A Study on Facility Planning using Discrete Event Simulation: Case Study of a Grain Delivery Terminal.

Sarah M. Asio
University of Nebraska-Lincoln, sarah.asio@huskers.unl.edu

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A STUDY ON FACILITY PLANNING USING DISCRETE EVENT SIMULATION: CASE STUDY OF A GRAIN DELIVERY TERMINAL.

BY

SARAH M. ASIO

A THESIS

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A STUDY ON FACILITY PLANNING USING DISCRETE EVENT SIMULATION: CASE STUDY OF A GRAIN DELIVERY TERMINAL.

Sarah M. Asio, M.S.

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Adviser: Jeffrey Woldstad

The application of traditional approaches to the design of efficient facilities can be tedious and time consuming when uncertainty and a number of constraints exist. Queuing models and mathematical programming techniques are not able to capture the complex interaction between resources, the environment and space constraints for dynamic stochastic processes. In the following study discrete event simulation is applied to the facility planning process for a grain delivery terminal. The discrete event simulation approach has been applied to studies such as capacity planning and facility layout for a gasoline station; predicting optimum replenishment parameter values for various inventory levels; and evaluating the resource requirements for a manufacturing facility. To the best of my knowledge, no case study for the use of the discrete event simulation tool to evaluate a grain delivery terminal facility’s requirements as a whole is available. The following study will develop an approach tailored to a grain delivery terminal with fundamental concepts that can be applied to any other type of facility planning activity with an underlying stochastic process. A 2000ft by 1000ft facility was considered in the study and four scenarios evaluated with varying number of resources, queue capacities and mode of operation of human operators. A comparative assessment of the scenarios was done. The results showed the relative change of performance in the grain delivery process as the resources were increased. The discrete event simulation tool developed in this study can be used in combination with the cost analysis of resources to determine the optimal design in the construction of grain delivery terminals.
To my sisters and brothers,

There are no limits.
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CHAPTER 1: INTRODUCTION

1.1 Introduction

Organizations invest a huge amount of capital in assets – tangible or intangible, that are intended to generate profits for the firm in the course of conducting business. Assets such as facilities, equipment, machinery, raw materials, products, services and human resources can be controlled to produce value for stakeholders. For every asset available to a company there is a threshold of return that can be achieved from it, and for a given number of assets there exists an ‘ideal’ combination that can be put to use to generate the highest value possible. This is known as the optimal set which is the best set from a number of alternatives that maximizes returns to the organization. This combination can be evaluated for any size of organization with any amount of assets available to it; the larger the organization the more complex the analysis. The optimum set of assets is not always obvious and is better determined by applying a combination of mathematical and managerial tools and techniques. A key theory that is used to carry this out is optimization in which a number of techniques such as programming - linear, nonlinear, stochastic, parametric, discrete and dynamic; control theory and game theory; optimization algorithms; iterative methods; simulation modeling and analysis; are used.

The following study investigates a number of feasible facility plan alternatives and proposes a tool to determine the optimal facility plan for a grain delivery terminal using discrete event simulation modeling. This approach was previously applied to a case study in which ways of improving the scale and efficiency of operations in a grain delivery terminal were devised using the discrete event simulation tool. The design of a grain delivery terminal involves a number of considerations such as the number and size of
workstations, space requirements, capacity of the terminal, and resource requirements. Although designers can qualitatively assess these factors and develop a blueprint for a facility, this in itself does not account for the stochastic properties inherent in the system. Even mathematical programming techniques (linear programming, integer programming, quadratic assignment techniques and other deterministic procedures; Pandey et al. 2000) do not cater for the interaction between the process, the customers and resources (space, equipment, and manpower; Smith and Bouanaka 1985). A number of recent algorithms (heuristic and meta-heuristic approaches) focus on the physical layout and placement of departments or processes in a manufacturing facility or distribution center without giving a collective assessment of space and resource requirements. On this basis, discrete event simulation is proposed as a tool to be applied in a holistic facility planning process using a case study of a grain delivery terminal. A generic grain terminal facility planning process using discrete event simulation will be discussed followed by the case study.

**Problem statement**
Grain as a commodity has gained increasing value over the past decades not only as a food crop but as biomass for renewable energy production (bioethanol production). In 2009 renewable energy constituted one quarter of global power capacity and delivered 18% of global electricity supply. 83 countries have instituted some form of renewable energy promotion policy including developing countries (REN21, 2010 Annual Report). An increased demand for renewable energy sources such as biomass from grain is being experienced. As a result grain delivery processes need to be capable of handling increased volumes of stock in the most efficient manner.
Facility planning, layout and design, become key concerns to terminal managers who have to organize operations in such a way as to maximize resource usage and overall system throughput. The level of planning for any given grain terminal facility determines the efficiency of the entire delivery operation. Improper planning of facilities is detrimental to operations. Any existing bottleneck in a grain delivery system results in long queues, long waiting times, stock outs, high operating costs, low throughput and overall system inefficiency. Such a system would operate below capacity.

A well planned facility is essential for effective grain delivery in a terminal. Properly planned and arranged workstations on available facility space, with optimal assignment of available resources, are expedient for the maximization of resource capacity and the level of efficiency of operations. Several studies have focused on the facility layout problem, a segment of facility planning that focuses on the arrangement of departments, work stations and storage areas for an existing or proposed facility such that the most efficient use of all resources involved is realized, (Singh and Singh (2011), Sule (1994) and Tompkins et al. (1996)). Notably, it has been emphasized that poor layout designs lead to accumulation of work-in-process (WIP), inefficient set-ups and longer queues (Chiang and Chiang 1998) making poor facilities design a long term costly investment that may require rearrangement and modification later on leading to huge expenses. It is therefore worth investing in extensive facilities planning before set up to ensure that higher efficiencies, reduced costs and increased productivities can be realized later on.

This study considers a proposition for the establishment of a hypothetical 2000ft by 1000ft ($2 \times 10^6$ Sq. ft.) rectangular delivery terminal that serves an ethanol plant with a peak hour demand of 50 trucks of a single grain type. The task is to develop the most
logical and close to optimal facility plan that will ensure achievement of an acceptable service level for the terminal. A generic simulation model will be developed in ARENA simulation software in order to evaluate an optimal facility plan. This problem will be confined to the receiving and unloading operations of the terminal only. Other processes such as grain storage, method of dispatch and subsequent use of the grain delivered will not be evaluated. Consequently the plans that will be proposed will not consider grain storage silos, their capacity, method of damping grain into silos, different grain types and railway trucks for shipping grain to and from the terminal. The focus of the study will be on developing a modular delivery terminal unit that easily synchronizes with other sections of the organization’s operations.

**Objectives of the study**
The overall objective of this study is to develop a facility plan for a grain delivery terminal using a discrete event simulation-based approach. The commonly used metrics for evaluating performance of a system are system throughput (number of customers serviced within a given time period), the average waiting time and total time spent in the system by customers. The specific objectives of the study are:

- Determination of process constraint/bottleneck.
- Determination of optimal number of resources - workstations and operators required at each stage of the process.
- Determination of system performance measures such as:
  
  (i) average waiting time for each activity or process,
  
  (ii) average length of queue at each work station,
  
  (iii) average total time spent in the system by a customer,
(iv) and level of resource utilization at each work station.

**Benefits of the study**

It is anticipated that this study will contribute the following to the operations of the grain terminal:

- Reduction of waiting times and queue lengths for customers;
- Reduction of total service time for customers;
- A facility design with conflict free routing of trucks;
- Maximization of system throughput through optimal use of resources, space and slack capacity.

These benefits will lead to an enhancement of the overall operational efficiency of the grain terminal which translates into higher profits for the organization.

**Research question**

This study will seek to answer the research question: “What is the optimal facility plan for a grain delivery terminal?” The rest of this thesis is arranged into chapters for literature review, methodology, case study, and conclusion.
CHAPTER 2: LITERATURE REVIEW

2.1 Facility planning
Tompkins et al. (2003) points out that facilities planning should not be used as a synonym for facilities location, facilities design, facilities layout, or plant layout. Rather facilities’ planning determines how an activity’s tangible fixed assets best support achieving the activity’s objective. The location of the facility refers to its placement with respect to customer, suppliers, and other facilities with which it interfaces as well as its placement and orientation on a specific plot of land. The design of a facility refers to the determination of how the design components support achieving the facility’s objectives. Facilities or plant layout is a subset of facilities design and it deals with the equipment, machinery, and furnishings within a building envelop or piece of land for a facility with outdoor activities. Other components of facilities design are facility systems (structural systems, the atmospheric system, the enclosure systems, the lighting / electrical / communication systems, the life safety systems, and the sanitation systems) and handling system (mechanisms needed to satisfy the required facility interactions).

As an example, for a manufacturing firm, facility planning involves determining how the manufacturing facility best supports production; for an airport, facilities’ planning determines how the airport facility is to support the passenger-airplane interface and for a hospital, it determines how the facility supports providing medical care to patients. Figure 2.1 depicts the relationship between facilities planning, location, and design for a health care provider’s system.
Facilities planning is intended to enable an organization to achieve supply chain excellence through a six step process, that includes business as usual, link excellence, visibility, collaboration, synthesis, and velocity. In order to support supply chain excellence, every facility should be flexibility, modular, upgradable, and adaptable (Tompkins et al, 2003).

