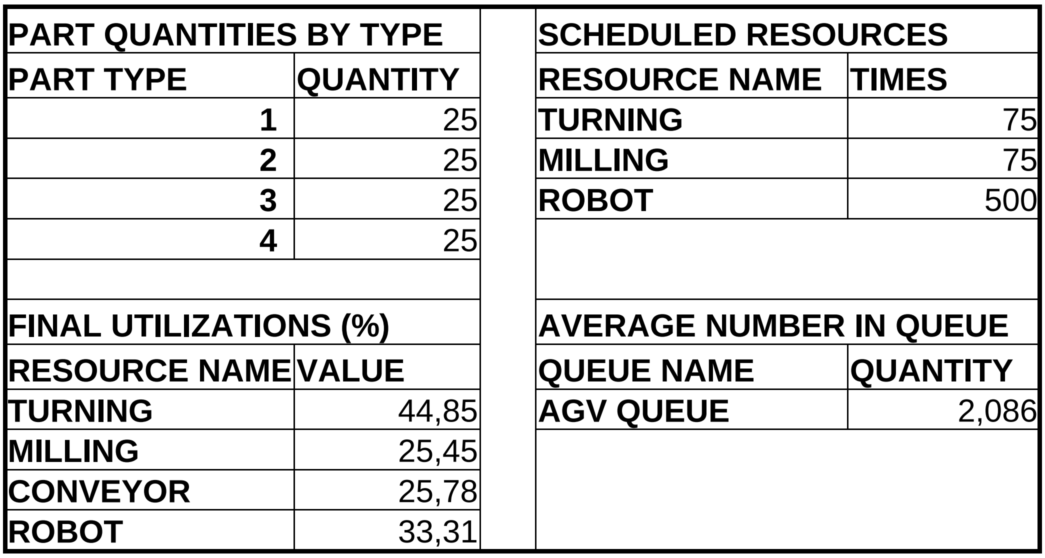


Figure A.4 Time in system for parts under the LPT scenario

The same information on part statistics that is graphically available on Figures A.1 and A.2 is also supplied in worksheets under the “statistics” tab. Figure A.5 shows those results of the LPT scenario According to the production plan 25 parts of each types is produced scheduling the turning and milling machines for 75 times and the robot for 500 times. The average number of parts on the AGV queue is about 2. The utilizations of the machinery is almost the same with the other production scenarios.



PART QUANTITIES BY TYPE	
PART TYPE	QUANTITY
1	25
2	25
3	25
4	25

SCHEDULED RESOURCES	
RESOURCE NAME	TIMES
TURNING	75
MILLING	75
ROBOT	500

FINAL UTILIZATIONS (%)	
RESOURCE NAME	VALUE
TURNING	44,85
MILLING	25,45
CONVEYOR	25,78
ROBOT	33,31

AVERAGE NUMBER IN QUEUE	
QUEUE NAME	QUANTITY
AGV QUEUE	2,086

Figure A.5 Summary of statistics under the LPT scenario

The “simulation results” tab supplies information for all of the parts that are processed in the system in worksheets. The averages of the statistics which is important to calculate the average machining times, time parts spend in system and earliness and lateness values are also presented at the end of Table A.1.

The pattern of the results shows that parts of the same type are prone to be taken into the system consequently as their production times are almost the same. After the first a few parts that enter the system because of the non-existence of other types of parts, parts with longer processing times are accepted to the system (Types 3 and 4). During this time the other parts that enter the system are forced to wait in the AGV queue. As an example Part no 15, with a part type of 1, enters the system at 25th minute however waits until the 220th minute for the other parts with longer processing times. Accordingly, the times those parts with shorter machining times spend in system is longer compared to parts with longer machining times.

Table A.1 Part dependent simulation results.

No	Type	Start	End	Duration	Earliness	Lateness	Turning	Milling	Machining
1	1	7,83	98,92	91,08		43,74	2,48	1,48	3,96
2	2	13,02	119,74	106,72		28,76		2,87	2,87
3	3	17,52	131,45	113,93		67,70	7,35		7,35
4	4	23,57	138,58	115,01		56,56	10,26	6,02	16,28
5	3	27,66	139,18	111,51		53,92	7,71		7,71
6	4	29,01	141,60	112,60		62,12	9,99	6,01	16,00
7	4	65,68	155,94	90,26		33,07	10,37	6,17	16,55
8	3	46,59	156,53	109,94		100,27	7,65		7,65
9	3	73,92	157,13	83,20	6,87		7,26		7,26
10	4	98,04	169,35	71,31	26,12		10,13	5,96	16,09
11	3	109,87	169,94	60,08	23,86		7,59		7,59
12	4	130,79	196,34	65,54		65,44	10,31	6,14	16,45
13	3	158,02	207,63	49,61		26,92	7,44		7,44
14	4	165,38	219,49	54,11	4,77		10,20	5,91	16,11
15	1	25,25	221,91	196,67		145,43	2,55	1,54	4,09
16	2	41,84	230,60	188,76		112,31		3,15	3,15
17	1	71,04	249,50	178,46		94,17	2,53	1,53	4,06
18	2	108,38	261,19	152,81		96,35		3,09	3,09
19	1	100,76	271,40	170,64		112,39	2,53	1,52	4,04
20	1	139,34	276,15	136,80		91,29	2,52	1,49	4,01
21	1	39,89	291,20	251,31		170,48	2,48	1,46	3,94
22	1	203,48	301,06	97,58		31,66	2,51	1,56	4,06
23	4	232,81	310,90	78,09		75,61	10,04	6,02	16,06
24	3	215,20	311,49	96,29		69,20	7,57		7,57
25	2	26,55	323,62	297,07		212,26		3,08	3,08
26	2	252,48	332,52	80,04		73,76		3,03	3,03
27	4	274,14	339,73	65,60		32,29	10,05	6,25	16,30
28	3	269,43	342,95	73,52		1,29	7,67		7,67
29	4	296,23	346,47	50,24	49,46		9,94	5,88	15,82
30	3	278,49	347,07	68,58	3,97		7,51		7,51
31	1	251,28	356,81	105,53		40,16	2,50	1,48	3,98
32	2	73,81	370,31	296,49		236,08		2,99	2,99
33	3	345,75	383,51	37,76	25,72		7,46		7,46
34	2	277,03	384,10	107,07		50,94		2,99	2,99

Table A.1 (continued)

35	1	317,78	402,82	85,04		33,98	2,48	1,45	3,93
36	1	275,06	403,41	128,35		30,96	2,42	1,48	3,89
37	2	338,18	416,70	78,52		70,27		2,98	2,98
38	4	365,19	428,61	63,42		30,42	10,25	6,03	16,28
39	3	390,96	440,52	49,57	0,48		7,40		7,40
40	2	379,50	441,12	61,62		29,50		3,04	3,04
41	4	403,00	441,90	38,90		29,05	10,34	5,95	16,30
42	2	207,15	442,68	235,53		231,27		2,95	2,95
43	2	157,60	446,84	289,24		285,37		2,88	2,88
44	1	366,76	447,62	80,86		16,88	2,51	1,57	4,08
45	1	405,00	448,97	43,97		28,49	2,56	1,47	4,03
46	2	449,82	463,66	13,84	1,69			3,11	3,11
47	3	451,68	464,44	12,77		12,53	7,42		7,42
48	4	470,10	492,96	22,85		10,30	10,10	5,90	16,00
49	1	488,01	502,99	14,97	21,69		2,59	1,54	4,13
50	2	496,69	507,28	10,59	40,12			3,04	3,04
51	3	512,84	542,90	30,07	14,50		7,24		7,24
52	4	517,80	545,24	27,44	5,12		9,77	5,90	15,67
53	1	522,02	553,29	31,27	48,29		2,46	1,51	3,97
54	2	548,22	557,55	9,32	66,21			2,99	2,99
55	3	562,22	598,04	35,83		10,06	7,46		7,46
56	4	567,52	598,64	31,12		10,45	10,26	5,63	15,89
57	2	578,00	606,51	28,52	54,14			3,04	3,04
58	3	588,16	607,30	19,13	2,16		7,44		7,44
59	1	569,97	607,89	37,92		3,16	2,48	1,49	3,96
60	4	625,52	647,14	21,61	59,94		9,99	5,97	15,96
61	1	689,15	700,16	11,01	64,68		2,45	1,59	4,04
62	2	700,90	708,55	7,65		6,51		2,99	2,99
63	3	716,17	727,03	10,87	20,69		7,55		7,55
64	4	716,63	749,39	32,76	50,28		10,23	5,97	16,20
65	2	751,10	817,24	66,14	22,82			2,99	2,99
66	1	737,07	824,05	86,98		44,26	2,49	1,54	4,03
67	3	754,30	824,65	70,35		16,27	7,39		7,39
68	4	756,92	825,24	68,32		58,67	9,86	6,26	16,12
69	4	783,70	832,15	48,45		10,15	10,26	5,70	15,96
70	3	782,80	832,75	49,94	37,74		7,36		7,36
71	2	780,26	835,27	55,01		13,73		3,12	3,12
72	1	758,23	849,21	90,98		80,36	2,53	1,42	3,95
73	2	820,50	870,76	50,25	17,09			3,07	3,07
74	1	817,42	893,11	75,69		18,48	2,53	1,49	4,02
75	3	834,71	893,70	59,00		11,71	7,49		7,49
76	4	836,57	903,16	66,60		8,45	10,17	5,79	15,96
77	4	860,47	913,60	53,13		29,34	9,85	5,94	15,79

