CHAPTER 1
INTRODUCTION

1.1 Problem Statement

1.1.1 Background

New inventions and new technologies are constantly introduced to the construction industry and need to be implemented by contractors. Typically, these contractors have some rough ideas on how to employ the new technologies. Designing a construction operation that has never been done before may be difficult and expensive. A construction operation involves many interrelated activities and resources. There are always several ways to carry out an operation. It is therefore in the interest of new technology suppliers and contractors to proceed up the learning curve without having to execute installations that may be costly or to install material incorrectly.

1.1.2 Statement of Problem

Designing construction operations for new technologies is a challenge because there are many interactions of the operation that may not be well understood or are beyond comprehension without visualization. Designing a new operation requires a thorough understanding of all related issues. The designers need to consider all possible circumstances of field implementation. Before deciding on a good installation procedure, the designers have to try out numerous options, and make assumptions about many issues. The process involves consultation with experts, meeting with foremen, and contacting suppliers.

Polyvinyl chloride (PVC) geocomposite membrane is a new product that has been recently introduced as a strain energy absorber and moisture barrier in bridges and flexible pavements. Several field installations were completed on two bridges in Italy,
but testing to insure proper installation and determine construction sequencing was
needed. This membrane was currently tested at the Virginia Smart Road Project. No
detailed installation procedure was currently available, as it had not been introduced in
the market.

1.1.3 Case Study

In order to gain a better understanding of geosynthetic fabric installation in
flexible pavements, this research focused on the installation of a newly developed
geocomposite membrane. This membrane was installed for performance testing in two
test sections at the highly instrumented Smart Road in Blacksburg, Virginia (Loulizi et al.
2001, Al-Qadi et al. 2000). This geocomposite membrane consists of a polyvinyl
chloride (PVC) geomembrane sheet sandwiched between two layers of polyester non-
woven geotextile. It had been successfully used as an impermeable material for dams,
canals, reservoirs, floating covers, cofferdams, and hydraulic tunnels (Scuero and
Vaschetti 1997). It had also been installed on a bridge deck over the Po River in Italy.
However, this was the first time that this geocomposite membrane was installed in a
flexible pavement in the United States for water impermeability and absorption of the
strain energy responsible for crack initiation. The membrane was installed at two
different locations in the pavement system: between the subbase (aggregate) layer and an
asphalt treated open-graded drainage layer (OGDL) to quantitatively measure its moisture
barrier effectiveness using buried moisture sensors (two types of time domain
reflectometers); and within a hot-mix asphalt (HMA) base layer (at the upper third) to
quantify its strain energy absorption capability.

The contractor had an initial installation procedure for common membranes based
on past experience, but several issues were different for this product. The operation was,
therefore, performed on a trial and error basis for the test installations. The equipment
involved in the operation included a front-end loader, an asphalt distributor truck, a
modified wheel tractor that was specially built to lay membrane rolls (the installer), and a
pneumatic compactor. The operation began as the backhoe lifted a membrane roll that
was positioned in advance and mounted it onto the installer as shown in Figure 1.1.
FIGURE 1.1 - The membrane roll was lifted by the front-end loader.

The asphalt distributor truck then sprayed a PG64-22 heated tack coat binder on the surface of the HMA when the membrane was installed within the HMA layer. No tack coat was needed when the membrane was installed on the aggregate subbase because the friction between the aggregate and the non-woven geotextile was sufficient to prevent any slippage. This research focuses on the installation of the membrane on the HMA surface. The tack coat was not sprayed until the installer had a membrane roll mounted and was ready to unroll. It was preferable to deploy the membrane while the tack coat was still hot to attain good bonding. Figure 1.2 illustrates the asphalt distributor truck spraying the tack coat on the center of the road’s surface, with the membrane already installed and compacted on the right side of the road.
FIGURE 1.2 - The asphalt distributor truck sprayed a tack coat on the road’s surface.

FIGURE 1.3 - The installer unrolled the membrane on the heated tack coat.

Immediately after the tack coat was sprayed, the installer unrolled the membrane on top of the tack coat as shown in Figure 1.3. The geocomposite membrane rolls were 1.97m (6.46 ft) wide and 37.00 m (121.39 ft) long. There are two types of rolls. Type A rolls have one 50mm (~2 in)-wide PVC exposed area, whereas type B rolls have two PVC exposed areas. The exposed areas are intended to overlap with an adjacent roll in such a manner that the thickness at the overlap is minimum. Figure 1.4 shows the details of a geocomposite membrane roll and two overlapped membrane rolls.
The test sections were on a typical 2-lane highway constructed according to VDOT specifications. The membrane covered a 10 m (33 ft) wide by 50 m (164 ft) long section. Five membrane strips were required to cover the width of each section. Two type A rolls were installed at the edges of the road, while three type B rolls were installed in the middle. Since a roll was only 37 m long, connection joints for two membrane rolls were needed (i.e., between a 37-m-long roll and a 13-m-long piece of membrane). Therefore, the membranes were staggered to prevent a continuous transverse joint. After the membrane was laid, the compactor ran over it as illustrated in Figure 1.5. The tack
coat on the surface of the membrane was included in the modeling as it is a normal process when HMA is installed.

FIGURE 1.5 - The compactor compacted the laid membrane.

The installations of this geocomposite membrane were recorded on videotapes, which were observed and stripped to obtain data for activity durations using PAVIC+ (Bjornsson 1987). PAVIC+ (Productivity Analysis with Video and Computer) is a computer-based system in which videotape can be examined frame by frame, to determine if that frame marks the start or end of any activity. The software can determine the duration of an activity by counting the number of frames between its start and end, and can export the list of recorded durations to a database. The data from the database was analyzed using Stat::Fit (http://www.geerms.com/), a software that analyses the activity duration data, and determines the probability distribution and parameters that best describe the process that generates the data. These distributions were later used in the simulation model and are shown in Table 1. In the case where the operation has never been performed, or where video footage is not available, subjective probability distributions from people with similar experience (as in Pert) could be used.
TABLE 1 - Distributions of Activities Using Data Obtained From the Video