- Flexibility. Flexible facilities are able to handle a variety of requirements without being altered.
- Modularity. Modular facilities are those with systems that cooperate efficiently over wide range of operating rates.
- Upgradability. Upgraded facilities gracefully incorporate advances in equipment systems and technology.
- Adaptability. This means taking into consideration the implications of calendars, cycles, and peaks in facilities use.
- Selective operability. This means understanding how each facility segment operates and allows contingency plans to be put in place.
The facilities planning process

The following are the objectives of any facilities planning process.

- Improve customer satisfaction by being easy to do business with, conforming to customer promises, and responding to customer needs.
- Increase return on assets (ROA) by maximizing inventory turns, minimizing obsolete inventory, maximizing employee participation, and maximizing continuous improvement.
- Maximize speed for quick customer response.
- Reduce costs and grow the supply chain profitability.
- Integrate the supply chain through partnerships and communication.
- Support the organization’s vision through improved material handling, material control and good housekeeping.
- Effectively utilize people, equipment, space and energy.
- Maximize return on investment (ROI) on all capital expenditures.
- Be adaptable and promote ease of maintenance.
- Provide for employee safety and job satisfaction.

These objectives are achieved through a systematic facilities’ planning process (Figure 2.2) involving the following steps similar to the traditional engineering design process:
2.2.1 Define the problem.

*Define (or redefine) the objective of the facility.* Whether planning a new facility or the improvement of an existing facility, it is essential that the product(s) to be produced and/or services to be provided be specified quantitatively. Volumes or levels of activity need to be identified whenever possible. The role of the facility within the supply chain must also be defined.

*Specify the primary and support activities to be performed in accomplishing the objective.* The primary and support activities to be performed and requirements to be met should be specified in terms of the operations, equipment, personnel, and material flows involved. Support activities allow primary activities to function with minimal interruption and delay. As an example, maintenance is a support activity for manufacturing.
2.2.2 **Analyze the problem.**

*Determine the interrelationships among all activities.* Establish whether and how activities interact with or support one another within the boundaries of the facility and how this is to be undertaken. Both quantitative and qualitative relationships should be defined.

2.2.3 **Determine the space requirements for all activities.**

All equipment, material and personnel requirements must be considered when calculating space requirements for each activity. Alternative designs should be generated.

2.2.4 **Evaluate the alternatives.**

On the basis of accepted criteria, rank the plans specified. For each, determine the subjective factors involved and evaluate whether and how these factors will affect the facilities and its operation.

2.2.5 **Select the preferred design.**

The problem is to determine which plan, if any, will be the most acceptable in satisfying the goals and objectives of the organization. Most often, cost is not the only major consideration when evaluating a facilities plan. The information generated in the previous step should be utilized to arrive at the final selection of a plan.

2.2.6 **Implement the design.**

*Implement the facilities plan.* Once the plan has been selected, a considerable amount of planning must precede the actual construction of a facility or the layout
of an area. Supervising installation of a layout, getting ready to start up, actually starting up, running, and debugging are all part of the implementation phase of facilities planning.

*Maintain and adapt the facilities plan.* As new requirements are placed on the facility, the overall facilities plan must be modified accordingly. It should reflect any energy-saving measures or improved material handling equipment that becomes available. Changes in product design or mix may require changes in handing equipment or flow patterns that, in turn, require an updated facilities plan.

*Redefine the objective of the facility.* As indicated in the first step, it is necessary to identify the products to be produced or services to be provided in specific, quantifiable terms. In the case of potential modifications, expansions, and so on for existing facilities, all recognized changes must be considered and integrated into the layout plan.

**Ergonomic considerations in facilities planning and design**

Facility layout design has to take into account important ergonomic considerations for both complex and simple structures. A number of criteria are important in planning the placement of machines and humans in a human-machine system. Bonney and Williams (1977) pointed out 1) the type of user population; 2) comfort of use; 3) safety; 4) aesthetics; 5) closeness of devices; 6) ease of utilization; 7) appropriate distance (separation) between the devices to reduce potential error; 8) division of work between upper and lower extremities; 9) anthropometric dimensions; and 10) functional
relationships between devices; as key aspects in ergonomic considerations for facilities planning and design.

A number of aspects pertaining to facility design cannot be simply incorporated into mathematical models to obtain measurable quantities. Formal models simply aid the design process. Grobelny and Karwowski (2006) describe first order and second order criteria for assessing layout design based on the cost of placing machines/objects and the transportation costs required for such placements respectively. They also apply a linguistic approach proposed by Grobelny et al. (1995) and Karwowski et al. (1999) in which fuzzy sets and systems theory using ‘IF’, ‘THEN’ rules are applied for deriving layout design matrices. These approaches were based on the design criteria recommended by McCormick (1976) for ergonomic layout design. These are: importance, frequency of use, order of use and functional use.

**Facility planning models**

Facility planning models related to grain delivery/handling that are available in literature either focus on the entire supply chain process or on the sub components of facilities planning individually along with economic considerations. Most literature available focuses on the Facility Layout Problem (FLP). Numerous methods have been developed over the years to provide an optimal or close to optimal solution to different forms of FLP.

The main objective of facility design is to minimize material handling costs. In its general form, the facility layout problem is expressed as follows:

\[
Z = \sum_{i=1}^{N} \sum_{j=i+1}^{N} C_{ij} f_{ij} d_{ij}
\]
for N departments with known area and interdepartmental material flow requirements; where Z is the objective function, \( d_{ij} \) is the distance between departments i and j for a specified distance metric, \( f_{ij} \) is the amount of material flow, and \( C_{ij} \) is the material handling cost per unit flow per unit distance travelled between departments i and j; subject to constraints such as departmental area requirements, boundaries of layout, departmental shape, maximum aspect ratio (Tate and Smith 1995), and minimum side length (Coit et al., 1996).

2.4.1 Facility layout planning models and design algorithms
A number of individuals or corporations have advanced layout planning models upon which their facilities were based. These are usually a set of procedures that when followed keenly result in considerably efficient layouts. For example Apple’s (1997) plant layout procedure advances 20 steps that can be tailored to different facilities with appropriate alternations, noting that the steps need not be followed in a specific order, but planners can go back and forth until the desired result is achieved. Reed (1961) proposed a 10-step “systematic plan of attack” required in “planning for and preparing the layout”. Muther (1973) developed the systematic layout planning (SLP) that is based on input data and activity relationships. It is a 10-step process that involves deriving the spatial relationship between activities and evaluating a set of alternatives for the layout with the most optimal proximity of activities.

Algorithmic approaches to the facility layout planning process are based on “closeness ratings” or “material flow intensities”. Although algorithms can be executed by hand, most real world algorithms are evaluated by computers but still require qualitative input and analysis that can only be done by humans. Layout algorithms are classified according
to whether they are qualitative or quantitative. Other classifications are based on objective functions: where one kind aims at minimizing the sum of flows multiplied by distances while the other maximizes the adjacency score. Algorithms are further classified on the basis of their layout representation, in which case we have discrete or continuous layout representations.

A number of modeling techniques are used in various layout algorithms and include the pairwise exchange method, graph-based method, CRAFT, BLOCPLAN, MIP, LOGIC, and MULTIPLE. The pairwise exchange method is an improvement-type layout algorithm that can be used with both an adjacency-based and distance-based objective, (Reed et al., 1961 and Buffa et al. 1964). The graph-based method is a construction-type layout algorithm that is often used with an adjacency-based objective. Its recognition dates back to the late 1960s (Krejcirik, 1969) and early 1970s (Seppanen and Moore, 1970). The use of graph theory methods has strong similarities with the SLP method developed by Muther (1973). CRAFT (Computerized Relative Allocation of Facilities Technique) is also an improvement-type algorithm that was introduced by Armour, Buffa, and Vollman (1963). It uses a from-to chart as input data for the flow and layout "cost" is measured by distance-based objective functions. In this method, departments are not restricted to rectangular shapes and the layout is represented in a discrete fashion. BLOCPLAN which was developed by Donaghey (1990) and Pire (1987) is a continuous layout representation method that is rectangular based and utilizes a from-to chart that can be measured either by the distance-based objective or the adjacency-based objective. Other approaches that are applied to the facility layout problems include: the mixed integer programming (MIP) problem which is a continuous representation of the problem,
and Simulated Annealing (SA) and Genetic Algorithms (GAs) which are relatively new concepts in optimization are also used in combination with the basic layout algorithms to give better solution alternatives. Simulated Annealing makes use of statistical mechanics and combinatorial optimization approaches in identifying the best solution for a facility layout problem (Kirkpatrick et al. 1983). Simulated Annealing algorithms include Simulated Annealing-based Layout Evaluation (SABLE) which was developed by Meller and Bozer (1996) and LOGIC (Tam, 1991). Genetic Algorithms in contrast to Simulated Annealing which works with one solution at a time, work with a family of solutions and progressively obtain better solutions from one generation to the next within each current population. This technique was introduced by Holland (1975) based on the natural principle of ‘survival of the fittest’ (SOF). Other early layout algorithms that have acted as a basis for many facility layout algorithms include: ALDEP (1967), COFAD (1976), CORELAP (1967), PLANET (1972), DISCON (1980), FLAC (1985), and SHAPE (1986 and 1994).