Table A.1 (continued)

78	3	860,44	914,20	53,76		7,93	7,38		7,38
79	2	843,02	918,73	75,71		3,97		2,93	2,93
80	1	839,19	919,52	80,33		75,23	2,45	1,51	3,96
81	1	890,06	920,87	30,81	31,93		2,47	1,45	3,91
82	2	923,23	930,87	7,64	77,35			2,98	2,98
83	3	939,91	963,67	23,76	73,71		7,38		7,38
84	4	948,57	971,64	23,07	55,81		9,73	6,20	15,93
85	1	963,52	982,09	18,57	21,37		2,52	1,50	4,02
86	2	978,31	986,70	8,40	16,84			3,08	3,08
87	3	991,78	1015,39	23,61		21,84	7,30		7,30
88	4	997,78	1027,69	29,91		6,50	10,16	6,18	16,34
89	2	1015,06	1033,75	18,69		15,26		3,00	3,00
90	1	998,26	1034,54	36,28	59,44		2,57	1,53	4,10
91	3	1050,41	1140,14	89,73		13,63	7,47		7,47
92	4	1052,17	1140,74	88,56	1,31		10,01	5,95	15,96
93	4	1070,62	1141,43	70,81		66,67	10,19	5,79	15,99
94	3	1069,97	1147,23	77,26		33,75	7,76		7,76
95	2	1060,89	1147,92	87,03		44,18		3,06	3,06
96	3	1102,26	1152,02	49,76	2,85		7,40		7,40
97	2	1090,55	1152,70	62,15		17,47		3,02	3,02
98	4	1117,94	1153,68	35,74	63,82		9,89	5,92	15,81
99	1	1057,40	1154,37	96,96		54,24	2,44	1,49	3,94
100	1	1077,00	1155,15	78,15	4,55		2,50	1,56	4,06
AVERAGES		**520,80**	**596,16**	**75,36**	**30,78**	**56,55**	**6,69**	**3,50**	**7,64**

APPENDIX B

MODELED SYSTEM

Chapter 3’s first section was devoted to the details of the modeled FMS. Although a sketch of the system was given at that stage in Figure 3.1, the photographs of the system in action is also provided here to help the reader grasp the main characteristics of the system. The first picture is the operating system in general; the other figures are the pictures of the system components.