<table>
<thead>
<tr>
<th>Activity</th>
<th>Distribution (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup distributor truck</td>
<td>Pearson5 (0, 66.1, 24.7)</td>
</tr>
<tr>
<td>Spray one meter of tack coat</td>
<td>Pearson5 (0, 25.6, 0.382)</td>
</tr>
<tr>
<td>Mount</td>
<td>Pearson5 (1, 30, 32.9)</td>
</tr>
<tr>
<td>Setup Installer</td>
<td>Erlang (1, 13, 0.044)</td>
</tr>
<tr>
<td>Unroll one meter of membrane</td>
<td>Lognormal (0, -2.8, 0.0856)</td>
</tr>
<tr>
<td>Installer travels one meter</td>
<td>Uniform (0.00501, 0.005667)</td>
</tr>
<tr>
<td>Compact one meter</td>
<td>Uniform (0.027667, 0.027767)</td>
</tr>
</tbody>
</table>

1.1.4 Simulation Modeling for Construction Process Design

The geocomposite membrane is an example of a new material introduced in the construction industry. Similarly, there are other new technologies introduced to the construction world for which installation methods could be designed before introduction to the market. One potential way to address this problem is by simulation modeling.

A simulation model is a representation of a real or imaginary system such that it, rather than what it represents, can be studied, experimented on, and optimized. Discrete event simulation is a time-based modeling and analysis procedure in which the state of the system is assumed to change only at specific, but variably separated, points in time. As a result, simulation modeling is a useful tool for planning and decision making. For example, it can be used to design sequencing and deployment of equipment. For the past three decades, computer simulation has been used as a tool for construction process design and optimization (Liu 1995). It has provided a practical and cost-effective means to investigate the characteristics of construction operations before actual construction. Moreover, computer simulation allows experimenting with several scenarios to improve initial construction technique and to help find the optimum construction strategy.

Simulation modeling can be a very useful technique for designing new operations. Simulation modeling forces the modeler to think through the operation before carrying it out in the field. In essence, developing simulation models requires that one mentally perform the work. Simulation modeling helps one come up with good initial designs for installation of new technologies in the field. It may be advantageous to use simulation...
modeling when there are new technologies that need to be installed in the construction world. Simulation modeling is highly recommended when the operation is repetitive or initially very expensive.

1.2 Purpose, Scope, and Objectives

1.2.1 Purpose

The purpose of this research was to produce an example of how to develop simulation models for construction operations of new products. In addition, the research provided the geocomposite membrane supplier with a tool that he/she could give to his/her customers as part of the service. This tool could be used to design the installation process for this geocomposite membrane in roadways. The output of this research helped customers and contractors design an operation that optimizes resource usage, reduces costs, and improves productivity. The research also produced a visual tool that creates computer animations. This visual tool displayed animated representations of the operations in accordance with simulation models, and could also be used for tutorials.

1.2.2 Scope

This study focused on developing simulation models and a visual tool for the installation of a geocomposite membrane in flexible pavements in the United States. The models considered the installation of this membrane in roads of different sizes. For example, some of the input parameters were the width and the length of the road to be covered by the geocomposite membrane. Besides, the roll characteristics (length and width) could also be varied in the models. This allowed us to vary the parameters of the membrane rolls to optimize the manufacturing process which caused dramatic improvement on the installation process. Therefore, the models were flexible enough to simulate the installation of the membrane in roads of different sizes and also with rolls of different characteristics.
Other issues that were not included in the study are as follows:

- The transportation of the geocomposite membrane to the construction site.
- The installation of this membrane in severe weather conditions.
- The installation of this membrane on curved roads.
- The installation as part of a rehabilitation process.

1.2.3 Specific Objectives

1. Develop guidelines for creating simulation models of new technologies and products.
2. Develop a tool (parametric simulation model) that can be used to design geocomposite membrane installations.
3. Develop a visual tool that produces computer animations that may serve customers and contractors as tutorials.

1.3 Benefits

There were two main benefits from the successful completion of this research project. The first benefit was methodological in nature. This thesis provided a blueprint for developing simulation models for new product application. The study addressed the procedures and suggested how to design installation operations for new technologies. The output of the research was valuable for suppliers who wish to develop simulation models and computer animations for their products.

The other main benefit of this research was to provide users and contractors with guidelines on the installation process. The simulation tool would help users design the most appropriate and cost effective geocomposite membrane installation operation. In addition, the visual tool that this research produced will be very useful to customers and contractors. The visual tool consists of computer animations that illustrate the mechanisms and logic used in the simulation model. The visual tool also displayed operation performance measures together with other statistical data of the operation.
1.4 Applicability of This Research and Expected Significance

This research provided guidelines on how to develop simulation models for new operations. This research is highly applicable to geosynthetic suppliers who wish to develop simulation models and visual tools for their new products that related to flexible pavements. The parametric simulation model and the visual tool developed in this research will be of great help to users, contractors, and suppliers and will enhance the geocomposite membrane installation process understanding. The tool would help its users and the contractors to determine the most appropriate and cost effective installation procedure. In addition, the supplier would be able to use the tool to design the optimum roll specifications and as a marketing tool.
CHAPTER 2  
Use of Geosynthetics in Flexible Pavements

2.1 Introduction

The United States’ highway system is rapidly deteriorating. Approximately $212 billion are necessary to rehabilitate it (DiMaggio and Cribbs 1996). Stripping and spalling may occur due to the unavailability or ineffectiveness of the drainage layer when water infiltrates into hot-mix asphalt (HMA) pavement. One possible way to build more durable and better highways is to incorporate advanced materials in them and to maintain free water drainage. Geosynthetics, for example, are among the new materials used to improve flexible pavement performance. Geosynthetics can be divided into six main categories: geotextiles, geogrids, geonets, geomembranes, geocells, geosynthetic clay liners, and geocomposites. The application of some geosynthetics as an interlayer in roads and highways has many benefits. Some types of geosynthetics are thought to prevent water infiltration, absorb stress between pavement layers, dissipate strain energy responsible for crack initiation, prevent intermixing of adjacent layers, and/or allow for good drainage.

The use of geosynthetics may extend the service-life of roads and highways as described above. Unfortunately, geosynthetics may not perform as intended if they are not installed properly. The geosynthetic installation process, which is a key factor in pavement performance, is usually overlooked. This results in contradicting results as to their actual effectiveness in pavement systems.