Recent areas of research in facility layout design have advanced several exact, heuristic and meta-heuristic methods for solving the FLP. Efforts to solve the facility layout problem using exact approaches have been proposed by a number of scholars Montreuil (1990), Meller et al. (1998, 2007), Sherali et al. (2003), Castillo et al. (2005), Castillo and Westerlund (2005), and Konak et al. (2006). These exact approaches are limited as to the size of the problem that can be optimally solved due to the computational intractability of the problem. As a result, many facility layout problems have focused on heuristic and meta-heuristic approaches to find good solutions. Meta-heuristic approaches include simulated annealing (Meller and Bozer 1996), genetic algorithms (Tate and Smith 1995,

Most recently, Kulturel-Konak and Konak (2011) propose an ant colony optimization (ACO) algorithm to solve the Facility Layout Problem with Flexible bay Structure (FBS) [Tong (1991), Tate and Smith (1995), Arapoglu et al. (2001), Kulturel-Konak et al. (2004, 2007), Enea et al. (2005), Konak et al. (2006), and Alagoz et al. (2008)], using swap and insert local search operators. In comparison with metaheuristics such as GA, the hybrid fuzzy model and genetic search (Enea et al., 2005), the MIP approach (Konak et al., 2006; Castillo et al., 2005), AntZone approach (Montreuil et al., 2004), the GA with a slicing tree approach (Gau and Meller, 1999), the MIP-based GA approach (Liu and Meller, 2007), the MIP approach of the TS with slicing tree (Scholz et al., 2009), the AS with slicing tree approach (Komarudin and Wong, 2010) and exact methods; the algorithm was reported to have shown a 17% improvement in solutions to the FLP as well as less CPU usage. Other approaches similar to the FBS were developed by Donaghey and Pire (1990), Goetschalckx (1992), Meller (1997), Peters and Taho (1997), Yang and Peters (1997), and Castillo and Peters (2004).

A number of recent studies have also focused on developing algorithms and heuristics for specific applications. For example for automated guided vehicle (AGV) routing, studies
have been done by Sarker and Gurav, (2005); Reveliotis (2000); Bish et al, (2001); Lim et al, (2002); Naiqi and Zeng, (2002); Qiu et al, (2002); Singh and Tiwari, (2002); and Qui and Hsu, (2001).

2.4.2 Discrete event simulation as a facility planning tool
There have been recent shifts from traditional systems to complex integrated systems of people, information, materials and equipment in order to produce innovative and efficient products and organizations. In particular boundaries between traditional engineering and science and arts disciplines are blurring producing synergistic research that is more beneficial to all fields. Simulation which is applied in engineering as a valuable operations research tool was first applied to the social sciences field in the 1960s but gained wide acceptance in the 1990s, (Gilbert, 2005). It is now gaining popularity across many fields with applications in the biological sciences, engineering, humanities and social sciences. In most cases, when analytical methods cannot be applied to solve a problem, simulation becomes a viable option. In simulation modeling an existing or proposed system is statistically imitated using probability distributions or a computer program code such as in intelligent agents-based simulation in order to observe the performance of the system as though the real world system were being observed.

As opposed to continuous event simulation, discrete event simulation “describes systems that are assumed to change instantaneously in response to certain sudden or discrete events or occurrences.” For example in a capacity planning study involving a grain terminal we may wish to simulate how the quantity of grain received changes over the course of a day. We would then model the hourly arrival of truckloads of grain as discrete (specific time point) events involving instantaneous arrival of grain loads as opposed to a
continuous evaluation of the gradually increasing quantity of grain received. Such an assumption would be appropriate since we are modeling the system on an hour-by-hour, truckload-by-truckload basis instead of a second-by-second, grain-by-grain basis. Although discrete event simulation of real world systems reduces our ability to capture a certain degree of detail that can only be observed in continuous change, it allows a simplified approach for analyzing otherwise complex systems. Two basic ideas common to all simulations is the need to use randomness and to describe dynamic behavior, (Ribeiro and Antunes, 2000).

Ribeiro and Antunes (2000) propose mixed integer programming (MIP) methods based on the XPRESS software for discrete facility planning problems aimed at finding the optimal size and locations for facilities in order to meet predefined objectives. With consideration of economic requirements, Zamboni et al. (2009) developed a mixed integer linear programming model for optimization of an entire bioethanol supply chain right from transportation of biomass feedstock to production and distribution of the bio-fuel to customers.

Kalaitzandonakes et al. (2001) describe a simulation model that focuses on the cost of Identity Preservation (IP) of the different feed crops involved in a grain storage operation following stringent rules requiring the classification of food depending on whether they are purely organic or genetically modified. Case studies of three high oil corn and their empirical identity preservation costs were considered. The study advanced the “Process and Economic Simulation of IP (PRESIP) hybrid economic engineering simulation model that is designed to capture the subtle intricacies of day-to-day operations of IP supply chains”, (Kalaitzandonakes et al., 2001).
While Cafaro et al. (2010), Rangel et al (2010), Brito et al. (2010), and Kalaskyet et al. (2010) applied discrete event simulation modeling to unique case studies involving oil-derivatives pipeline logistics, evaluation of sugarcane supply systems, steel plant logistics system planning, manpower planning and scheduling in a distributed multi-user environment; no studies on facility planning for grain delivery terminals were found.
CHAPTER 3: METHODOLOGY

3.1 Discrete event simulation modeling

Discrete event simulation will be used in the design and analysis of the grain delivery terminal. As one of the most widely used and accepted tools in operations research and systems analysis, simulation modeling imitates the operation of a real world process or system overtime, from which data is collected as if the real system were being observed. This data is used to estimate various measures of performance of the system. Simulation tools can be used for modeling complex real world systems, experimenting with new designs or policies before implementation and for verifying analytical solutions. Simulation tools are flexible allowing analysts to vary inputs in order to gain insight into different scenarios and tackle unforeseen situations proactively.

The following steps are involved in discrete event simulation modeling, (Banks et al., 2009):

- **Step 1:** Formulate the problem and set overall objectives and project plan
- **Step 2:** Conceptualize the simulation model and determine the assumptions.
- **Step 3:** Collect data for the simulation study.
- **Step 4:** Translate, verify and validate the simulation model.
- **Step 5:** Set up the experimental design and conduct analysis of the output data.
- **Step 6:** Document, report and recommend the optimal solution.

Chwif and Medina (2006) generalize the simulation modeling process into three stages: conception, implementation, and analysis, Figure 3.1 which encompass the steps outlined above. Step 1 has already been done in chapter one. The following subsections embody
the rest of the steps involved. For Step 3, in lieu of collecting data, statistical, empirical and standard estimates of process durations will be made.

**System description (conception stage)**

### 3.2.1 The grain delivery process

A typical grain delivery operation consists of five stages. They include: identification, probing, quality testing, weighing, and unloading. Identification and weighing are done more than once. A fully loaded truck of grain is weighed twice; first to determine the gross weight, and after unloading, to determine the tare weight. Identification is done two to three times: first at the probing stage; then when the first weight (gross weight) is measured; andthirdly when the second weight (tare weight) of an unloaded truck is measured. Figure 3.2 shows a flow chart of the generic grain delivery process.

---

**Figure 3.1: Development of a simulation model (Chwif and Medina 2006).**
In light of these processes, facility planning has to be done in such a manner as to obtain the optimal arrangement of workstations that gives the quickest and most efficient way of receiving the grain. An optimal layout is the one that has an acceptable waiting time, queue length, total time in the system and level of resource utilization. In the rest of this section, detailed descriptions of the processes and equipment involved in grain delivery are presented; descriptions of the facility plans and scenarios to be simulated are provided; the simulation model is developed; and results are presented.
Figure 3.2: Generic Grain Delivery Process Flow Chart
Process requirements and service distribution estimation

3.3.1 The probing process

Probing is the first step in the grain delivery process. It is carried out using a probe. A Grain Sampling Probe is a tubular device used to obtain specified amounts of grain from different sections of a delivery being made by truck, car, wagon or barge load, or from a batch stored in an elevator; in order to get a representative sample. Probes are constructed using plastics or heavy gauge tubing for durability. A number of manufacturers make probes of different types and sizes conforming to USDA specs. Figure 3.3 shows a picture of a 40” brass probe with 6 slots and an open handle. Slots are openings that are equally spaced along the length of the probe tube through which grain enters as the probe is dipped into the grain. This process can be done either manually or by use of a robotic arm.

![Grain probe sampler by Best Harvest with partitions as required by USDA and all grain inspectors.](image)

3.3.1.1 Probability distribution for probing process

Probes are usually placed at the very beginning of the grain delivery terminal. Probing can be done manually by hand or automatically by use of an extended robotic arm. In the case of automation, open-ended probes without partitions are used to draw a sample from
the grain and different mechanisms such as gravity or suction used to dump the sample into a receptor.

Using empirical data from the case study described in Chapter 4; we assign a triangular distribution to the probing operation of TRIA(30,85,193) seconds. A triangular distribution models a process for which only the minimum, most likely, and maximum values of the distribution are known, (Banks et al., 2005).