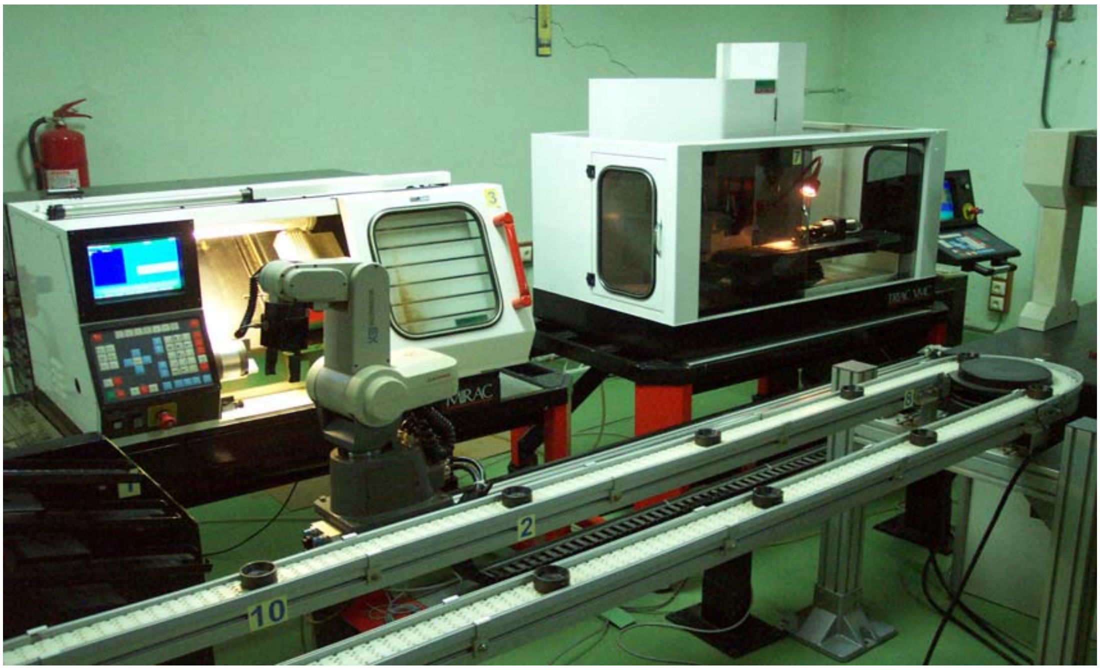


Figure B.1 The general view of the system under operation

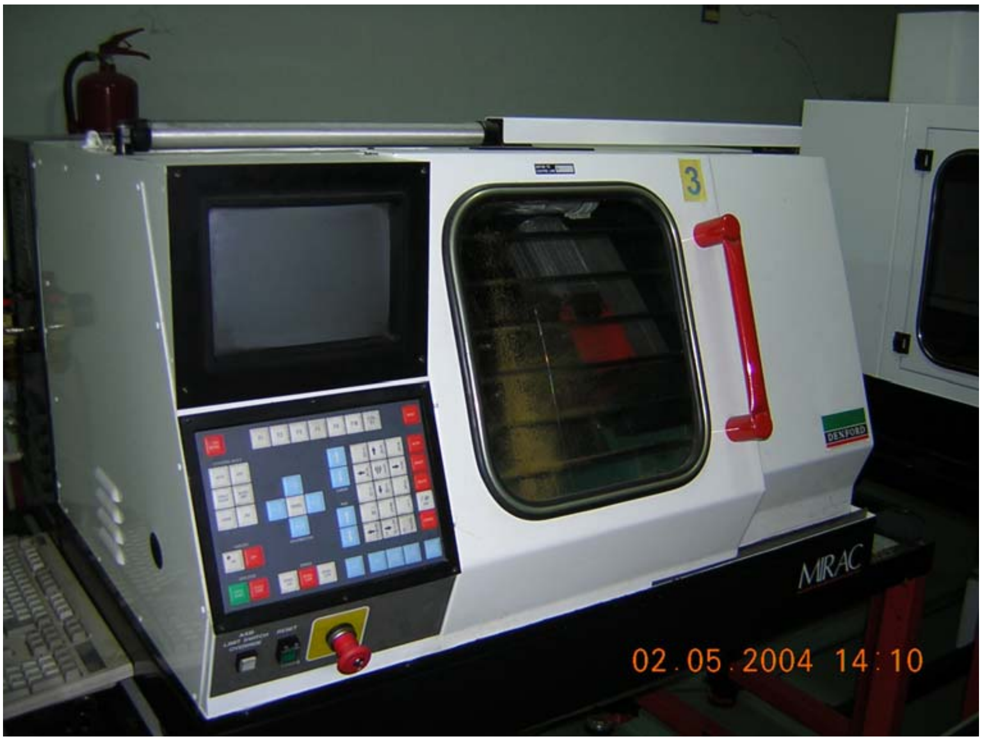


Figure B.2 The CNC turning machine

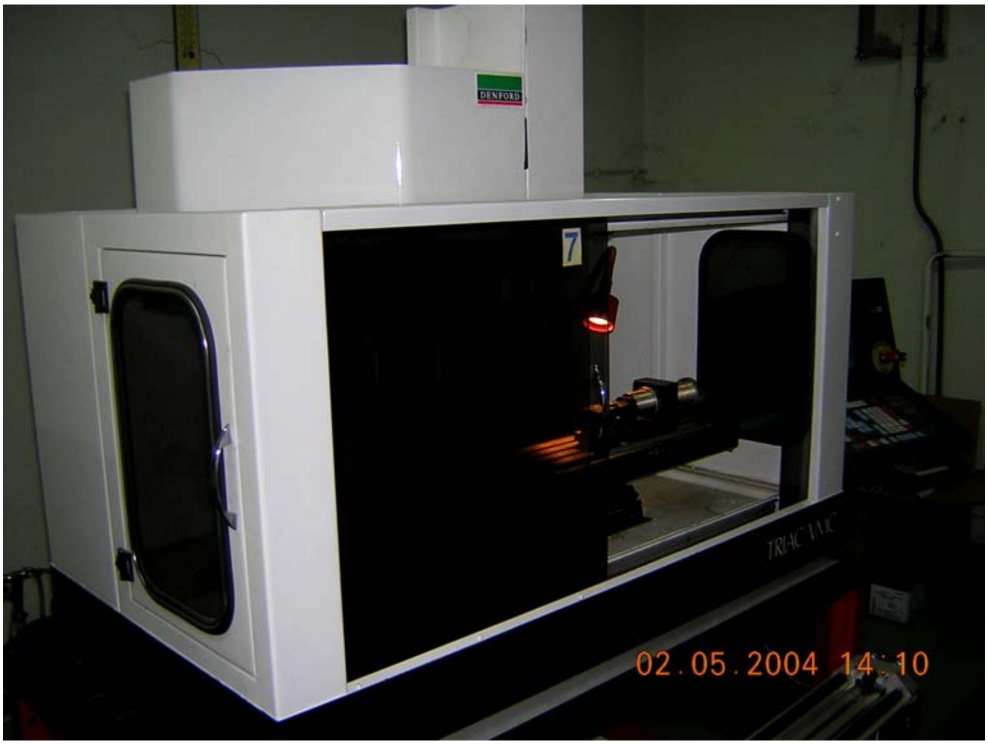


Figure B.3 The CNC milling machine

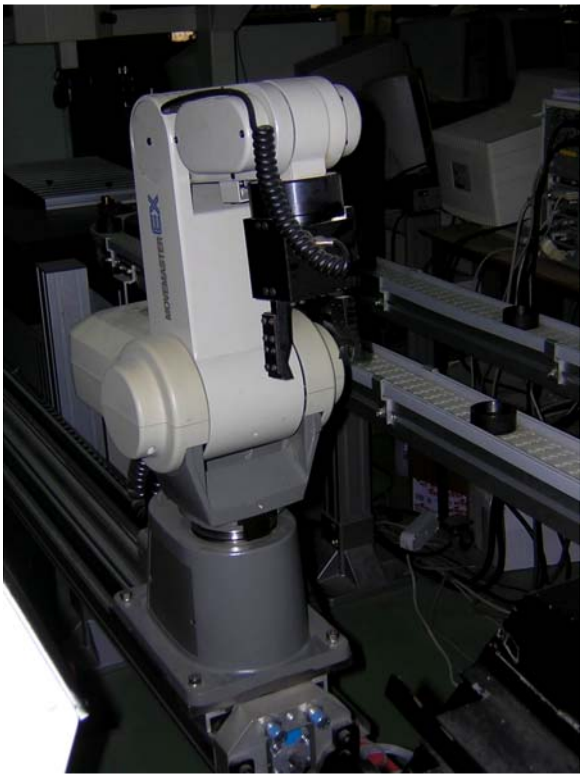


Figure B.4 The Robot on PLRD and the conveyor

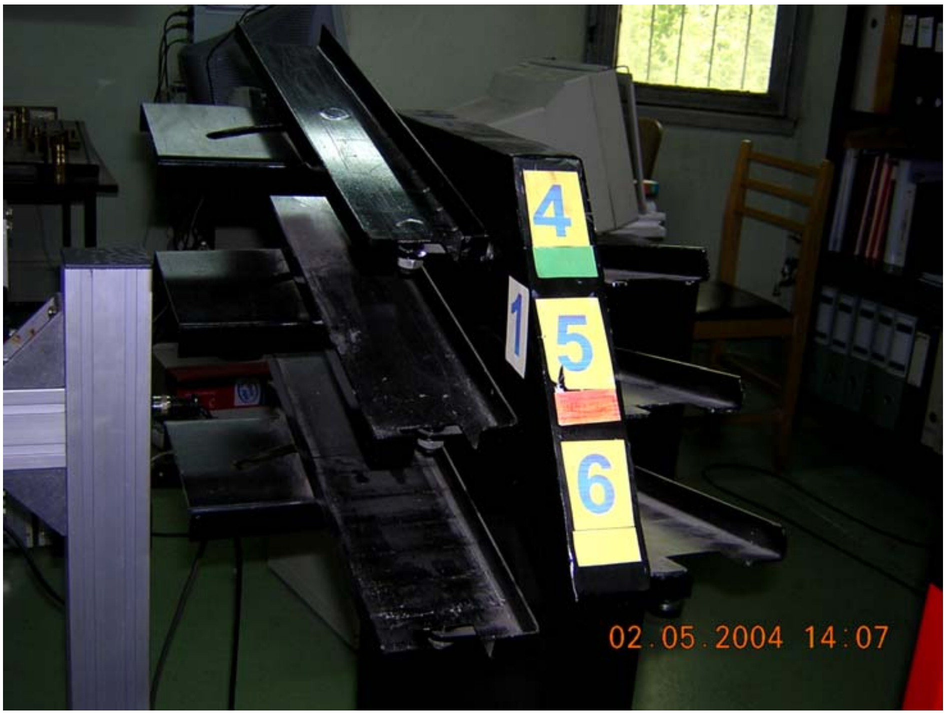


Figure B.5 The Stationary buffer modeled as AGV

APPENDIX C

SUB-MODELS

In Chapter 3, the detailed explanations for the sub-models developed were given. This appendix comprises the screenshots of the sub-models developed in ARENA®. The models can be seen in the accompanying disk, and the sub-models can be identified through the labels over them. It is not possible to print the models of turning and milling sub-models due to space restrictions, so the interested reader expected to open and review the models for the details. It should be kept in mind that the figures supplied here only give the outlines of the modules and each module has details which can be reached by double-clicking on them.

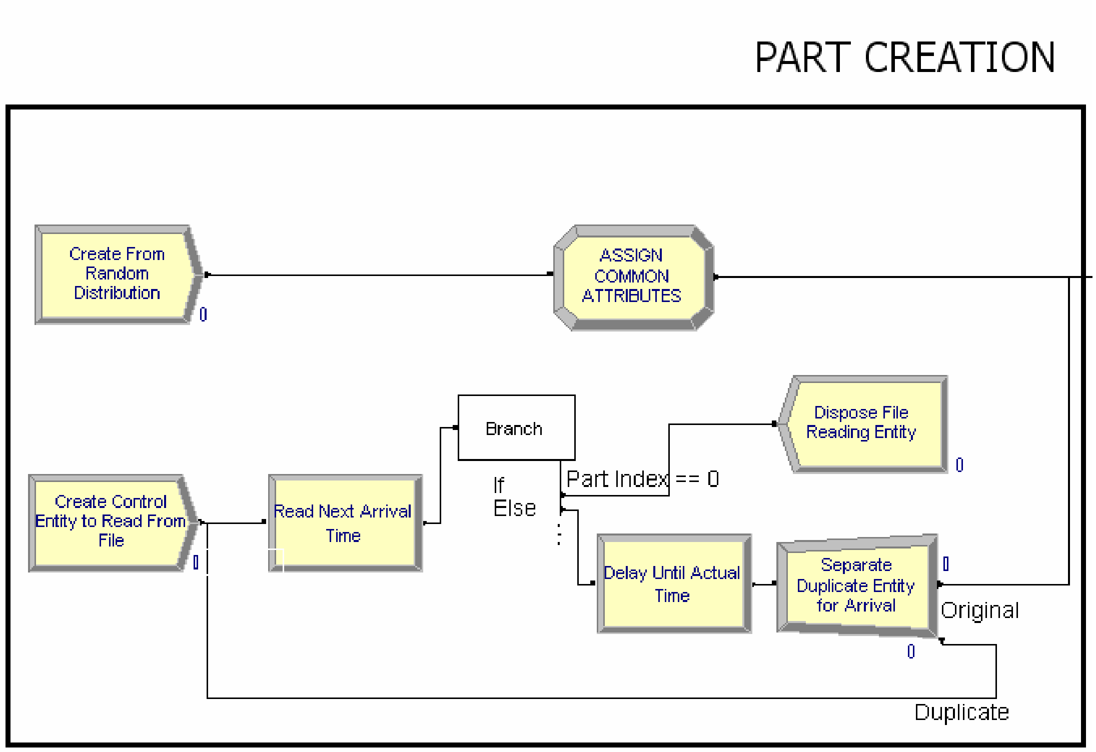

PART CREATION
Create From Random Distribution
0
ASSIGN COMMON ATTRIBUTES
Branch
If
Else
Part Index == 0
Dispose File Reading Entity
0
Create Control Entity to Read From File
0
Read Next Arrival Time
Delay Until Actual Time
Separate Duplicate Entity for Arrival
0
0
Original
Duplicate