The installation process must be designed such that the geosynthetics are correctly placed, resulting in an effective life-cycle cost. Geosynthetics are currently installed in the field by trial and error relying on the experience and intuition of contractors, or following guidelines provided by FHWA and/or manufacturers, which usually do not address the installation economics. Experienced contractors can make reasonable assumptions and perform quick calculations that result in acceptable initial installation
procedures. A reasonable assumption by a contractor, for example, would be to maximize the area of tack coat spray per pass in order to improve production. The contractor may not realize that this would allow some of the tack coat to cool to the extent that it loses its adhesiveness, and would force the contractor to spray another layer. This may result in too much tack coat and subsequently lead to slippage. A simulation of the process can prevent this from happening by allowing the contractor to see the consequences of applying too much tack coat at the same time. Errors like this are costly if discovered during actual installation, and the corrections that would be quickly made may lead to inefficiencies in other aspects of the operation.

For installation processes that involve new technologies, these installation procedures can be quite inefficient. As the contractor performs an initial installation, the experience gained allows for significant improvements. Subsequent installations with the improved procedure provide yet more experience that allows for even further improvements. Eventually, it is possible to arrive at installation procedures that are quite reasonable. In cases where many pieces of equipment are needed for installation and where the process is complex and subject to variability, numerous iterations may be performed without reaching a truly effective and economical installation procedure.

Contractors want to know the type, size, and number of machines that will make up the fleet. They want to know the production rate of the operation, the unit cost, and the utilization of their equipment. Ultimately, contractors want to be able to try out many installation options and consider different parameters to search for the best installation procedure, but without spending much money. In essence, contractors would benefit from going through the iterative cycle of designing the operation, implementing it, gaining experience from it, and using the experience to re-design it, but without actually investing the time and resources that are traditionally used in doing so. Computer based discrete-event simulation, DES, allows just that. This paper illustrates the use of DES for the design of the installation procedures for a newly developed impermeable geocomposite membrane that may provide strain energy absorption in flexible pavements.
2.2 Discrete Event Simulation

A model is a representation of a real or imaginary system. Models can be studied, changed, and analyzed in an effort to better understand the system they represent. Experimentation with properly designed models may reveal how real systems would respond to real world conditions. Discrete-event simulation is a computer-based modeling and analysis procedure in which the state of the system is assumed to change only at specific, but variably separated, points in time. DES has been used to analyze and design many construction operations (e.g., Martinez et al. 1994, Liu 1995, Martinez and Ioannou 1995).

2.3 Geosynthetics Installation

Geotextiles, geomembranes, and geocomposites are usually installed as an interlayer in pavements. A number of studies have been conducted on the installation of geosynthetics in the field. According to Wright and Guild (1996), one of the most important factors in installing geotextiles as moisture barriers is that they be laid perfectly flat with minimum wrinkles or air bubbles on top of a uniformly sprayed tack coat. If wrinkles are greater than 25mm (1 in), they should be cut and laid flat in the direction of the paving. The tack coat application rate directly contributes to the geosynthetic performance. Too much tack coat will cause slippage or rutting, while an inadequate tack coat may result in poor bonding and poor waterproofing. In hot weather, the rubber tires of construction equipment may stick to the laid tack coated geosynthetic and cause it to detach. Sand may be sprinkled on top of the geosynthetic to prevent this from happening (Marienfield and Guram 1999). Seaming of geosynthetic strips can be done by using solvent seams, contact adhesives, tapes and mechanical seams, and hot air and welding (Teigeiro 1994).
3.1 Modeling the Operation

The process involved in the installation of this geocomposite membrane was modeled using STROBOSCOPE (Martinez 1996). Stroboscope is a discrete-event simulation programming language designed for modeling complex operations. A Stroboscope model describes the details of how the operation takes place by generating input processes (such as the duration of activities) from probability distributions, carrying out the processes as described by a model network, and recording the consequences or outcomes of the operation (e.g., production rates and resource utilization). Proof Animation (Henricksen 1997), a post-processing general-purpose animator, was used for computer-animated output.

The design of the installation process involved several participants. These included a geosynthetics expert; a simulation modeling expert; the geocomposite supplier; and the installation contractor, who has extensive experience in geosynthetics installation. In the model, the installation process was designed on a section basis. A section consisted of a number of membrane strips. The number of membrane strips required was calculated from the width of the road and the width of the membrane roll. For example, on a 10-m (33ft) wide section, five 2-m-wide (6.60 ft) rolls were used. The length of a section was equal to the length of the membrane roll. Figure 3.1 shows a plan view of the designed installation process for two sections.
In this particular example, the operation starts in section one. Five strips of membrane are installed in the order shown. Each strip is always laid from the section start point to the section end point (from left to right). This means that after finishing one membrane strip, the equipment travels back to the section start point. After the equipment finishes installing five membrane strips, i.e., finishes section one, it moves to the start point of section two and the process starts over again.

The membrane is designed for left to right installation to prevent gaps at the joints and cutting excessive membrane. When installed backward, i.e., from the section end point to the section start point, it is very difficult, if not impossible, to ensure that the new strip will end exactly where the laid membrane strip of the previous section ends. In these cases there is a chance of having either a gap, or excessive membrane at the joint where two membrane strips meet. In addition, it would be necessary for the rolls to be rolled in reverse order, which would introduce confusion. Therefore, the installation is designed in only one direction.

Originally, the operation was modeled such that the truck could spray the tack coat as soon as it was ready, i.e., as soon as it returned to the section start point. However, after observing the animation of the process, it was decided that the truck should wait for the installer to be ready to unroll the membrane before spraying asphalt to assure that the asphalt binder is still hot. The model was therefore adjusted such that the
truck would not spray the tack coat unless the membrane roll was mounted onto the installer and ready to unroll.

Although it appears cost effective for the compactor to start compacting as soon as the membrane is laid, it is difficult to correct the alignment when, for some reason, the membrane is not properly aligned. Consequently, the compactor was modeled such that it started compacting only after one membrane roll was completely placed. Setting up the operation properly is important because correcting errors is cumbersome. Once the membrane is compacted, it is very hard to redo the work. Therefore, the compactor will not start compacting until an unrolled membrane strip is satisfactorily straight and free of wrinkles. In addition, the compactor can compact the membrane in either direction (left to right or right to left). The compactor does not have to travel to the section start point every time it finishes one membrane strip.