3.3.2 The quality testing process
Grain testing at a delivery terminal is an important stage that the buyer carries out before accepting any grain from the seller. Grain is not naturally a uniform commodity. A lot of variation is present in any grain load due to a wide range of factors. Variation in grain can be caused by how it is grown resulting in variation in each ear of grain, each plant of grain, each field of grain and across different grain farms. Variation also occurs in harvested grain as a result of moisture variation during the day, variation in truck loads, mixing of dried and un-dried grain, and variation of storage destinations for the grain. As a result, each grain load has to be sampled adequately and evaluated for moisture content, specific weight, foreign material, dockage (lighter damaged grains and husks), temperature and other desired characteristics.

A number of pieces of equipment are used for testing grain for quality – either manually or automatically. These include moisture meter, weighing scale, sieve, and other cleaning and separation devices. In the manual case, handpicking is done to sort foreign material or damaged grain from the sample and results are entered into a computer manually. Whereas in the automatic case, a grain analyzer connected to the probe is configured to
carry out the entire process without human interference and the results are instantly displayed on a computer via a middleware. Decisions are taken to accept or reject the grain by comparing the results from the analysis to preset tolerance levels for each characteristic grain property. Based on the quality test result, an offloading bay is assigned to grain that passes the test, while rejected grain exits the facility. The following subsections explore some of the equipment used in grain testing, briefly describing their functions, specifications and examples.

3.3.2.1 Moisture meter

Figure 3.4 shows a picture of a moisture meter. It is used for determining the percentage moisture content of a grain sample. A moisture meter consists of a removable 3.5" dump & test cell, glass thermometer – red liquid filled, 120 volts 60 Hz AC/DC power adapter, and 9 volts DC plug. Operation is manual with all CGC charts.

![Figure 3.4: Model 919™ moisture tester by Dimo’s Labtronics.](image)

3.3.2.2 Grain test weight scale

Used for evaluating grain production in order to guide determination of expected yield, price discounts, storage capacities, feed quality, and milling quality of grain. Figure 3.5
shows a simple to use scale that can be used to determine pounds per bushel and kg. per hectoliter for all grain types. Scale is extremely accurate and USDA approved.

Figure 3.5: A grain test weight scale by Berckes Manufacturing.

Figure 3.6 shows another type of scale that is made of ABS plastic. It has a 0.5L measure capacity and a regulation cox funnel with strike-off stick and conversion charts.

Figure 3.6: Complete test weight determination kit by Dimo’s Labtronics.

3.3.2.3 Sieve

This is used for removing chaff and dockage from a grain sample. Figure 3.7 shows a 13” diameter 2-piece sieve with an injection molded frame design to avoid bending, warping or breakage. The sieve is fastened at six points.
Figure 3.7: Hand held dockage sieve by Dimo’s Labtronics.

3.3.2.4 Grain temperature probe

A grain temperature probe is used to determine the temperature of the grain. Figure 3.8 shows a laser-based gun-type infrared thermometer with a range of -30°C to 550°C, auto power off function, low battery indication, back-light display feature, and C or F user-selective. The laser mark measures surface temperature of difficult to reach objects.

Figure 3.8: Gun-Type Digital Infrared thermometer by Dimo’s Labtronics

Figure 3.9 shows a different type of thermometer with a plastic case.

Figure 3.9: Plastic case glass thermometer by Dimo’s Labtronics
3.3.2.5 Automated grain grading system – autokicker

This is a robust unit that directly connects to the probe and embodies all the accessories required for grain testing. Figure 3.10 shows a standalone autokicker unit and an installed one. It has the ability to analyze test weight, moisture, dockage, protein, oil, starch, fiber, shrunken and broken grain, foreign material, grain temperature and clean grain percentage. It automatically transmits results to a receipt via an application software on a computer. The autokicker program is designed to allow ease of operation, and identifiers such as contract or lot numbers can be easily changed or selected. From the manufacturer’s specifications, the standard process time of the autokicker machine is anywhere from 45 to 150 seconds per sample depending on the grain type and configuration of the machine.

Figure 3.10: MCi autokicker by Mid-Continent Industries Inc.

Based on the standard process time, we assign a uniform distribution to the automated quality testing process, UNIF (45, 150).

3.3.2.6 Damage count process

For grain loads that do not pass the quality test requirements, a further manual damage count process is conducted. The tolerance levels are relaxed and if a grain load is
acceptable it is offloaded, otherwise it is rejected and the truck load exits the terminal. The manual damage count process will be assumed to have a constant duration of 2.35 minutes (141 seconds) based on empirical data from the case study.

### 3.3.3 Weighing

It is essential to weigh a load of grain before offloading in order to know how much grain is being delivered. A grain truckload is weighed using a platform scale known as a weighbridge or truck scale. It is built over the road on the path of the trucks. It may be installed above the ground or in a pit along the road and is made of either steel or concrete decks. Once a truckload settles on the bridge the weight appears on a digital display and is registered on a computer software. Weighbridges are available in different makes with varying capacities. One manufacturer, METTLER TOLEDO, makes concrete/steel weighbridges with a capacity of 20 – 200,000 lbs; length of 10’-120’ and a width of 10’; and either mounted in a pit or on the road. Figure 3.11 shows a face view of a weighbridge and a line of weighbridge platforms mounted on the road.

![Figure 3.11: A weighbridge platform with truck loads (METTLER TOLEDO)](image)

A grain terminal usually has two or more weighing scales depending on the type of its operations. The scales are divided into inbound and outbound for taking the gross and
tare weights of a grain load respectively. Weighing scales are positioned at the beginning (inbound scale) and at the end (outbound scale) of the grain delivery process. According to manufacturer’s specifications, a standard weighing operation takes 30 – 60 seconds depending on how fast the driver is able to position the truck on the platform. Based on this, a uniform distribution will be assigned to the weighing process, UNIF (30, 60) seconds.

3.3.4 Offloading bays
Grain is offloaded by emptying the contents into a hopper that conveys the grain to the appropriate storage silo via an elevator/conveyor. The number of bays at a grain terminal depends on its capacity and the different kinds of grain that the firm deals in. Offloading bays are conveniently placed after the inbound scale. Based on data collected for the case study, an offloading operation takes 2 to 5 minutes to perform depending on the size of the trailer and speed of the driver. We will therefore model this process according to a triangular distribution with parameters TRIA (2, 3.5, 5) - units in minutes, or TRIA (120, 210, 300) – units in seconds.

3.3.5 Staging area
Grain is a seasonal crop. This means that during harvest seasons there will be more traffic than other seasons. Consequently, a grain terminal should have ample staging space especially at the entrance. Depending on how quickly traffic flows through the terminal, additional space may be necessary for trucks to wait in queue at each subsequent work station. Placement of the staging area depends on the available space at the facility and the number of truckloads handled.
3.3.6 Queuing type and placement
The grain delivery process follows the First Come First Served (FCFS) queue discipline. There may be a few exceptions in special cases where a particular grain type is needed urgently or storage space for a certain grain type is not available. In such a case, a general queue discipline may be applied. Queue staging areas are conveniently placed en-route to workstations.

3.3.7 Office
A centrally located office is necessary for coordinating the activities at a grain terminal especially if most processes are automated or semi-automated. Well positioned external cameras are helpful in enabling the operator to physically observe and control the process flow from within the office.

3.3.8 Parking for office visitors
A parking lot for the office workers and guests is placed adjacent to the office building. This allows quick access to the office by both workers and customers.

3.3.9 Automatic identification systems
3.3.9.1 Barcodes
Barcodes are Automatic Identification Data Capture (AIDC) systems that are used in the identification of traders in the delivery process by use of a swipe card. A barcode system essentially consists of an optical machine-readable bar code and a 12-digit human-readable Universal Product Code (UPC) number. A barcode reader (optical scanner) is used to read the codes which show data on the trader it is representing via an interpretative computer software. Figure 3.12 shows an example of a barcode and reader.
Barcodes can be printed on delivery receipts, bills of lading, grain transfer documents and ID cards and used to easily retrieve vendor information from a preexisting database.

![Barcode and Portable Scanner](image)

Figure 3.12: A barcode and portable scanner

3.3.9.2 RFID technology

RFID stands for Radio Frequency Identification. Just like bar codes, it is an automatic data capture (ADC) system that consists of an interrogator (reader) with an antennae and transponders (tags). The tags send a signal to the antenna being powered by a battery or by the radio frequency energy from the reader’s pulse. This is then read by the reader and displayed on a computer (host) via a middleware. The main advantage that RFID has over the barcode is that there is no need for line of sight between the reader and the tags taking readings. In addition some RFID systems have the capability of reading objects at very long ranges.

Among its many uses RFID has proved to be very important in supply chain logistics and retail management. RFID supports information in the supply chain by enabling visibility - the ability of anyone, including customers, to have access to any information in the supply chain in real-time. The benefits of implementing an RFID system in a grain delivery terminal are:

- Fast and easy identification of traders and their grain loads;
- Information sharing over network connections between the supplying centers and the receiving centers in real-time;
- Reduction of time and labor which would otherwise be spent receiving and inspecting slips and receipts from traders;
- Reduction/elimination of human error.