Figure C.1 Part creation sub-model

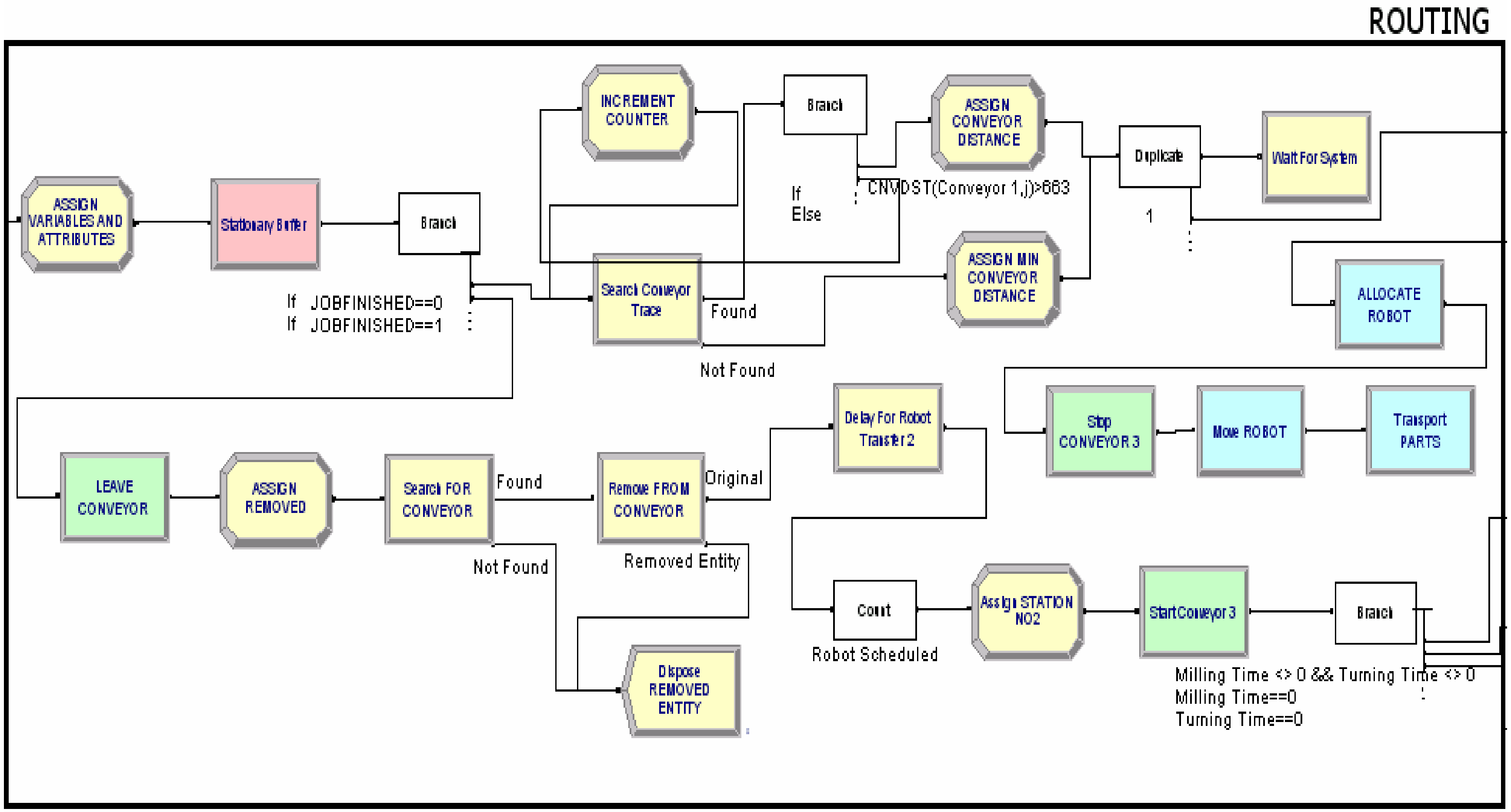


Figure C.2 Routing and assignment Sub-model

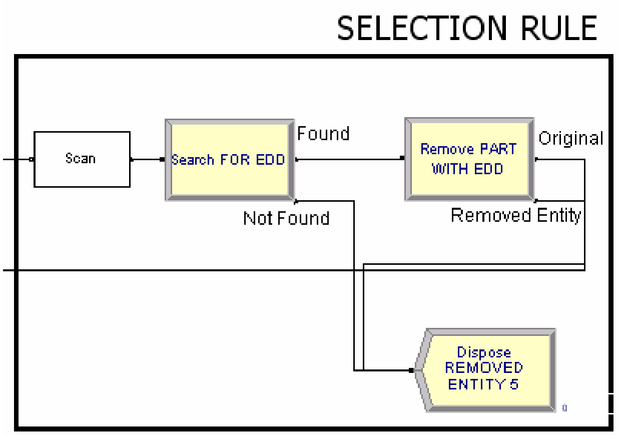


Figure C.3 Selection rule sub-model

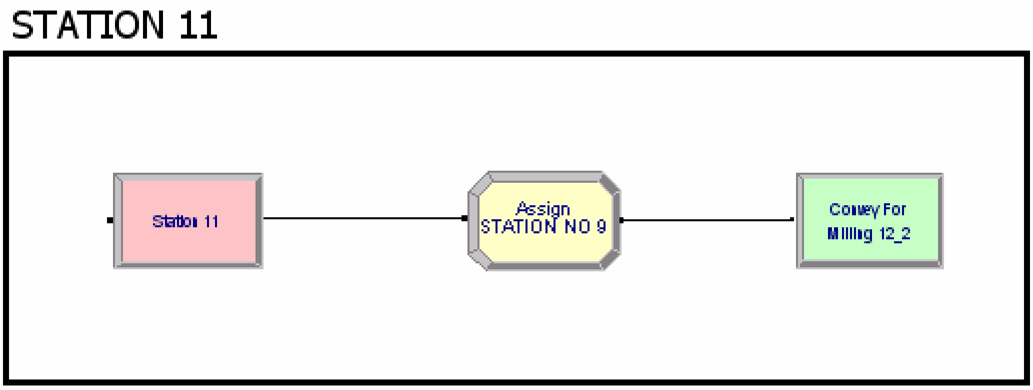


Figure C.4 Station 11 sub-model

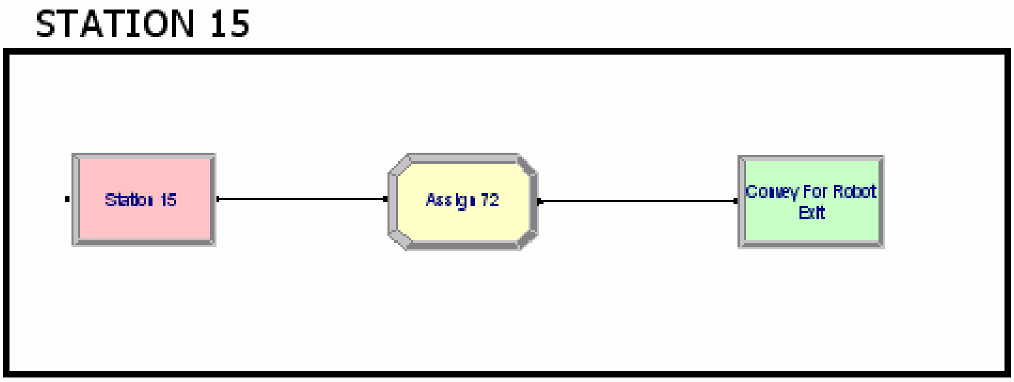


Figure C.5 Station 15 sub-model

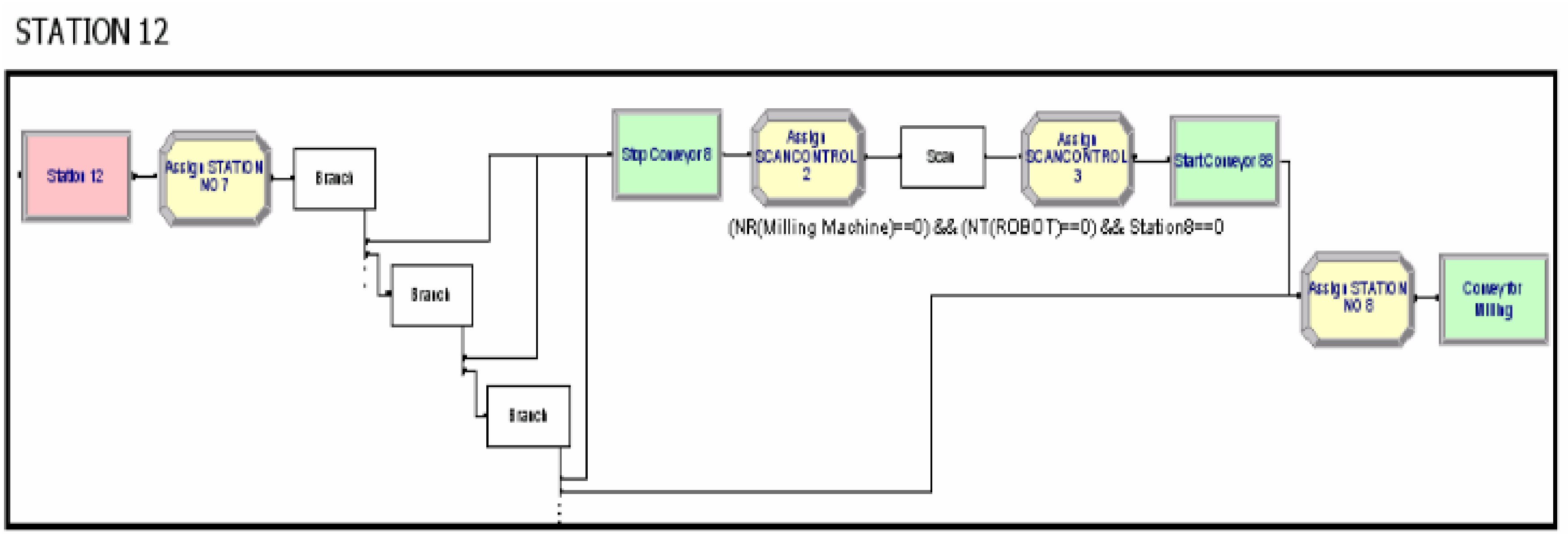


Figure C.6 Station 12 Sub-models