The loader, on the other hand, is modeled to stay at the section start point at all times because the other equipment will eventually return to that point. After the loader mounts all the geocomposite membrane rolls required for one section, it moves to the start point of the next section.

### 3.2 Development of Simulation Models

The amount of time between spraying the tack coat and the placement of the geocomposite membrane is critical. The geosynthetic expert recommended that the time should be very short. The tack coat exposed time was therefore one of the guiding criteria in modeling the operation. In the initial model, the installer followed the tack coat truck closely in an attempt to limit the time during which the tack coat was exposed. However, observations of the computer animation showed that the truck had to start and stop many times, leaving thick spots of tack coat which may lead to slippage and shoving. Consequently, the model was developed such that the truck only stopped when it finished spraying an entire strip of tack coat.
FIGURE 3.2 - The operation with two installers.

The authors also thought of using two installers in the operation, as shown in Figure 3.2. Two installers could work alongside one another with a few meters of lagging distance. The authors decided, however, that the second installer should start unrolling only after the first installer finished unrolling a membrane strip. This was to ensure that the first membrane strip was satisfactorily straight and free of wrinkles. When two installers were used, the truck would spray the tack coat wider to accommodate two membrane strips. The setup time and the duration of spraying the tack coat was relatively constant regardless of the spraying width. Hence, the width of the tack coat was insignificant to the calculation in the simulation model. However, the exposed time of the tack coat was very important in this case. The longer the first installer took to unroll one membrane strip, the longer the tack coat remained exposed. Figure 3.3 shows a snapshot of the distributor truck spraying the tack coat twice as wide as the normal width.
FIGURE 3.3 - The asphalt distributor truck sprays the tack coat two membrane rolls wide.
CHAPTER 4

ANALYSIS OF INSTALLATION ALTERNATIVES

4.1 Installation Process Improvements

There were several improvements in installation that were thought possible, including changes in the width and length of the membrane rolls. While manufacturing longer rolls is not an issue, making them wider requires a substantial capital investment. Both cases increase the weight of the rolls and may require larger installers. Thus, there is a tradeoff between the capital investment in new installers by the contractors and the capital investment in new manufacturing equipment by the manufacturer. The models, however, are based on the assumption that it is possible to manufacture rolls of various widths and lengths. Table 2 summarizes the results from possible alternatives for installing the geocomposite membrane.

TABLE 2 - Summary of Results From Various Possible Alternatives

<table>
<thead>
<tr>
<th>Covered Distance</th>
<th>350 Meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Num. Installers ea</td>
<td>1 227 2.05 35 8.2 2870 4.77 – 4.79 0.39 – 0.39 12.22 – 12.28</td>
</tr>
<tr>
<td></td>
<td>1 454 2.05 70 8.2 2870 3.18 – 3.19 0.27 – 0.27 17.99 – 18.07</td>
</tr>
<tr>
<td></td>
<td>1 454 4.1 35 8.2 2870 2.28 – 2.30 0.16 – 0.17 30.18 – 30.37</td>
</tr>
<tr>
<td></td>
<td>2 227 2.05 35 8.2 2870 2.29 – 2.30 0.23 – 0.24 20.75 – 20.87</td>
</tr>
<tr>
<td></td>
<td>2 454 2.05 70 8.2 2870 1.80 – 1.81 0.18 – 0.18 26.56 – 26.63</td>
</tr>
</tbody>
</table>
4.2 Results Discussion

The confidence intervals of each alternative were calculated from simulation results of 10 replications. When one installer was used in the operation, the 90% confidence interval for the productivity was [12.2, 12.3] m²/min. This means that there is a 90% chance that the true average productivity is between 12.2 and 12.3 m²/min. The mean unit cost for this alternative was $0.39/m². If the membrane rolls were made longer (70 meters long), results showed that the 90% confidence interval for the productivity was [18.0, 18.1] m²/min with a $0.27/m² mean unit cost. The improvement was a result of the ability to unroll the membrane twice as long before stopping. In addition, the loader would not have to load membrane rolls as often. When wider rolls were used, the production rate and the unit cost improved significantly, and with 90% certainty were estimated to be [30.2, 30.4] m²/min at [0.16, 0.17]$/m². In this case, the installer unrolled two strips of membrane simultaneously and thus reducing the number of passes needed per section. Wider rolls may be more difficult to handle and may require greater care during installation to avoid excessive wrinkles. In addition, it would be more difficult to coordinate the wider rolls with various road widths, because the road width may not be divisible by the roll width. However, wider or longer rolls are advantageous because there are fewer joints, which are assumed to be the weak points of the system.

Simulation results also revealed a substantial improvement when two small installers were used with regular rolls. The 90% certain production rate increased to [20.8, 20.9] m²/min and its unit cost fell to [0.23, 0.24] $/m². The authors felt that this option was the best alternative if two installers were used because small installers are already available in the market. The last alternative was to use two big installers and membrane rolls that are 70 meters long. Simulation results showed that the 90% certain production rate would be [26.5, 26.6] m²/min at a $0.18/m² mean unit cost. Although this alternative yielded a very high production rate, it may require significant investment by the contractors.

The measures of performance obtained by the simulation are those of the model, and not necessarily those of the system represented by the model. Generally speaking, it is impossible for a model to accurately include each and every aspect of the system it
represents. If coffee breaks are not included in a model, for example, the performance measures obtained by simulation will be better than those observed in the field. This is common and typically recognized by simulation modelers, and does not adversely affect the value of simulation studies as might seem to appear at first glance. This is because simulation is mostly used to make decisions, which by definition implies the selection of one alternative from among several.

If we assume that the difference between a model and the system it represents is constant across all alternatives, the difference between the measures of performance among models and among the systems they represent are minimal. Assume for example, that including coffee breaks increases the costs of a certain operation by $0.15/m^2. A model for one alternative may indicate a unit cost of $0.35/m^2 when in effect the unit cost of the system it represents is $0.50/m^2. A model for another alternative may indicate a unit cost of $0.38/m^2 when in effect the unit cost of the system it represents is $0.53/m^2. Although the costs obtained by each model are off by $0.15/m^2, the difference in cost between the two models can be fairly accurately estimated to be $0.03/m^2. The decision to choose the first alternative based on the cost reduction of $0.03/m^2 given by the models would be a good one.