The most appropriate RFID tags for use on trucks are active tags (these are powered by batteries and emit stronger signals over longer ranges unlike passive tags that wait for a signal from the reader). These tags can be clamped / attached to the side of the truck body. An RFID portal or overhead system is then setup and as trucks pass through (Figure 3.13) they are automatically identified with no need for stopping or having the driver step outside of his truck to swipe an ID card. A very effective RFID system has the potential to reduce the identification process duration to zero provided other factors are favorable.

Figure 3.13: An RFID tagged truck on a weighbridge scale with an RFID portal (www.rfidjournal.com).
Proposed facility plans

3.4.1 Process flow and workstation placement in grain facility

The grain delivery processes discussed above are best placed as shown in Figure 3.14. The first station is the probe workstation followed by the quality test and inbound scale workstations concurrently. After a quality decision is made, an accepted grain load proceeds to the offloading workstation to unload. Thereafter the emptied truck weighs-out at the outbound scale and exits the terminal. A rejected grain load, on the other hand, proceeds to the exit right after the quality analysis process. As a truck progresses through the workstations, identification of the vendor is done by use of a swipe card (barcode-based) or RFID tag at three of the stop points: the probe and the two weighing scales. Identification is not regarded as a separate process in this system because it is done during the course of the main process.

Figure 3.14: Best workflow/workstation arrangement for processes in grain
3.4.2 Two distinguishing cases for the facility layout design

Figures 3.15 and 3.16 show two schematics of the proposed 2000ft by 1000ft facility layout design for the terminal; Case 1 and Case 2 respectively. Case 1 is a more compact design with a longer inbound traffic lane to the probe workstation. This allows more staging area for the probe queue but limits space for more resources at the workstations. Case 1 therefore consists of a single line of workstations (fewer resources) with a long queuing area for the probe and a longer travel distance and routing time.

Case 2 has a shorter inbound traffic lane to the probe workstation. This makes the layout less compact making the installation of a second probe and inbound scale possible. A second quality test machine is added as well as a second lane for rejected trucks. As a result, Case 2 has less staging area for the probe queue and more resources—two lines of workstations (probe, quality test and inbound scale), with a shorter travel distance and routing time compared to Case 1.

Common to both cases is the placement of the quality test workstation inside the office and a parking lot adjacent to the office. A lane for rejected grain loads is provided from the inbound scale to the outbound traffic lane for both layouts, a single one for case 1 and two lanes for case 2. Driving distances between all workstations are assumed to be the same.
Figure 3.15: A schematic of the proposed facility plan for Case 1 with process/workflow
Figure 3.16: A schematic of the proposed facility plan for Case 2 with process/workflow

3.4.3 Dimensions to aid in facility design

A grain trailer has an average length of 28 to 40 feet with a width of 8.5 feet and height of 14 feet. Trucks with single trailers can have lengths of up to 75 feet. However, for seasonally harvested products the federal government mandates a cargo load of length 71.5 feet (US DOT Federal Highway Administration, 2004). Specific dimensions vary according to state laws, regulations and other factors such as weight of the load. As a baseline for comparison of the proposed facility design cases, we will assume a truck average length of 75 feet. All workstations will therefore have a length of at least 80 feet. The width of the lanes and staging areas for trucks should be more than the minimum width of the trucks (8.5 feet). We will assume this to be equivalent to the standard
minimum lane width of an interstate highway of 12 feet. A clearance of 10ft will be allowed in-between lanes, off the facility boundaries and between each workstation and adjacent lane(s). Figures 3.17 and 3.18 show the dimensions for the proposed facility plans - 1 and 2.

Figure 3.17: A schematic of the proposed facility plan for Case 1 with dimensions
3.4.4 Workstation routing times

Assuming a uniform driving speed of 15mph for linear driving directions, routing times to workstations were computed using the dimensions from Table 3.4 and the formula:

\[
\text{Routing Time} = \frac{\text{Distance}}{\text{Speed}}
\]

Assuming it takes 10 seconds for a single trailer truck to navigate a curve, an additional 10 seconds was added for every turn that a truck makes along the routes. The routing times are summarized in Table 3.1.
Table 3.1: Summary of routing times to workstations

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Routing Time (seconds)</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route to Probe</td>
<td></td>
<td>258</td>
<td>162</td>
</tr>
<tr>
<td>Route to Inbound Scale</td>
<td></td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Route to offloading</td>
<td></td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Route to Outbound Scale</td>
<td></td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Route rejected trucks to exit</td>
<td></td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>Route offloaded trucks to exit</td>
<td></td>
<td>27</td>
<td>29</td>
</tr>
</tbody>
</table>

3.4.5 Workstation queue capacities

Assuming a minimum distance of 3 feet between trucks in queue, maximum queue capacity was calculated by dividing route length minus clearance by truck length in order to determine the maximum number of trucks that fit on the driveway. The following expression will be used to calculate maximum queue length:

\[
\text{Maximum queue length} = \frac{(\text{Route Length} - 10)}{75 + 3}
\]

The value 10 represents the 10ft clearance between every workstation and adjacent lane(s). The maximum number of trucks per queue per workstation are shown in Table 3.2.

Table 3.2: Maximum number of trucks per queue / queue capacity for each workstation

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Queue Capacity</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe Queue</td>
<td>64</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Inbound Scale Queue</td>
<td>7</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Offloading Bay Queue</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Outbound Scale Queue</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>
3.4.6 Simulation scenarios

A set of four scenarios will be modeled for the proposed facility plans by varying the number of human operators and their mode of operation. In this context, the human operators either work independently or help each other. Independent operators (Case a) work on grain deliveries from start to finish separately while helping operators (Case b) assist each other with the damage count process thus more than one operator may be serving customers at the same workstation line at the same time. Table 3.3 shows the combination of resources and the mode of operation of human operators for each scenario.

Scenarios 1a and 1b are patterned according to the facility design plan for Case 1 with a single line of workstations and human operators working independently or helping each other respectively. Although both scenarios have the same number of resources, 1b is expected to have an improvement over 1a. When the operators assist each other less waiting is expected. Helping operators can expedite the process resulting in a shorter total time in system. There is a higher chance that one of the operators is always available at the probe thus less or no balking is experienced. Balking refers to the process in which an arriving customer is unable to enter into the terminal because it is operating at full capacity with no more queuing space at the entrance. It is expedient that the facility plan allows enough space for as many trucks as required to enter the terminal. If a customer is balked more than once or twice, they may choose to take their grain elsewhere.

Scenarios 2a and 2b are patterned against the facility design plan for Case 2 with double resources at the probe, inbound scale and quality test workstations. Just as in the previous scenarios, Case a represents human operators that work independently while Case b
represents those that help each other. One distinction is that scenarios 2a and 2b have three human operators. The more resources are available the faster the service process thus less or no balking is expected with increased resources. In addition, less waiting and total time in system with higher throughput is anticipated.

Table 3.3: Four facility plan scenarios to be simulated

<table>
<thead>
<tr>
<th>Variable/resource</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario 1a</td>
<td>Scenario 1b</td>
</tr>
<tr>
<td>Probe</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Quality Test Machine</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>In-bound Scale</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Offloading Bays</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Out-bound Scale</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Operators</td>
<td>2 X</td>
<td>2 X</td>
</tr>
</tbody>
</table>

I = Independent Operators
X = Helping Operators

Simulation model (implementation stage)

3.5.1 Input probability distributions

A peak hour demand of 50 trucks per hour \( \lambda = 50 \) was considered for all scenarios giving a mean interarrival rate of \( \mu = \frac{1}{\lambda} = \frac{1}{50} \times 3600 \) 72 seconds. This arrival process will therefore be modeled as an exponential distribution with parameter \( \frac{1}{\lambda} = 72 \); \text{EXPO} (72).

The exponential distribution was chosen because it models the time between independent events – the customers arriving from a large population act independently of each other, (Banks et al., 2005).

In the simulation model, 7% of the trucks will be assumed to require the manual damage count test while the remaining 93% pass the quality test after one analysis. Of the 7% that undergo the damage count test, 1% will be rejected while 99% will be accepted. The list
of process probability distributions to be used in the simulation models are summarized in Table 3.4.

Table 3.4: Summary of probability distributions for the facility plan scenarios

<table>
<thead>
<tr>
<th>Process</th>
<th>Probability Distribution (Time units in seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interarrival Time</td>
<td>EXPO(72)</td>
</tr>
<tr>
<td>Probing Time</td>
<td>TRIA(30, 85, 193)</td>
</tr>
<tr>
<td>Quality Test Time</td>
<td>UNIF (45, 150)</td>
</tr>
<tr>
<td>Damage Count Time</td>
<td>CONSTANT (141)</td>
</tr>
<tr>
<td>Probability for damage count</td>
<td>0.07</td>
</tr>
<tr>
<td>Probability for grain rejection</td>
<td>0.01</td>
</tr>
<tr>
<td>Inbound Scale Time</td>
<td>UNIF(30, 60)</td>
</tr>
<tr>
<td>Offloading Time</td>
<td>TRIA (120, 210, 300)</td>
</tr>
<tr>
<td>Outbound Scale Time</td>
<td>UNIF(30, 60)</td>
</tr>
</tbody>
</table>

3.5.2 Assumptions for the simulation model

The following assumptions were made in developing the simulation model.

- All processes involved in grain delivery were considered to be linear, unidirectional, and streamlined with no interruptions due to machine failure or brief absence of operator(s).