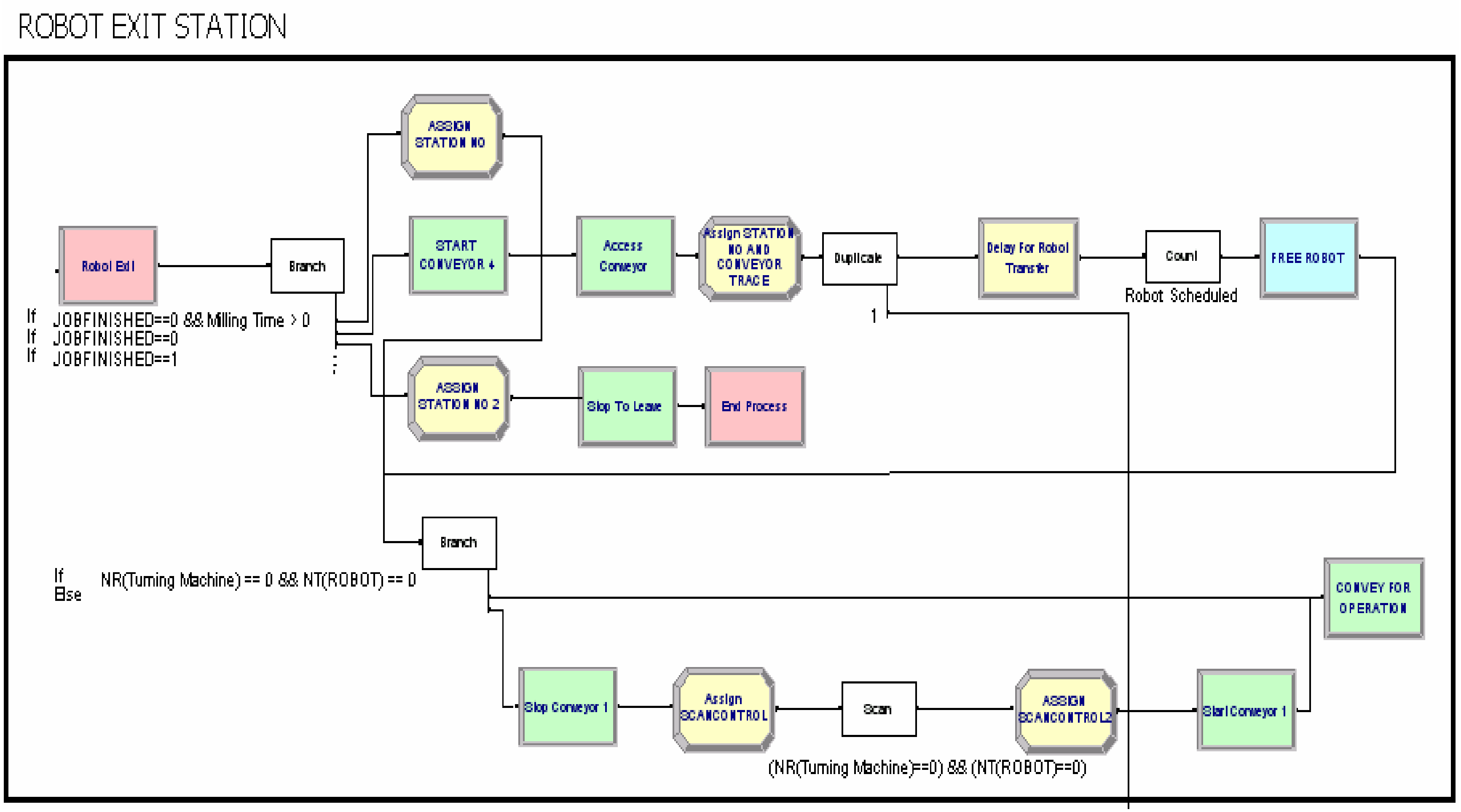


Figure C.7 AGV loading and unloading sub-model

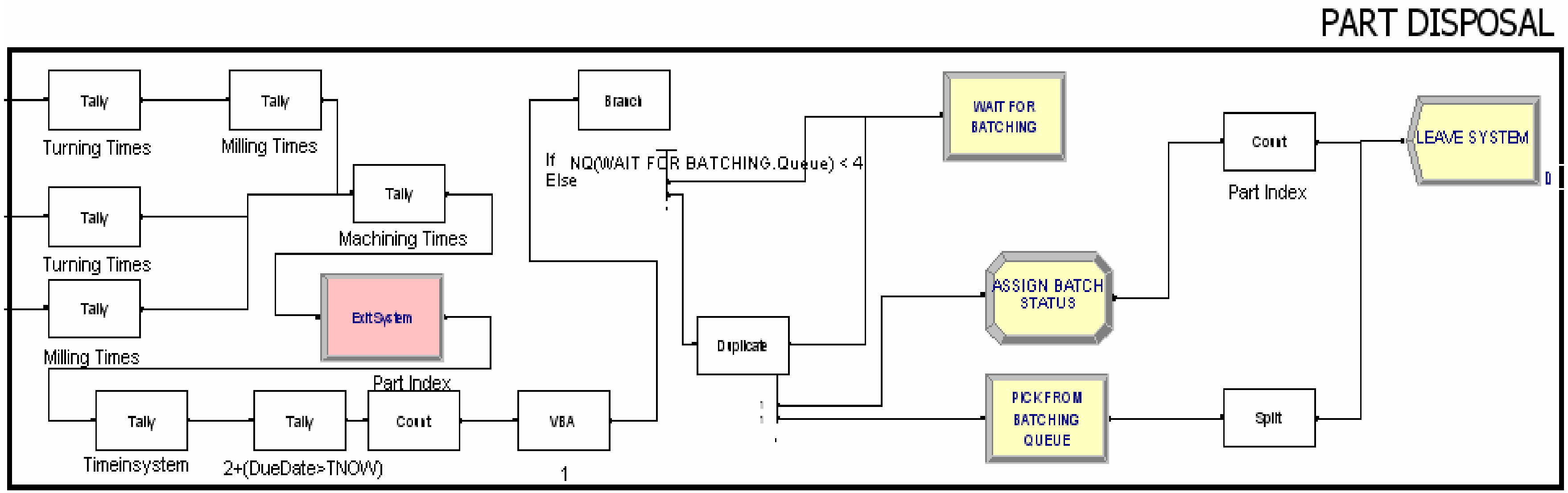


Figure C.8 Part Disposal Sub-model

APPENDIX D

SAMPLE CODE

The following pieces of code are of sample code developed through the realization of integration of simulation models with external applications. The code and the associated module are given consecutively.