The key to the validity of models is, thus, to exclude from them only those realities that are thought to impact all alternatives equally. As long as this is the case, the decisions made by observing the performance of models are likely to be the same as the decisions made by experimenting with the alternatives in reality. This issue is discussed in detail within the context of construction operations by Ioannou and Martinez (1996), and in general by Law and Kelton (1991).

Sometimes the purpose of simulation models is to predict the absolute performance of a system rather than to select from among alternatives. This is the case, for example, when simulation is used to estimate the cost of a proposed system that will be compared with an existing system for which actual costs are available. In these cases, the simulation model must include as much detail as possible (e.g., machine breakdown frequency and downtime, coffee breaks, shift and overtime work, rework, disruptions and weather). In addition, additional factors such as the frequently assumed 50-minute hour may be used to account for details that have not been explicitly modeled.
Using computer animations as a visual tool greatly helped the development of the simulation model. The computer animations allowed experts to visualize the operation. They were able to make comments and to decide whether or not the operation was sound. The researchers then modified the simulation model according to the comments and again discussed it with the experts. This process was repeated several times until the researchers and the participants were satisfied. Had there not been computer animations, it would have been very difficult for participants to visualize the operation and make comments.

The use of discrete-event simulation and computer animations had a very significant impact on the design of this geocomposite membrane installation. The process forced the participants to think hard on the installation process. Obvious mistakes were found and eliminated by just looking at computer animations. Many issues were raised and clarified by observing preliminary simulation results. Computer animation helped facilitate the communication among participants. The participants worked as a “team” to come up with a good installation process. The expertise from each participant was effectively shared and input into the design process. This “team” effort in the design process was a key benefit of using discrete-event simulation and computer animations to design the operation.
CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Guidelines for Simulation Model Development

Explained below are guidelines and advice on how to develop simulation models for other operations that involve new products or where procedures are not readily available.

1. *Obtain video footage of the test operation* – Record the operation with video cameras. Use more than one camera if possible. Make sure to have the date and time displayed on the screen to help keep track with the operation in the case where the recording is not continuous. If the operation is performed outdoor, select a good camera’s location so that the camera does not face the sun when recording. Have plenty of extra batteries on hand. Keep in mind that a test operation is not performed on a regular basis. It could be the only operation you will ever have a chance to record.

2. *Understand the operation* - Study the video and try to understand the overall process. It may be helpful to do research and gain knowledge of similar operations. After being acquainted with the process identify key activities and resources involved. This will be of great help when stripping activity durations from the video. At this time a preliminary simulation model should be developed. Consult experts to validate the underlying concept.

3. *Determine activity durations* – Use PAVIC+ to determine activity durations from the video (stripping data). A regular television set could be added to the PAVIC+ system for better image quality. This process is usually time consuming, yet essential. Take considerable amount of quality time to plow through all video recording and strip activity durations as many as possible.
4. **Determine distributions** – Use Stat::Fit software to determine the most appropriate distribution representing each activity. This distribution fitting process can be done quickly. The more durations the better the distribution.

5. **Create simulation model** – Create a simulation model (model hereafter) with Stroboscope. Try to keep the model simple and easy to understand. Participation of everybody involved in the operation is necessary: supplier, contractor, design agency, product expert, etc. Hold a meeting to define the scope of work and clarify any ambiguities. Verify and validate the model.

6. **Create computer animations** – Create computer animation of the designed model with Proof Animation software. It is advisable not to spend too much time creating the animations in great detail. The animations should be just complex enough for viewers to understand what is going on. At this stage the model is far from final. Time should be spent more on the logic of the model than making the animations beautiful.

7. **Spiral participation** – Use the computer animations as a visual tool to explain to the participants (supplier, product expert, contractor, etc.) the designed process. Listen carefully and take good notes of their comments. A small voice-recording device might be useful. Note that holding several meeting with all participants may be very difficult. One possible solution is to meet one participant at a time. Therefore, be well prepared and use the time efficiently.

   Each participant will give recommendations and may identify blunders in the designed process. Based on comments received, modify the simulation model and the computer animations, then revisit. Repeat this process with all participants until the final model with everyone’s approval is achieved. The model and the animations’ complexity will increase over time. Remember to keep all correspondence and put everything in writing for future reference.

8. **Test and fine-tune** – Fine-tune the model. Remove unnecessary elements from the model. Test it with several different sets of parameters. Add aesthetics to the computer animations. Test and retest.
5.2 Conclusion

Guidelines for creating discrete-event simulation model and computer animations of new technologies and products were developed. These guidelines are very useful to geosynthetic suppliers who wish to develop similar simulation models and computer animations for their new products that related to flexible pavements. Other products suppliers such as pipes or windows may also find these guidelines applicable to their products.

Data from the test sections at the highly instrumented Virginia Smart Road were collected and analyzed. A parametric simulation model that describes the installation process of a geocomposite membrane in flexible pavements was developed. Several installation alternatives were studied and recommendations were made to the membrane supplier. The model enhanced the installation process understanding.

The visual tool that produces computer animations of the simulation model was created. The animations show the mechanism and logic used in the model. This visual tool was also used effectively to communicate among participants. Computer animations helped identify obvious mistakes in the installation process. The membrane supplier also used the computer animations as a marketing tool when he explained installation procedures to a prospective client.

5.3 Recommendations

As for new technologies, there are limitations in data collection. Unlike developing simulation models for existing systems where data is plentiful, there are limited opportunities to observe operations that involve new technologies. Experimental installations can be limited due to high expenses. Therefore, in this research, there were only a few durations that could be obtained from the videotapes. Moreover, the activity durations were from the experimental installations where workers were still learning and gaining experience. These durations may not accurately represent the durations of actual installation after the contractor has become more familiar with the process.
The simulation model developed in this study is beneficial in comparing different alternatives, but not as effective in determining absolute results. This is because there are limitations in data gathering and the level of detail included in the model. If the main interest is to determine absolute results, it would be necessary to observe inefficiency, coffee breaks, machine breakdowns, transportation of rolls from stock pile to the installation location, etc., and to include them in the model. Furthermore, the modeler will need to rely on the intuition of experienced contractors in order to estimate the potential differences between experimental and real installation. These factors then should be included in the model.