- No backlogging, re-routing, or random stoppages by trucks before and/or after the delivery process were modeled.

- The identification processes at the respective work stations were assumed to be overlapping/ embedded in the main process at the workstation and were not modeled separately.

- All processes were assumed to be mechanized or automated except for the manual damage count process.
3.5.3 Structure and logic of the simulation model

A discrete dynamic stochastic simulation model was developed for the scenarios using ARENA® Version 13.0 (Kelton, Sadowski, and Sturrock 2007). A snap shot of the simulation model for scenario 1a is attached in Appendix 1. Every truck that arrives in the system undergoes a similar process. Branch blocks are used at each workstation to regulate queue capacity. Wait and signal blocks are used to control the movement of entities through the model. At each branch block a decision is made to let the truck proceed or wait until the desired resource becomes available or room is created in the queue if it was previously full. Whenever a truck leaves a workstation, it releases the resource(s), except for the human operator. Human operator(s) are released after all processes requiring manual/human input are completed, these are: probing, quality test and damage count test. Whenever a resource is released, the truck releasing it sends a signal to the one at the wait block at the previous workstation.

In the model, trucks arrive at the terminal following an exponential distribution with a mean interarrival time of 72 seconds. If the probe is available, the arriving truck proceeds to the probe workstation right away and seizes the resource. If the resource is not available, the entity waits in queue provided the queue capacity has not yet been exceeded. If the queue capacity has been exceeded, the arriving entity is balked and does not enter the system.

At the probe, the truck undergoes a process delay (in seconds) following a TRIA(30,85,193) distribution. Before releasing the probe resource, the truck goes through a second decision branch to establish whether the inbound scale resource is available or whether there is room at the queue. If yes, the truck proceeds to the inbound
scale workstation and seizes it; if not it waits at the probe for a signal. Upon receiving a signal from the truck that previously seized the inbound scale resource, the truck at the probe can then proceed there and in so doing, releases the probe resource for next truck in-line.

While at the inbound scale, the quality test process is carried out concurrently. To aid this, a duplicate of the truck is made at the inbound workstation. As the duplicate undergoes an inbound scale time delay (in seconds) given by the uniform distribution, [UNIF (30, 60)], the original truck either undergoes the quality test process delay (in seconds) of UNIF (45, 150) distribution alone, with a probability of 0.93 (93%), or both the quality and damage count tests with a probability of 0.07 (7%). The damage count delay is a constant time process that takes 141 seconds. The duplicated truck is disposed off after the inbound scale delay while the original one waits for a signal from the offloading bay depending on whether the grain was accepted (probability 0.99 (99%)) or rejected (probability 0.01 (1%)). Rejected grain loads (those that fail the damage count) are routed to the terminal exit.

At the offloading bay, the truck undergoes a delay (in seconds) given by a TRIA (120,210,300) distribution. It then proceeds to the outbound scale if the resource is available or waits at the queue or offloading bay. At the outbound scale the truck undergoes a process delay following UNIF (30, 60) distribution and thereafter exits the terminal. The same simulation logic was applied to all four scenarios simulated with differences arising in the number of resources and the mode of operation of the human resources. When the operators work independently, the quality test and damage count processes occur sequentially; while when they help each other, the two processes overlap.
3.5.4 Model verification and validation

3.5.4.1 Verification

The simulation model was compared to the conceptualized grain delivery process described in Section 3.2 to ascertain that it was a correct representation. All process input probability distribution and durations were double checked for accuracy. The model was run several times and closely observed by two other researchers to check for anomalies in the process logic. The model animation was watched closely for any irregularities as well. Errors observed in the model were debugged.

3.5.4.2 Validation

After verifying the model, the results were critically analyzed to check whether they were consistent with what was expected in a real life scenario. In comparison to the case study described in the following chapter, the system bottleneck was the probe which always had the longest waiting times. This is the same with the simulation results. For example scenario 1a which is synonymous with the current system in the case study had an average probe waiting time of 25.54 minutes for a demand of 50 trucks per hour while the case study had a probe waiting time of 11.3 minutes for the same demand. The results are not exactly the same due to the difference in the input probability distributions for the case study and generic grain delivery terminal considered in this study. The trend of the results for all scenarios discussed later on in this section show that the probe is the system bottleneck and has the highest number of trucks waiting in queue just as in the case study.

A simulation scenario with more resources was expected to have shorter waiting times, shorter total time in the system, less work in progress, less arrivals balked and more entities out of the system. This was observed both in the scenario results and case study.
Each scenario was judged as to whether it was accurately representing real life by benchmarking against the case study. Corrections and adjustments were made to streamline the models.

### 3.5.5 Experimental design

To simulate the operation of the facility at a peak hour, a demand level of 50 trucks was estimated. All pertinent probability distributions, process and route durations were estimated using available literature, standards and empirical data from the case study described in Chapter 4. The model was run for a simulation length of 2 hours. Initially the system is assumed to be empty. The system was modeled as a transient/terminating (non-steady state) simulation thus requiring no warm-up/initialization period. The method of independent replications was applied and a total of 100 replications are run for each scenario.

**Simulation results and output data analysis (analysis stage)**

The goal of this simulation study was to develop a facility plan for a grain delivery terminal, identify the process bottleneck and optimize the number of resources required to run the system with an acceptable level of waiting. The performance metric for the system is waiting time.

We define $\theta$ as the estimation parameter for the waiting time for the discrete-time simulation output data of the form $\{Y_1, Y_2, ..., Y_n\}$; where $n$ is a discrete valued index. $\theta$ is the mathematical expectation of $\bar{Y}_i$, the sample mean.

$$
\theta = \mathbb{E} \left[ \left( \frac{1}{m} \right) \sum_{i=1}^{R} \bar{Y}_i \right]
$$
Let $Y_{ij}$ be the waiting time for the $j$th truck in the $i$th replication of the simulation. Each replication represents a 2-hour run length thus a different number of trucks are processed in each replication. For a terminating simulation based on the method of independent replications, the across replication data are formed by summarizing the within-replication data. A symbolic representation of the results for $R$ replications is shown in Table 3.5.

<table>
<thead>
<tr>
<th>Within-Replication Data</th>
<th>Across-Replication Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{11}$, $Y_{12}$, ..., $Y_{1n_1}$</td>
<td>$\bar{Y}<em>{1.}$, $S</em>{1.}^2$, $H_1$</td>
</tr>
<tr>
<td>$Y_{21}$, $Y_{22}$, ..., $Y_{2n_2}$</td>
<td>$\bar{Y}<em>{2.}$, $S</em>{2.}^2$, $H_2$</td>
</tr>
<tr>
<td>$\vdots$</td>
<td>$\vdots$</td>
</tr>
<tr>
<td>$Y_{R1}$, $Y_{R2}$, ..., $Y_{Rn_R}$</td>
<td>$\bar{Y}<em>{R.}$, $S</em>{R.}^2$, $H_R$</td>
</tr>
</tbody>
</table>

$\bar{Y}_i$ is the sample mean of the $n_i$ waiting times from the $i$th replication, $S_{i.}^2$ is the sample variance and $H_i$ is the confidence-interval half-width based on this dataset. The overall statistics for the waiting time are computed from the across-replication data as follows (Banks et al., 2005):

**Average waiting time:**

$$\bar{Y}. = \frac{1}{R} \sum_{i=1}^{R} \bar{Y}_i$$

**Sample variance of the waiting time data:**

$$S^2 = \frac{1}{R-1} \sum_{i=1}^{R} (\bar{Y}_i - \bar{Y}.)^2$$

**Confidence-interval half-width:**

$$H = t_{\alpha/2,R-1} \frac{S}{\sqrt{R}}$$

Giving a confidence interval of: $\bar{Y}. \pm t_{\alpha/2,R-1} \frac{S}{\sqrt{R}}$, based on the assumption that the data is normally distributed. The quantity $\frac{S}{\sqrt{R}}$ is the standard/average error in $\bar{Y}.$ as an estimator of $\theta$.

Another performance measure commonly used is the quantile. Quantile-estimation is the inverse of probability estimation. Given a number of replications, $R$, that is large enough,
usually \( R \geq 50 \); the number of the independent replication \( Y_1, \ldots, Y_R \) is large enough that 
\[ t_{a/2, R-1} = z_{a/2}. \]
The confidence interval for the probability \( p \) becomes:

\[
\hat{p} + /- z_{a/2} \sqrt{\frac{\hat{p}(1-\hat{p})}{R-1}}
\]

where \( \hat{p} \) is the sample proportion. Quantile estimation thus involves finding the \( \theta \) such that

\[
\Pr\{(Y \leq \theta)\} = p
\]

Thus to estimate the \( p \) quantile, we find that value \( \theta \)-hat such that 100\( p \)% of the data in a histogram is to the left of \( \theta \)-hat.

In Table 3.6 the average number in, average number out and average number balked in the system for the scenarios is shown. The highest number of vendors completing service in the grain terminal is observed in scenario 2b, followed by 2a, 1b, and 1a respectively. The more resources are available in the system, the higher the throughput. Helping operators have higher throughput. The results also show that balking is negligible because staging area in both cases is long. Considering that these trucks drive long distances to arrive at the terminal, they would be very disappointed if there is no space to park and wait for offloading.