D.1 Import Data Module:

```
Private Sub CommandButton1_Click()
          Dim i, FreeRow, RowValue As Integer
          Dim oWorksheet As Excel.Worksheet

                    FreeRow = 1
                    i = 0

                    Sheets("DATA").Select
                    Set oWorksheet = ActiveSheet

                    With oWorksheet

                              If .Cells(2, 1) <> 0 Then

                                        Do While i < FreeRow
                                                  RowValue = .Cells(i + 2, 1).Value
                                                  i = i + 1

                                        If RowValue > 0 Then
                                                  FreeRow = FreeRow + 1
                                        End If

                                        Loop

                                        q = "A2: D" & FreeRow
                                        Range(q).Select
                                        Selection.Delete Shift:=xlUp
```

```
            End If

        End With

        Sheets("MAIN").Select
        Range("G9,I9,K9,M9").Select
        Selection.ClearContents
        Range("I11").Select
        ActiveCell.FormulaR1C1 = "Data Cleared"

End Sub

Private Sub LoadButton_Click()
    Dim j, FreeRow2, RowValue2 As Integer
    Dim oWorksheet2, oWorksheet3 As Excel.Worksheet

        FreeRow2 = 1
        j = 0
        Range("I11").Select
        Selection.ClearContents
        part = Cells(9, 7).Value
        arr = Cells(9, 9).Value
        due = Cells(9, 11).Value
        pri = Cells(9, 13).Value

        If part > 0 And part < 5 And arr >= 0 Then
            Sheets("DATA").Select
            Set oWorksheet2 = ActiveSheet

            With oWorksheet2

                Do While j < FreeRow2
                    RowValue2 = .Cells(j + 2, 1).Value
                    j = j + 1

                    If RowValue2 > 0 Then
                        FreeRow2 = FreeRow2 + 1
                    End If

                Loop
                FreeRow2 = FreeRow2 + 1
                q = "A" & FreeRow2 & ":" & "D" & FreeRow2
                .Range(q).Select
                Selection.Insert Shift:=xlDown
                .Cells(FreeRow2, 1) = part
                .Cells(FreeRow2, 2) = arr
                .Cells(FreeRow2, 3) = due
                .Cells(FreeRow2, 4) = pri
                q = "A1: D" & FreeRow2
                q2 = "D" & FreeRow2
                .Rows("2:" & FreeRow2).Select
                Selection.Sort Key1:=Sheets("DATA").Range("B2"),
                Order1:=xlAscending, Header:=xlNo,
                OrderCustom:=1, MatchCase:=False,
                Orientation:=xlTopToBottom,
                DataOption1:=xlSortNormal
            End With

            Sheets("MAIN").Select
            Range("G9,I9,K9,M9").Select
            Selection.ClearContents
            Range("I11").Select
            ActiveCell.FormulaR1C1 = "Data Loaded"

        Else
            Range("I11").Select
            ActiveCell.FormulaR1C1 = "Erroneous Data"

        End If

End Sub
```