5.4 Future Research Perspectives

Future work that may follow this research may include the economic study of the whole installation process. Simulation results could be more specific that they provide users additional information on the life cycle cost for each installation alternative. That information may include, but are not limited to, the total cost of money, and the payback period of the investment. The input parameters could be the interest rate and the expected square meters of membrane to be installed per year. Hence, the contractor and the manufacturer have a better picture of the operation to support their decisions.

Assuming that this geocomposite membrane is proven to be very effective in flexible pavements and widely accepted by several state department of transportation (DOTs). In that case, millions of square meters of this membrane will be put in new road construction and rehabilitation projects. Many contractors, subsequently, will want to bid on these projects. These contractors want to have a business strategy that will earn them the most profit. Firstly, they want to know if getting into this business is a good decision, and when they will see the profit. And if they decide to purchase new equipment, they want to know what type and how many equipment that are just enough to do the job. At the same time, the manufacturer want to determine whether or not to invest on the production line to produce wider rolls. Simulation results from this research do not offer a complete picture of overall economic of the investment on equipment and
manufacturing process. An enhancement of this parametric simulation tool could be performed.

In addition, a more complete analysis of results from this study can be carried out to compare various installation alternatives. For example, results from chapter 4 show that the production rate of using two installers with regular rolls is lower than that of using one big installer with twice-as-wide rolls. However, these numbers do not explicitly reveal that using one big installer is always better.

Due to limitations in data gathering in this research, activity durations used in the simulation model were derived from a limited number of observations. More observations are needed for better activity durations. Future research should collect more data from other installations and increase the level of detail by including in the model other factors and scenarios such as coffee break, inefficiency, machine breakdowns, installation on curve roads, and installation on bridges, etc. A new model should be so comprehensive that it could be applied to any kind of geosynthetics installation. This study can be used as an example for developing other future simulation models.
6.1 Web-Interactive Simulation Model

Web-interactive simulation model is under the development of Dr. Julio C. Martinez. Web-interactive simulation offers users the opportunity to run simulation models via the World Wide Web. For more information about the web-interactive simulation please visit http://strobos.ce.vt.edu/websim/. The simulation model for the installation of a geocomposite membrane in flexible pavements was developed and stored in this server. Users are able to experiment with various simulation parameters and observe the simulation results directly from the web. This chapter contains the printouts of the geocomposite membrane installation web pages.
Welcome to the web-interactive STROBOSCOPE simulation model for the installation of a geocomposite membrane in flexible pavements.

Geosynthetics are currently being incorporated in flexible pavement systems to improve their performance. However, geosynthetics must be used in the correct application and installed properly in order to produce good results. One of the newly developed geosynthetics is geocomposite membrane that thought to provide strain energy absorption and a moisture barrier. This research discusses the application of discrete-event simulation (DES) to design and analyze the installation of geocomposite membranes in flexible pavements. Data collected from two test sections at the Virginia Smart Road in Blacksburg, Virginia was used for modeling and analysis. STROBOSCOPE, a programming language designed for modeling complex operations, was used as the simulation engine. The process used in the development of simulation models is discussed. A number of installation alternatives were studied and simulated to examine their practicality and to investigate their productivity, resource utilization, and unit cost.

Check the box below if you would like to go directly to the simulation page.

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Or click the button below to continue.

Proceed to models/carpi/carpi.str step 2
BACKGROUND

This research focused on the installation of a newly developed geocomposite membrane. This membrane was installed for performance testing in two test sections at the highly instrumented Smart Road in Blacksburg, Virginia. This geocomposite membrane consists of a polyvinyl chloride (PVC) geomembrane sheet sandwiched between two layers of polyester non-woven geotextile. It had been successfully used as an impermeable material for dams, canals, reservoirs, floating covers, cofferdams, and hydraulic tunnels (Scuero and Vascetti 1997). It had also been installed on a bridge deck over the Po River in Italy. However, this was the first time that this geocomposite membrane was installed in a flexible pavement in the United States for water impermeability and absorption of the strain energy responsible for crack initiation. The membrane was installed at two different locations in the pavement system: between the subbase (aggregate) layer and an asphalt treated open-graded drainage layer (OGDL) to quantitatively measure its moisture barrier effectiveness using buried moisture sensors (two types of time domain reflectometers); and within a hot-mix asphalt (HMA) base layer (at the upper third) to quantify its strain energy absorption capability.

The contractor had an initial installation procedure for common membranes based on past experience, but several issues were different for this product. The operation was, therefore, performed on a trial and error basis for the test installations. The equipment involved in the operation included a front-end loader, an asphalt distributor truck, a modified wheel tractor that was specially built to lay membrane rolls (the installer), and a pneumatic compactor.

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Proceed to models/carpi/carpi.str step 3
The operation began as the front-end loader lifted a membrane roll that was positioned in advance and mounted it onto the installer as shown in Figure 1.

Figure 1 - The membrane roll was lifted by the front-end loader

Check the box below if you would like to go directly to the simulation page.

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Or click the button below to continue.

Proceed to models/carpi/carpi.str step 4
SPRAY TACK COAT

The asphalt distributor truck then sprayed a PG64-22 heated tack coat binder on the surface of the HMA when the membrane was installed within the HMA layer. No tack coat was needed when the membrane was installed on the aggregate subbase because the friction between the aggregate and the non-woven geotextile was sufficient to prevent any slippage. This research focused on the installation of the membrane on the HMA surface. The tack coat was not sprayed until the installer had a membrane roll mounted and was ready to unroll. It was preferable to deploy the membrane while the tack coat was still hot to attain good bonding. Figure 2 illustrates the asphalt distributor truck spraying the tack coat on the center of the road’s surface, with the membrane already installed and compacted on the right side of the road.

![Image](image_url)

Figure 2 - The asphalt distributor truck sprayed a tack coat on the road’s surface

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Or click the button below to continue.

Proceed to models/carpi/carpi.str step 5
UNROLL AND COMPACT

Immediately after the tack coat was sprayed, the installer unrolled the membrane on top of the tack coat as shown in Figure 3.