Table 3.6: Average number in, average number out and average number balked in the system.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Avg. Number in</th>
<th>Avg. Number out</th>
<th>Avg. Number balked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1a</td>
<td>101.00</td>
<td>49.37</td>
<td>0.09</td>
</tr>
<tr>
<td>Scenario 1b</td>
<td>99.64</td>
<td>60.16</td>
<td>0.00</td>
</tr>
<tr>
<td>Scenario 2a</td>
<td>102.45</td>
<td>78.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Scenario 2b</td>
<td>101.19</td>
<td>83.63</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Results for average waiting time in the system and number waiting are shown in Table 3.7. These reveal that the probe workstation is the system bottleneck. The largest average total waiting time and number waiting is observed in scenario 1a, 1b, 2a and 2b respectively. From scenario 1a to 1b, a 32% decrease is observed and from 2a to 2b a 58% decrease. Increasing the probe, inbound scale, quality test machine and human operators results in reduced waiting time. The reduction is much more evident when operators help each other than when they work independently. As the probe and inbound scale waiting times reduce for scenarios 2a and 2b, a slight increase in offloading bay and outbound scale time is observed. As the probing, weighing-in and quality testing processes get faster, the outbound and offloading workstations become congested.

Total time in the system is least for scenario 2b, followed by 2a, 1b and 1a. Figure 3.19 shows a plot of these results. The trend shows a decrease in wait time, number waiting and total time in system as the number of resources increase.

Table 3.7: Average waiting time, average total number waiting and average total time in system

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Scenario 1a</th>
<th>Scenario 1b</th>
<th>Scenario 2a</th>
<th>Scenario 2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_Probe</td>
<td>25.5440</td>
<td>17.3247</td>
<td>9.3851</td>
<td>2.7701</td>
</tr>
<tr>
<td>Q_Inbound Scale</td>
<td>0.1827</td>
<td>0.0044</td>
<td>0.0535</td>
<td>0.0005</td>
</tr>
<tr>
<td>Q_Offloading</td>
<td>0.0009</td>
<td>0.0204</td>
<td>0.2375</td>
<td>1.2011</td>
</tr>
<tr>
<td>Q_Outbound Scale</td>
<td>0.0458</td>
<td>0.0677</td>
<td>0.1409</td>
<td>0.1671</td>
</tr>
<tr>
<td><strong>Avg Total waiting time</strong> (minutes)</td>
<td><strong>25.7734</strong></td>
<td><strong>17.4172</strong></td>
<td><strong>9.8169</strong></td>
<td><strong>4.1388</strong></td>
</tr>
<tr>
<td><strong>Avg Total number waiting</strong></td>
<td>21.2600</td>
<td>14.3100</td>
<td>8.4300</td>
<td>3.4900</td>
</tr>
<tr>
<td><strong>Avg Total Time in System (minutes)</strong></td>
<td>37.3376</td>
<td>31.4299</td>
<td>21.2294</td>
<td>17.8187</td>
</tr>
</tbody>
</table>
The average resource utilization results shown in Table 3.8, show an increase in the utilization values for scenarios with the same number of resources when human operators help each other than when they work independently. It is generally desirable to make the most use of all resources available in a facility. Figure 3.20 (a), and (b) show plots comparing scenarios 1a versus 1b, and 2a versus 2b. The trends show that case b is better than case a.
Table 3.8: Average resource utilization

<table>
<thead>
<tr>
<th>Resource</th>
<th>Scenario 1a</th>
<th>Scenario 1b</th>
<th>Scenario 2a</th>
<th>Scenario 2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_Probe</td>
<td>0.7581</td>
<td>0.9539</td>
<td>0.6033</td>
<td>0.6712</td>
</tr>
<tr>
<td>R_Inbound Scale</td>
<td>0.3284</td>
<td>0.4114</td>
<td>0.2605</td>
<td>0.2909</td>
</tr>
<tr>
<td>R_Quality Test Machine</td>
<td>0.7048</td>
<td>0.8942</td>
<td>0.5628</td>
<td>0.6321</td>
</tr>
<tr>
<td>R_Offloading</td>
<td>0.4936</td>
<td>0.6053</td>
<td>0.7837</td>
<td>0.8402</td>
</tr>
<tr>
<td>R_Outbound Scale</td>
<td>0.3096</td>
<td>0.3778</td>
<td>0.4910</td>
<td>0.5252</td>
</tr>
<tr>
<td>R_Operator</td>
<td>0.8925</td>
<td>0.9241</td>
<td>0.9201</td>
<td>0.8689</td>
</tr>
</tbody>
</table>

(a) A plot of resource utilization for scenario 1a and 1b
Using the average probe queue waiting time replication-by-replication (across-replication) data attached in Appendix 2, the confidence intervals for each scenario were computed. The results are shown in Table 3.9. A plot is also shown in Figure 3.21. The trend is similar to that observed for the average waiting times above. A decrease in waiting time is observed from scenarios 1a to 1b and from 2a to 2b.

Table 3.9: Confidence intervals for probe waiting time for 100 replications for each scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( \bar{y} )</th>
<th>( S )</th>
<th>( H )</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( t_{\alpha/2,R-1} )</td>
</tr>
<tr>
<td>Scenario 1a</td>
<td>25.5440</td>
<td>4.8117</td>
<td>2.2760</td>
<td>0.4812</td>
</tr>
<tr>
<td>Scenario 1b</td>
<td>17.3247</td>
<td>5.6736</td>
<td>2.2760</td>
<td>0.5674</td>
</tr>
<tr>
<td>Scenario 2a</td>
<td>9.3851</td>
<td>4.4728</td>
<td>2.2760</td>
<td>0.4473</td>
</tr>
<tr>
<td>Scenario 2b</td>
<td>2.7701</td>
<td>2.2217</td>
<td>2.2760</td>
<td>0.2222</td>
</tr>
</tbody>
</table>
Figure 3.21: A plot of across replication probe waiting time average for each scenario with confidence bounds.

Table 3.10 shows the results for the 95th quantiles of the probe queue lengths and waiting times for each scenario. In scenario 1a the probe queue length is less than 21 trucks 95% of the time and their waiting time is less than 53 minutes 95% of the time; for scenario 1b the length is less that 14 and the waiting time is less than 40 minutes; for scenario 2a the probe queue is less than 9 trucks 95% of the time while the waiting time is less than 24 minutes 95% of the time; for scenario 2b the probe queue length is less than 4 trucks while the waiting time is less than 9 minutes 95% of the time.
Table 3.10: Results for 95th quantile for number of trucks waiting in the probe queue and waiting time

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probe queue length</th>
<th>Probe waiting time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1a</td>
<td>21</td>
<td>53</td>
</tr>
<tr>
<td>Scenario 1b</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>Scenario 2a</td>
<td>9</td>
<td>24</td>
</tr>
<tr>
<td>Scenario 2b</td>
<td>4</td>
<td>9</td>
</tr>
</tbody>
</table>
CHAPTER 4: CASE STUDY

4.1 Introduction

Aurora West Grain Terminal provides grain to an ethanol plant located next to the terminal and to different customers in the United States of America via railways. Farmers deliver grain (corn and soybeans) in truck loads of 1000 bushels with an average of 50-100 trucks a day. A new ethanol plant located next to the terminal is under construction. With the opening of the new plant, the demand is expected to increase to an average of 200-300 trucks a day with a peak of 500 trucks. Terminal managers are searching for ways to improve the efficiency of the grain delivery process so that truck waiting times are within acceptable limits. A study of the current flow of trucks at the terminal was done and recommendations made to improve the process so that capacity of the terminal could be raised to meet the expected increase in demand.

Current system

Grain is delivered to the West Grain Terminal by truck. The trucks arrive at the terminal from a highway and turn in via a driveway. At the end of the driveway, a truck goes through a number of stations where the quality of the grain is tested, weight of the load determined, grain offloaded, tare weight of the truck determined and then the truck exits using the outbound lane.

Current peak hour demand is 25 trucks on average. 7% of trucks delivered have poor quality grain that requires the damage count test. Both machine and manual testing of grain is carried out. The Auto-kicker takes an average of 1:18 minutes with a standard deviation of 0:13 minutes to complete and the data collected fitted a beta distribution with
parameters, [65.5 + 35 * BETA (0.27, 0.463)]. The manual testing takes an average of 2:38 minutes with a standard deviation of 0:43 minutes without a damage count and the data collected fitted a triangular distribution with parameters, [87, 130, 290]. The damage count process was assigned a constant duration of 2 minutes. There are currently two operators working at the quality test workstation and one autokicker machine. The operators help each other as in Case b described above. All the other work stations have one unit each except for the offloading workstation which has 3 bays. Data was collected on the current operations and probability distributions fitted to determine the input parameters as shown in Table 4.1.

Table 4.1: Probability distributions used in developing the simulation model for the case study.