D.2 Export Data Module:

```
Option Explicit

Dim oSIMAN As Arena.SIMAN, nArrivalTimeAttrIndex, nDueDateAttrIndex,
nTurnTimeAttrIndex, nMillTimeAttrIndex, nPartTypeIndex, nPriorityIndex,
nMaximumConveyor, nConveyorNumber As Long
Dim nConveyorTrace(1 To 25) As Long
Dim nNextRow As Long, nColumnA, nColumnB, nColumnC, nColumnD, nColumnE,
nColumnF, nColumnG, nColumnH, nColumnZ, nColumnY, nColumnP As Long
Dim dTurnScheduled, dMillScheduled As Integer
Dim nMaxTime As Long
Dim oExcelApp As Excel.Application, oWorkbook As Excel.Workbook, oWorksheet,
oWorksheet2 As Excel.Worksheet


Private Sub ModelLogic_RunBeginReplication()

Dim nReplicationNum As Long, i As Integer
```

```
    nReplicationNum = oSIMAN.RunCurrentReplication
    nColumnA = (8 * (nReplicationNum - 1)) + 4
    nColumnB = nColumnA + 1
    nColumnC = nColumnB + 1
    nColumnD = nColumnC + 1
    nColumnE = nColumnD + 1
    nColumnF = nColumnE + 1
    nColumnG = nColumnF + 1
    nColumnH = nColumnG + 1
    nColumnP = nColumnA - 1
    nColumnZ = nColumnA - 2
    nColumnY = nColumnA - 3

    With oWorksheet
        .Activate
        .Cells(2, nColumnY).value = "No"
        .Cells(2, nColumnZ).value = "Type"
        .Cells(2, nColumnP).value = "Priority"
        .Cells(2, nColumnA).value = "Start T."
        .Cells(2, nColumnB).value = "End Time"
        .Cells(2, nColumnC).value = "Duration "
        .Cells(2, nColumnD).value = "Earliness"
        .Cells(2, nColumnE).value = "Lateness"
        .Cells(2, nColumnF).value = "Turning"
        .Cells(2, nColumnG).value = "Milling"
        .Cells(2, nColumnH).value = "Machining"
        .Columns(3).Select
        oExcelApp.Selection.Columns.AutoFit

        For i = 0 To 7
            .Columns(nColumnA + i).Select
            oExcelApp.Selection.Columns.AutoFit
            oExcelApp.Selection.NumberFormat = "0.00"
        Next i
    End With

    nNextRow = 3
End Sub


Private Sub ModelLogic_RunBeginSimulation()
Dim j, nm As Integer

    Set oSIMAN = ThisDocument.Model.SIMAN
    nArrivalTimeAttrIndex = oSIMAN.SymbolNumber("timein")
    nDueDateAttrIndex = oSIMAN.SymbolNumber("DueDate")
    nTurnTimeAttrIndex = oSIMAN.SymbolNumber("Turning Time")
```

```
        nMillTimeAttrIndex = oSIMAN.SymbolNumber("Milling Time")
        nPartTypeIndex = oSIMAN.SymbolNumber("Part Index")
        nPriorityIndex = oSIMAN.SymbolNumber("Priority Index")
        nConveyorNumber = oSIMAN.SymbolNumber("Conveyor 1")
        nMaximumConveyor = oSIMAN.SymbolNumber("Max Conveyor")

        For nm = 1 To 25
            nConveyorTrace(nm) = oSIMAN.SymbolNumber("Conveyor Trace",
        nm, 1)
        Next nm

        Set oExcelApp = CreateObject("Excel.Application")
        oExcelApp.Visible = False
        oExcelApp.SheetsInNewWorkbook = 1
        Set oWorkbook = oExcelApp.Workbooks.Add
        Set oWorksheet = oWorkbook.ActiveSheet

'Worksheet 1
        With oWorksheet
                .PageSetup.CenterHeader = "&""Arial,Bold""&16SIMULATION
        RESULTS, TALLIES"
                .PageSetup.LeftMargin = 45
                .PageSetup.RightMargin = 45
                .Name = "Simulation Results"
                .Rows(1).Select
                oExcelApp.Selection.Font.Bold = True
                oExcelApp.Selection.Font.color = RGB(255, 0, 0)
                .Rows(2).Select
                oExcelApp.Selection.Font.Bold = True
                 oExcelApp.Selection.Font.color = RGB(0, 0, 255)
        End With



'Worksheet 2
        oWorkbook.Sheets.Add
        Set oWorksheet2 = oWorkbook.ActiveSheet

        With oWorksheet2
                .PageSetup.CenterHeader = "&""Arial,Bold""&16SIMULATION
        RESULTS, COUNTERS AND STATISTICS"
                .PageSetup.LeftMargin = 45
                .PageSetup.RightMargin = 45
                .Name = "Statistics"
                .Rows(2).Select
                oExcelApp.Selection.Font.Bold = True
                oExcelApp.Selection.Font.color = RGB(0, 0, 255)
                oExcelApp.Selection.Font.Size = 12
                .Rows(3).Select
                oExcelApp.Selection.Font.Bold = True
                oExcelApp.Selection.Font.color = RGB(255, 0, 0)
                oExcelApp.Selection.Font.Size = 12
                .Rows(10).Select
                oExcelApp.Selection.Font.Bold = True
                oExcelApp.Selection.Font.color = RGB(0, 0, 255)
                oExcelApp.Selection.Font.Size = 12
                .Rows(4).Select
                oExcelApp.Selection.Font.Bold = True
                .Rows(5).Select
                oExcelApp.Selection.Font.Bold = True
                .Rows(6).Select
                oExcelApp.Selection.Font.Bold = True
                .Rows(7).Select
                oExcelApp.Selection.Font.Bold = True
                .Rows(11).Select
                oExcelApp.Selection.Font.Bold = True
                oExcelApp.Selection.Font.color = RGB(255, 0, 0)
                oExcelApp.Selection.Font.Size = 12
                .Rows(12).Select
                oExcelApp.Selection.Font.Bold = True
                .Rows(13).Select
                oExcelApp.Selection.Font.Bold = True
                .Rows(14).Select
                 oExcelApp.Selection.Font.Bold = True
                .Rows(15).Select
                oExcelApp.Selection.Font.Bold = True
                .Cells(2, 1).value = "PART QUANTITIES BY TYPE"
                .Cells(3, 1).value = "PART TYPE"
                .Cells(4, 1).value = "1"
                .Cells(5, 1).value = "2"
                .Cells(6, 1).value = "3"
                .Cells(7, 1).value = "4"
                .Cells(3, 3).value = "QUANTITY"
                .Cells(10, 1).value = "FINAL UTILIZATIONS (%)"
                .Cells(11, 1).value = "RESOURCE NAME"
                .Cells(12, 1).value = "TURNING"
                .Cells(13, 1).value = "MILLING"
                .Cells(14, 1).value = "CONVEYOR"
                .Cells(15, 1).value = "ROBOT"
                .Cells(11, 3).value = "VALUE"
                .Cells(2, 6).value = "SCHEDULED RESOURCES"
                .Cells(3, 6).value = "RESOURCE NAME"
                .Cells(3, 8).value = "TIMES"
                .Cells(4, 6).value = "TURNING"
```

```
                .Cells(5, 6).value = "MILLING"
                .Cells(6, 6).value = "ROBOT"
                .Cells(10, 6).value = "AVERAGE NUMBER IN QUEUE"
                .Cells(11, 6).value = "QUEUE NAME"
                .Cells(12, 6).value = "AGV QUEUE"
                 .Cells(11, 8).value = "QUANTITY"
        End With

End Sub

Private Sub ModelLogic_RunEndSimulation()
Dim i As Integer

        oWorksheet2.Cells(12, 3).value = oSIMAN.DStatAverage(2) * 100
        oWorksheet2.Cells(13, 3).value = oSIMAN.DStatAverage(1) * 100
        oWorksheet2.Cells(14, 3).value = oSIMAN.DStatAverage(3) * 100
        oWorksheet2.Cells(15, 3).value = oSIMAN.DStatAverage(4) * 100
        oWorksheet2.Cells(12, 8).value = oSIMAN.DStatAverage(5)
        oWorksheet2.Columns(2).ColumnWidth = 12.14
        oWorksheet2.Columns(7).ColumnWidth = 12.14

        With oWorksheet
                .Cells(nNextRow, nColumnA).value = "=AVERAGE(R[-" &
        nNextRow - 3 & "]C:R[-1]C)"
                .Cells(nNextRow, nColumnB).value = "=AVERAGE(R[-" &
        nNextRow - 3 & "]C:R[-1]C)"
                .Cells(nNextRow, nColumnC).value = "=AVERAGE(R[-" &
        nNextRow - 3 & "]C:R[-1]C)"
                .Cells(nNextRow, nColumnD).value = "=AVERAGE(R[-" &
        nNextRow - 3 & "]C:R[-1]C)"
                .Cells(nNextRow, nColumnE).value = "=AVERAGE(R[-" &
        nNextRow - 3 & "]C:R[-1]C)"
                .Cells(nNextRow, nColumnF).value = "=AVERAGE(R[-" &
        nNextRow - 3 & "]C:R[-1]C)"
                .Cells(nNextRow, nColumnG).value = "=AVERAGE(R[-" &
        nNextRow - 3 & "]C:R[-1]C)"
                .Cells(nNextRow, nColumnH).value = "=AVERAGE(R[-" &
        nNextRow - 3 & "]C:R[-1]C)"
                .Rows(nNextRow).Select
                oExcelApp.Selection.Font.Bold = True
                oExcelApp.Selection.Font.color = RGB(0, 0, 255)
                .Columns(nColumnZ).Select
                oExcelApp.Selection.Columns.AutoFit
                .Columns(nColumnY).Select
                oExcelApp.Selection.Columns.AutoFit
                .Cells(nNextRow, nColumnY).value = "AVERAGES"
        End With
```

```
'Time In System Chart
        oWorkbook.Sheets("Simulation Results").Select
        oWorksheet.Range(oWorksheet.Cells(3, nColumnC),
oWorksheet.Cells(nNextRow, nColumnC)).Select
        oExcelApp.Charts.Add

        With oExcelApp.ActiveChart
                .ChartType = xlLineMarkers
                .SetSourceData Source:=oWorksheet.Range(oWorksheet.Cells(3,
                nColumnC), oWorksheet.Cells(nNextRow, nColumnC)),
                PlotBy:=xlColumns
                .SeriesCollection(1).XValues = ""
                .Location Where:=xlLocationAsNewSheet, Name:="Time In System"
                .HasTitle = True
                .HasAxis(xlValue) = True
                .HasAxis(xlCategory) = True
                .HasLegend = False
                .ChartTitle.Characters.Text = "Time In System"
                .Axes(xlValue).HasTitle = True
                .Axes(xlValue).AxisTitle.Characters.Text = "System times in minutes"
                .Axes(xlCategory).HasTitle = True
                .Axes(xlCategory).AxisTitle.Characters.Text = "Parts"
        End With

'Machining Times Chart
        oWorkbook.Sheets("Simulation Results").Select
        oWorksheet.Range(oWorksheet.Cells(3, nColumnH),
oWorksheet.Cells(nNextRow, nColumnH)).Select
        oExcelApp.Charts.Add

        With oExcelApp.ActiveChart
                .ChartType = xlLineMarkers
                .SetSourceData Source:=oWorksheet.Range(oWorksheet.Cells(3,
                nColumnH), oWorksheet.Cells(nNextRow, nColumnH)),
                PlotBy:=xlColumns
                .SeriesCollection(1).XValues = ""
                .Location Where:=xlLocationAsNewSheet, Name:="Machining
                Times"
                .HasTitle = True
                .HasAxis(xlValue) = True
                .HasAxis(xlCategory) = True
                .HasLegend = False
                .ChartTitle.Characters.Text = "Machining Times"
                .Axes(xlValue).HasTitle = True
                .Axes(xlValue).AxisTitle.Characters.Text = "Machining times in
                minutes"
        .Axes(xlCategory).HasTitle = True
        .Axes(xlCategory).AxisTitle.Characters.Text = "Parts"
    End With

    oWorkbook.Sheets("Simulation Results").Select

    With oExcelApp
        .Visible = True
        .DisplayAlerts = False
    End With

' SAVE AS HTML

    oWorkbook.SaveAs ThisDocument.Model.Path & "Results2.htm",
    FileFormat:=xlHtml, ReadOnlyRecommended:=False,
    CreateBackup:=False
    oWorkbook.SaveAs ThisDocument.Model.Path & "Results.xls"

End Sub
```