Figure 3 - The installer unrolled the membrane on the heated tack coat

The test sections were on a typical 2-lane highway constructed according to VDOT specifications. The membrane covered a 10 m (33 ft) wide by 50 m (164 ft) long section. Five membrane strips were required to cover the width of each section. Two type A rolls were installed at the edges of the road, while three type B rolls were installed in the middle. Since a roll was only 37 m long, connection joints for two membrane rolls were needed (i.e., between a 37-m-long roll and a 13-m-long piece of membrane). Therefore, the membranes were staggered to prevent a continuous transverse joint. After the membrane was laid, the compactor ran over it as illustrated in Figure 4.

Figure 4 - The compactor compacted the laid membrane

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The geocomposite membrane rolls were 1.97m (6.46 ft) wide and 37.00 m (121.39 ft) long. There are two types of rolls. Type A rolls have one 50mm (~2 in)-wide PVC exposed area, whereas type B rolls have two PVC exposed areas. The exposed areas are intended to overlap with an adjacent roll in such a manner that the thickness at the overlap is minimum. Figure 5 shows the details of a geocomposite membrane roll and two overlapped membrane rolls.

Figure 5(a) - Plan view of an unrolled geocomposite membrane roll

Figure 5(b) - Cross section of Type A membrane rolls

Figure 5(c) - Cross section of Type B membrane rolls

Figure 5(d) - Overlapping arrangement between two membrane rolls

Check the box below if you would like to go directly to the simulation page.

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DATA COLLECTION

The installations of this geocomposite membrane were recorded on videotapes, which were observed and stripped to obtain data for activity durations using PAVIC+. PAVIC+ (Productivity Analysis with Video and Computer) is a computer-based system in which videotape can be examined frame by frame, to determine if that frame marks the start or end of any activity. The software can determine the duration of an activity by counting the number of frames between its start and end, and can export the list of recorded durations to a database. The data from the database was analyzed using Stat::Fit (http://www.geerms.com/), a software that analyses the activity duration data, and determines the probability distribution and parameters that best describe the process that generates the data. These distributions were later used in the simulation model and are shown in Table 1.

Table 1 - Distributions of Activities Using Data Obtained From the Video

<table>
<thead>
<tr>
<th>Activity</th>
<th>Most Accepted Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup distributor truck</td>
<td>Pearson5 (0, 66.1, 24.7)</td>
</tr>
<tr>
<td>Spray one meter of tack coat</td>
<td>Pearson5 (0, 25.6, 0.382)</td>
</tr>
<tr>
<td>Mount</td>
<td>Pearson5 (1, 30, 32.9)</td>
</tr>
<tr>
<td>Setup Installer</td>
<td>Erlang (1, 13, 0.044)</td>
</tr>
<tr>
<td>Unroll one meter of membrane</td>
<td>Lognormal (0, -2.8, 0.0856)</td>
</tr>
<tr>
<td>Installer travels one meter</td>
<td>Uniform (0.00501, 0.005667)</td>
</tr>
<tr>
<td>Compact one meter</td>
<td>Uniform (0.027667, 0.027767)</td>
</tr>
</tbody>
</table>

Check the box below if you would like to go directly to the simulation page.

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Or click the button below to continue.
The simulation model was created using STROBOSCOPE. Stroboscope is a discrete-event simulation programming language designed for modeling complex operations. A Stroboscope model describes the details of how the operation takes place by generating input processes (such as duration of activities) from probability distributions, carrying out the processes as described by a model network, and recording the consequences or outcomes of the operation (e.g., production rates and resource utilization). Please click here to see the model network. For more information on how to develop simulation models using STROBOSCOPE simulation system, please visit the STROBOSCOPE web site.

Check the box below if you would like to go directly to the simulation page.

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Or click the button below to continue.
MODEL EXPLANATION

The process involved in the installation of this geocomposite membrane was modeled using STROBOSCOPE. Proof Animation was used for computer-animated output. A section consisted of a number of membrane strips. The number of membrane strips required was calculated from the width of the road and the width of the membrane roll. For example, on a 10-m (33 ft) wide section, five 2-m-wide (6.60 ft) rolls were used. The length of a section was equal to the length of the membrane roll. Figure 6 shows a plan view of the designed installation process for two sections.

![Direction of Installation Diagram]

Figure 6 - Plan view of a designed installation process

In this particular example, the operation starts in section one. Five strips of membrane are installed in the order shown. Each strip is always laid from the section start point to the section end point (from left to right). This means that after finishing one membrane strip, the equipment travels back to the section start point. After the equipment finishes installing five membrane strips, i.e., finishes section one, it moves to the start point of section two and the process starts over again.

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Or click the button below to continue.

Proceed to models/carpi/carpi.str step 10
DIRECTION OF INSTALLATION

The membrane is designed to be installed in one direction to prevent having a gap at the joint, or having to cut excessive membrane. When installed backward, i.e., from the section end point to the section start point, it is very difficult, if not impossible, to ensure that the new strip will end exactly where the laid membrane strip of the previous section ends. Figure 7 illustrates that, when installed backward, there is a chance of having either a gap, or excessive membrane at the joint where two membrane strips meet. Therefore, the installation is designed in only one direction, as shown in Figure 8.

Figure 7 - A gap or excessive membrane may occur at the joint if the membrane is installed backward

Figure 8 - The membrane is always installed in one direction

Check the box below if you would like to go directly to the simulation page.

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Or click the button below to continue.
Originally, the operation was modeled such that the truck could spray the tack coat as soon as it was ready, i.e., as soon as it returned to the section start point. However, after observing the animation of the process, it was decided that the truck should wait for the installer to be ready to unroll the membrane before spraying asphalt to assure that the asphalt binder is still hot. The model was therefore adjusted such that the truck would not spray the tack coat unless the membrane roll was mounted onto the installer and ready to unroll.

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Or click the button below to continue.

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COMPACTOR AND LOADER

Although it appears cost effective for the compactor to start compacting as soon as the membrane is laid, it is difficult to correct the alignment when, for some reason, the membrane is not properly aligned. Consequently, the compactor was modeled such that it started compacting only after one membrane roll was completely placed. Setting up the operation properly is important because correcting errors is cumbersome. Once the membrane is compacted, it is very hard to redo the work. Therefore, the compactor will not start compacting until an unrolled membrane strip is satisfactorily straight and free of wrinkles. In addition, the compactor can compact the membrane in either direction (left to right or right to left). The compactor does not have to travel to the section start point every time it finishes one membrane strip.