<table>
<thead>
<tr>
<th>Process</th>
<th>Fitted Distribution</th>
<th>Distribution Parameters</th>
<th>Min Value</th>
<th>Max Value</th>
<th>Mean Value</th>
<th>St. Dev.</th>
<th>No. of Data Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter arrival times</td>
<td>Exponential</td>
<td>5 + EXPO(140)</td>
<td>5</td>
<td>511</td>
<td>145</td>
<td>147</td>
<td>39</td>
</tr>
<tr>
<td>Check in &amp; Probe</td>
<td>Weibull</td>
<td>30 + WEIB(60.5, 1.67)</td>
<td>30</td>
<td>193</td>
<td>85</td>
<td>31.1</td>
<td>75</td>
</tr>
<tr>
<td>Weigh in and Go</td>
<td>Erlang</td>
<td>25 + ERLA(12.2, 2)</td>
<td>25</td>
<td>153</td>
<td>49.4</td>
<td>20.4</td>
<td>76</td>
</tr>
<tr>
<td>Probe &amp; Say ”Go” – Operator</td>
<td>Normal</td>
<td>NORM(117, 29.2)</td>
<td>81</td>
<td>271</td>
<td>117</td>
<td>29.4</td>
<td>74</td>
</tr>
<tr>
<td>Testing Type – A</td>
<td>Beta</td>
<td>65.5 + 35 * BETA(0.27, 0.463)</td>
<td>66</td>
<td>100</td>
<td>78.4</td>
<td>12.8</td>
<td>13</td>
</tr>
<tr>
<td>Testing Type - M1</td>
<td>Triangular</td>
<td>TRIA(87, 130, 290)</td>
<td>87</td>
<td>290</td>
<td>158</td>
<td>43.1</td>
<td>54</td>
</tr>
<tr>
<td>Testing Type - M2</td>
<td>Exponential</td>
<td>86 + EXPO(66.8)</td>
<td>86</td>
<td>319</td>
<td>153</td>
<td>57.9</td>
<td>21</td>
</tr>
<tr>
<td>All testing Types</td>
<td>Normal</td>
<td>NORM(145, 51.7)</td>
<td>66</td>
<td>319</td>
<td>145</td>
<td>52</td>
<td>88</td>
</tr>
<tr>
<td>Transfer Stop</td>
<td>Lognormal</td>
<td>34.5 + LOGN(31.8, 73.9)</td>
<td>35</td>
<td>126</td>
<td>61.1</td>
<td>30.7</td>
<td>18</td>
</tr>
<tr>
<td>fitting Triangular Dist.</td>
<td>Triangular</td>
<td>TRIA(34.5, 37, 127)</td>
<td>35</td>
<td>126</td>
<td>61.1</td>
<td>30.7</td>
<td>18</td>
</tr>
<tr>
<td>Offloading</td>
<td>Exponential</td>
<td>108 + EXPO(106)</td>
<td>108</td>
<td>533</td>
<td>214</td>
<td>96.9</td>
<td>76</td>
</tr>
<tr>
<td>Weigh Out &amp; Receipt</td>
<td>Normal</td>
<td>NORM(62.2, 23.1)</td>
<td>15</td>
<td>157</td>
<td>62.2</td>
<td>23.2</td>
<td>75</td>
</tr>
</tbody>
</table>
4.2.1 Simulation results for current System

The simulation model was run for 1.1 hours and 50 replications to simulate a busy peak hour. Different demand levels were simulated as presented in Table 4.2. The average wait time of a truck for the probe increased with the increase in demand. The average total time of a truck in the current system is estimated as 14.2 minutes. 95% of the trucks are expected to wait less than 8.1 minutes for the probe. When the demand level is increased to 125 trucks per hour, quantile computations of the wait time distribution for the probe reveals that 95% of the customers spend less than 44.2 minutes waiting for the probe to become available while the remaining 5% of the trucks wait for more than 44.2 minutes.

Table 4.2: Summary of wait time statistics for the current system at various demands

<table>
<thead>
<tr>
<th>Avg. wait time / Demand (D)</th>
<th>D=25</th>
<th>D=50</th>
<th>D=75</th>
<th>D=100</th>
<th>D=125</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. wait time for probe</td>
<td>2.1</td>
<td>11.3</td>
<td>17.9</td>
<td>21.0</td>
<td>22.9</td>
</tr>
<tr>
<td>Avg. wait time for inbound scale</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Avg. wait time for office stop</td>
<td>1.2</td>
<td>0.9</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Avg. wait time for offloading</td>
<td>0.04</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>Avg. wait time for outbound scale</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Avg. time in system</td>
<td>14.2</td>
<td>21.7</td>
<td>27.2</td>
<td>29.7</td>
<td>31.2</td>
</tr>
<tr>
<td>95th quantile of wait time for probe</td>
<td>8.1</td>
<td>25.9</td>
<td>35.9</td>
<td>41.3</td>
<td>44.2</td>
</tr>
<tr>
<td>Number of trucks</td>
<td>D=25</td>
<td>D=50</td>
<td>D=75</td>
<td>D=100</td>
<td>D=125</td>
</tr>
<tr>
<td>Average no of trucks in line for probe</td>
<td>1</td>
<td>10</td>
<td>22</td>
<td>35</td>
<td>48</td>
</tr>
<tr>
<td>95th percentile of no of trucks in probe line</td>
<td>3</td>
<td>20</td>
<td>43</td>
<td>68</td>
<td>93</td>
</tr>
</tbody>
</table>
CHAPTER 5: CONCLUSION

The foregoing study modeled a grain terminal facility for a 2000ft by 1000ft piece of rectangular space. Four scenarios were simulated (1a & 1b and 2a & 2b), each pair having a specific set of resources; Case 1 had less resources than Case 2 and sub-case a involved independent operators while sub-case b involved helping operators. At a glance, one may intuitively judge that Case 2 which has more resources is better. This can only be judged accurately upon observation of statistics and the performance measures for the real system if it is in place or results obtained from the simulation model. If the system is not yet in place as is the case in this study, observing the simulation model gives actual values that reveal which area in the system needs adjustment such as the system bottleneck. Such intricate details would otherwise not be figured out simply by intuition. Variables in the system such as resources can be adjusted deliberately to achieve a specific service level or acceptable waiting time in the system.

The goal of this study was to develop a facility plan for a grain delivery terminal using a discrete event simulation-based approach with the specific objectives being to: determine the process constraint/bottleneck, optimal number of resources - workstations and operators required at each stage of the process, system performance measures (average waiting time for each activity or process, average length of queue at each work station, average total time spent in the system by a customer, and level of resource utilization at each work station). All these objectives have been achieved. Two facility plans were proposed, a less expensive one with fewer resources and a more expensive one with more resources. Simulation statistics were collected on the system performance for the scenarios modeled. The probe workstation was identified as the process bottleneck. A
close to optimal combination of resources for each plan and scenario simulated was evaluated.

The results from the study show that when operators are helping each other shorter average probe waiting times, higher average resource utilizations and higher average number of trucks out of the system with less balking are experienced than when they work independently. The trends show that the more the resources the better the system and helping operators are always better than independent operators for the same set of resources. Increasing resources also results in less or no balking. Therefore when deciding on which facility plan to pursue, the decision maker has to put into consideration the costs involved. Although more resources are desirable, higher set up and maintenance costs are involved. However for any given set of resources a higher advantage is leveraged by setting up helping human operators.

Simulation is simply an imitation of a real world system to such an extent that the model behaves exactly as the system being imitated. This study presents a generic simulation model which was only based on estimates and assumptions of the statistical probability distributions for the grain delivery process. A more realistic case would be to use historical data from an existing facility for the analysis or to carry out time and motion studies to obtain empirical estimates for process durations.

In contribution to the body of knowledge, this study has advanced discrete event simulation as a tool for facility planning. This provides a relatively user friendly, easy to apply, alternative tool that researchers and practitioners can apply in facility planning and design studies. This tool can be used independently or in combination with other
complementary approaches to provide optimal solutions to facility and capacity planning problems.

In the future, the proposed discrete event simulation facility planning method can be applied to a new or existing grain delivery facility and improvements observed based on selected metrics in order to affirm the methodology. The research can also be extended to integrate the discrete-event simulation facility planning process with economic analysis of the cost of resources and materials handling so as to make facility planning decisions based on both capacity and financial parameters.


Donaghey, C. E., and Pire, V. E (1990) Solving the Facility Layout Problem with BLOCPLAN. *Industrial Engineering Department*, University of Houston, TX.


http://ops.fhwa.dot.gov/freight/publications/size_regs_final_rpt/index.htm#width


APPENDIX

Appendix A: Arena simulation model blocks for Scenario 1a.

Element blocks/labels for the model

1. Trucks arrive (entities are created) following an exponential distribution with mean 72

2. Trucks go to the probe workstation and undergo a process delay given by a triangular distribution with parameters (30, 85, 193)
3. (a) Trucks continue to the inbound scale. A duplicate of the truck remains there while the original entity proceeds to the quality test workstation undergoing process delays given by uniform distributions (30, 60) and (45,150) respectively. The optional damage count takes a constant time duration of 141 seconds.
(b) The duplicated entity is disposed off. Accepted trucks are routed to the offloading bay, while rejected trucks are routed to the terminal exit.

4. At the offloading bay accepted trucks undergo a process delay given by the triangular distribution: \( \text{TRIA}(120, 210, 300) \)

5. Offloaded trucks proceed to the outbound scale to weigh for the tare weight and receive receipts.
6. After the offloading bay trucks are routed to the terminal exit.
### Appendix B: Data for across replication probe queue waiting times for each scenario

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