D.3 VBA Modules:

```
Private Sub VBA_Block_1_Fire()
Dim dCreateTime As Double, dCurrentTime As Double
Dim dDueDate, dTurnTime, dMillTime As Double
Dim dPartIndex, dPriorityIndex As Integer

    dCreateTime = oSIMAN.EntityAttribute(oSIMAN.ActiveEntity,
    nArrivalTimeAttrIndex)
    dCurrentTime = oSIMAN.RunCurrentTime
    dDueDate = oSIMAN.EntityAttribute(oSIMAN.ActiveEntity,
    nDueDateAttrIndex)
    dTurnTime = oSIMAN.EntityAttribute(oSIMAN.ActiveEntity,
    nTurnTimeAttrIndex)
    dMillTime = oSIMAN.EntityAttribute(oSIMAN.ActiveEntity,
    nMillTimeAttrIndex)
    dPartIndex = oSIMAN.EntityAttribute(oSIMAN.ActiveEntity,
    nPartTypeIndex)
    dPriorityIndex = oSIMAN.EntityAttribute(oSIMAN.ActiveEntity,
    nPriorityIndex)

‘   assign part no create time current time and time in system

    With oWorksheet
        .Cells(nNextRow, nColumnY).value = nNextRow - 2
        .Cells(nNextRow, nColumnA).value = dCreateTime
        .Cells(nNextRow, nColumnB).value = dCurrentTime
        .Cells(nNextRow, nColumnC).value = dCurrentTime - dCreateTime
        .Cells(nNextRow, nColumnH).value = dMillTime + dTurnTime
        .Cells(nNextRow, nColumnZ).value = dPartIndex
        .Cells(nNextRow, nColumnP).value = dPriorityIndex

        If dPartIndex = 1 Then
            .Cells(nNextRow, nColumnZ).Interior.color = RGB(255, 255,
        0)
        ElseIf dPartIndex = 2 Then
            .Cells(nNextRow, nColumnZ).Interior.color = RGB(128, 128,
        0)
        ElseIf dPartIndex = 3 Then
            .Cells(nNextRow, nColumnZ).Interior.color = RGB(128, 0, 0)
        Else
            .Cells(nNextRow, nColumnZ).Interior.color = RGB(255, 0, 0)
        End If
    End With

'   assign earliness and lateness
    If (dDueDate >= dCurrentTime) Then
        oWorksheet.Cells(nNextRow, nColumnD).value = dDueDate -
        dCurrentTime
    Else
        oWorksheet.Cells(nNextRow, nColumnE).value = dCurrentTime -
        dDueDate
    End If
'   assign Turning and Milling times
    If dTurnTime > 0 Then oWorksheet.Cells(nNextRow, nColumnF).value =
dTurnTime
    If dMillTime > 0 Then oWorksheet.Cells(nNextRow, nColumnG).value =
dMillTime
    If (dCurrentTime - dCreateTime) > nMaxTime Then nMaxTime =
(dCurrentTime - dCreateTime)

    nNextRow = nNextRow + 1
    oWorksheet2.Cells(6, 8).value = oSIMAN.CounterValue(8)
    oWorksheet2.Cells(4, 3).value = oSIMAN.CounterValue(1)
    oWorksheet2.Cells(5, 3).value = oSIMAN.CounterValue(2)
    oWorksheet2.Cells(6, 3).value = oSIMAN.CounterValue(3)
    oWorksheet2.Cells(7, 3).value = oSIMAN.CounterValue(4)

End Sub

Private Sub VBA_Block_2_Fire()
oWorksheet2.Cells(4, 8).value = oSIMAN.CounterValue(6)
```

```
End Sub

Private Sub VBA_Block_3_Fire()

oWorksheet2.Cells(5, 8).value = oSIMAN.CounterValue(7)
End Sub
```

D.4 Interface Module

```
Private Sub ModelLogic_RunBegin()

frmArrivalTypeSelection.Show

End Sub

Private Sub cmdOK_Click()
Dim nCreateRandomProcessIndex As Long
Dim oCreateRandomProcessModule As Arena.Module
Dim nCreateFileIndex As Long
Dim oCreateFileModule As Arena.Module
Dim oModel As Arena.Model
Dim nSoundfileIndex As Long


        Set oModel = ThisDocument.Model
        nCreateRandomProcessIndex = oModel.Modules.Find(smFindTag, "Create
from random process")

        If nCreateRandomProcessIndex = 0 Then
                MsgBox "No Module with tag 'Create from random process'"
                frmArrivalTypeSelection.Hide
                Exit Sub
        End If

Set                    oCreateRandomProcessModule                    =
oModel.Modules(nCreateRandomProcessIndex)

nCreateFileIndex = oModel.Modules.Find(smFindTag, "Create from file")

        If nCreateFileIndex = 0 Then
                MsgBox "No Module with tag 'Create from file'"
                frmArrivalTypeSelection.Hide
                Exit Sub
        End If

Set oCreateFileModule = oModel.Modules(nCreateFileIndex)
```

```
If optFromRandomProcess.value = False Then
        oCreateRandomProcessModule.Data("Max Batches") = "0"
        oCreateFileModule.Data("Max Batches") = "1"
Else
        oCreateFileModule.Data("Max Batches") = "0"
        oCreateRandomProcessModule.Data("Max Batches") = "180"
End If

frmArrivalTypeSelection.Hide

Exit Sub

End Sub
```

APPENDIX E

PART PROCESS PLANS

The layout of METUCIM system was described in detail in Chapter 3. According to this layout, a part can have four possible process plans assuming that all operations of one single type (milling or turning) can be finished in one pass. The parts can have only one milling / turning operation or milling can follow turning or vice versa.

Part variability can be obtained by assigning different processing times for operations in the machines. The representation of entities that belong to the mentioned types is based on coloring in the simulation. Each type is shown with a different color and parts take the color of the type that they belong to. The types, associated colors and assigned machining sequences are given on Table E.1

Table E.1 Part types, process sequences and durations

PART TYPE	TURNING	MILLING	COLOR
1	2 / TRIA (2.4, 2.5, 2.6)	1 / TRIA (1.4, 1.5, 1.6)	YELLOW
2	-	1 / TRIA (2.8, 3.0, 3.2)	BRONZE
3	1 / TRIA (7.2, 7.5, 7.8)	-	RUBY
4	1 / TRIA (9.6, 10, 10.4)	2 / TRIA (5.6, 6, 6.4)	RED

In addition to coloring the parts, the completed level of the process plan can be followed on the parts. Each part that has finished its task on one of the machines takes a letter over its representing picture (M for Milling and T for Turning), which shows the completed tasks on the part. A part that has completed both of the operations has both T and M letters on it.

APPENDIX F

FLOWCHART

The basic flowchart of events for the developed models is given on Figure F.1.

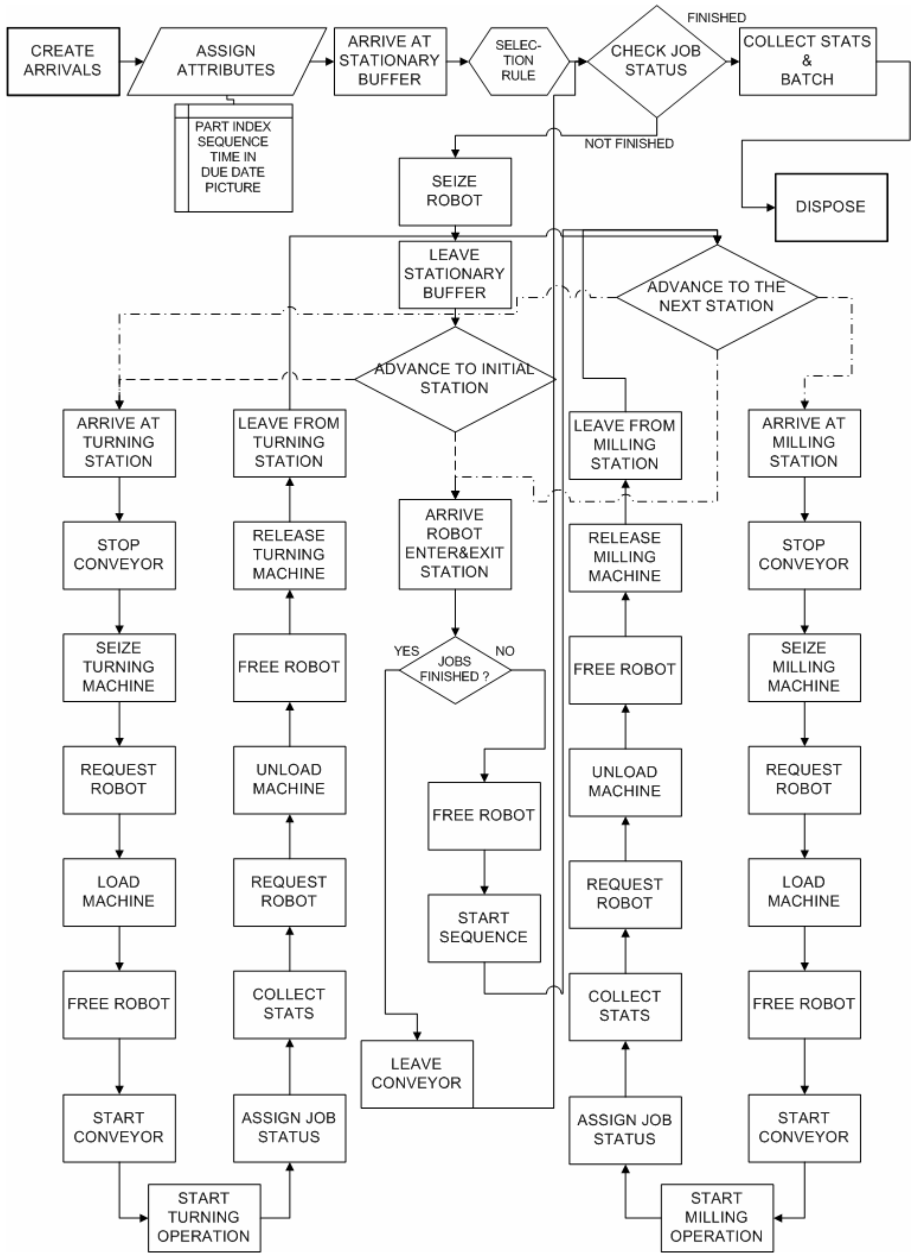


Figure F.1 Basic Flowchart of events for the models.