The loader, on the other hand, is modeled to stay at the section start point at all times because the other equipment will eventually return to that point. After the loader mounts all the geocomposite membrane rolls required for one section, it moves to the start point of the next section.

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INSTALLATION METHODS

There were several installation alternatives that were thought possible, including changes in the width and length of the membrane rolls. While manufacturing longer rolls is not an issue, making them wider requires a substantial capital investment. Both cases increase the weight of the rolls and may require larger installers. Thus, there is a tradeoff between the capital investment in new installers by the contractors and the capital investment in new manufacturing equipment by the manufacturer. The models, however, are based on the assumption that the membrane manufacturer has the capability to produce rolls in various widths and lengths. The model was designed such that the length and width of membrane rolls could be input as model parameters.

Check the box below if you would like to go directly to the simulation page.

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Or click the button below to continue.

Proceed to models/carpi/carpi.str step 14
COMPUTER ANIMATIONS

Please click on the links below to view movie clips of various installation alternatives.

1. **Alternative 1**: A regular installer with 2.05-meter-wide and 35-meter-long rolls.
2. **Alternative 2**: A large installer with 2.05-meter-wide and 70-meter-long rolls.
3. **Alternative 3**: A large installer with 4.10-meter-wide and 35-meter-long rolls.
4. **Alternative 4**: Two regular installers with 2.05-meter-wide and 35-meter-long rolls.
5. **Alternative 5**: Two large installers with 2.05-meter-wide and 70-meter-long rolls.

**Download**

Computer animations were created using Proof Animation software. For more information, visit [Wolverine Software Corporation](http://www.wolverine.com). You may download the Proof DemoView, the layout file, and sample trace files of the installation via the links below.

- Proof Demoview
- Layout File
- Sample Trace Files

Check the box below if you would like to go directly to the simulation page.

- [ ] Go directly to the simulation page

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PARTICIPANTS

The design of the installation process involved several participants. These included a geosynthetics expert, a simulation modeling expert, and the geocomposite supplier. The researcher appreciates their contribution to this research.

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Proceed to models/carpi/carpi.str step 16
## SIMULATE

Please input simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>Number of Installer(s)</td>
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</tr>
<tr>
<td>Installer Type</td>
<td>Regular</td>
</tr>
<tr>
<td>The width of membrane rolls</td>
<td>2.05</td>
</tr>
<tr>
<td>The length of membrane rolls</td>
<td>35</td>
</tr>
<tr>
<td>The width of the road</td>
<td>8</td>
</tr>
<tr>
<td>The length of the road</td>
<td>210</td>
</tr>
<tr>
<td>Slow factor</td>
<td>0%</td>
</tr>
<tr>
<td>Number of replications to run</td>
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</tr>
</tbody>
</table>

Proceed to models/carpi/carpi.str step 16
## SIMULATION RESULTS

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<thead>
<tr>
<th>Number of Installer(s)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Installer Type</td>
<td>Regular</td>
</tr>
<tr>
<td>Roll Width (meters)</td>
<td>2.05</td>
</tr>
<tr>
<td>Roll Length (meters)</td>
<td>35.00</td>
</tr>
<tr>
<td>Road Width (meters)</td>
<td>8.00</td>
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<tr>
<td>Road Length (meters)</td>
<td>210.00</td>
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</table>

<table>
<thead>
<tr>
<th>Repls</th>
<th>Operating Time (hrs.)</th>
<th>Production Rate (m²/hr)</th>
<th>Unit Cost ($/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.88</td>
<td>12.05</td>
<td>0.40</td>
</tr>
<tr>
<td>2</td>
<td>2.87</td>
<td>12.08</td>
<td>0.40</td>
</tr>
<tr>
<td>3</td>
<td>2.87</td>
<td>12.09</td>
<td>0.39</td>
</tr>
<tr>
<td>4</td>
<td>2.84</td>
<td>12.20</td>
<td>0.39</td>
</tr>
<tr>
<td>5</td>
<td>2.89</td>
<td>11.99</td>
<td>0.40</td>
</tr>
<tr>
<td>Ave</td>
<td>2.87</td>
<td>12.08</td>
<td>0.39</td>
</tr>
<tr>
<td>Min</td>
<td>2.84</td>
<td>11.99</td>
<td>0.39</td>
</tr>
<tr>
<td>Max</td>
<td>2.89</td>
<td>12.20</td>
<td>0.40</td>
</tr>
<tr>
<td>SD</td>
<td>0.02</td>
<td>0.08</td>
<td>0.00</td>
</tr>
<tr>
<td>90% CI</td>
<td>[2.85 - 2.89]</td>
<td>[12.01 - 12.16]</td>
<td>[0.39 - 0.40]</td>
</tr>
</tbody>
</table>

Proceed to models/carpi/carpi.str step 18
The table below shows the utilization and average waiting time of each equipment. These two measures of performance provide users an idea of how hard each equipment works. For example, if the truck's average waiting time is long while that of the installer's is very short, this reveals that the installer cannot keep up with the truck and is working very hard. As a consequence, the installer's utilization is very high. On the other hand, the truck's utilization is very low because what it is doing most of the time is waiting for the installer. Therefore, it is recommended to add another installer to balance the fleet.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Ave. Wt. Time (Min)</th>
<th>Utilization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td>4.86</td>
<td>27.72</td>
</tr>
<tr>
<td>Installer</td>
<td>0.00</td>
<td>81.56</td>
</tr>
<tr>
<td>Compactor</td>
<td>4.31</td>
<td>24.92</td>
</tr>
<tr>
<td>Loader</td>
<td>3.87</td>
<td>30.35</td>
</tr>
</tbody>
</table>

You may view the computer animation of the installation you have just designed. Please click the links below to download necessary software and animation files. The animation can be viewed using Proof Animation software. Note that the Proof Animation software provided here has a limitation that allows only a few minutes of viewing time.

For more information about Proof Animation and how to obtain a full version that allows unlimited viewing time, please visit Wolverine Software Corporation.

To view the animation: download Proof Animation, the animation layout file (carpi.lay), and the animation trace file (carpi.atf) and save them in the same directory. Next, unzip and run Proof Animation, and open both the layout and the trace file. Finally, click the run button to start the animation.

Download Proof Animation
Download Layout File
Download Trace File

HAVE A NICE DAY :)

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Proceed to models/carpi/carpi.str step 19