YAŞAR UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER THESIS

# ANALYSIS OF A DEDICATED FLEXIBLE MANUFACTURING SYSTEM WITH CLOSED LOOP LAYOUT

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# ABSTRACT

## ANALYSIS OF A DEDICATED FLEXIBLE MANUFACTURING SYSTEM WITH CLOSED LOOP LAYOUT

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This study concerns with a dedicated flexible manufacturing system with closed loop layout. The production system consists of different types of parts with different processing times moving on the closed loop conveyor. An analytical model is proposed to show the dynamics and interactions in the system. Since the model is nonlinear and ignores random machine failures, a detailed simulation model has been developed to be able to make a proper analysis of the system. The objective is to find the best configuration in order to maximize the throughput of the system. A number of scenarios representing different configuration settings have been evaluated and compared with respect to the objective. Existing optimization methods and tools, which are used along with simulation models, have been addressed and used to find the best solution. The results have been discussed and recommendations have been made for future work.

**Key Words:** production and service systems, simulation, optimization, flexible manufacturing systems

# ÖZ

## KAPALI DEVRE ESNEK ÜRETİM SİSTEM ANALİZİ

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Bu çalışma, kapalı devre düzene sahip özel bir esnek üretim sistemi ile ilgilidir. Üretim sistemi, kapalı düzende konveyör üzerinde hareket eden, farklı işlem sürelerine sahip farklı parça türlerinden oluşur. Sistemdeki dinamikleri ve etkileşimleri göstermek için analitik bir model önerilmiştir. Model doğrusal olmadığı için ve rasgele makine arızalarını önemsemediğinden, sistemin uygun bir analizini yapabilmek için ayrıntılı bir simülasyon modeli geliştirilmiştir. Amaç, sistemin verimliliğini en üst düzeye çıkarmak için en iyi konfigürasyonu bulmaktır. Farklı konfigürasyon ayarlarını temsil eden bir dizi senaryo değerlendirilmiş ve hedefe göre karşılaştırılmıştır. Simülasyon modelleri ile birlikte kullanılan mevcut optimizasyon yöntemleri ve araçları ele alınmış ve en iyi çözümü bulmak için kullanılmıştır. Sonuçları tartışılmış ve gelecekteki çalışmalar için önerilerde bulunulmuştur.

**Anahtar Kelimeler:** benzetim, servis sistemleri, üretim sistemleri, esnek üretim sistemleri, optimizasyon

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I would like to express my gratitude to my family and to my love for providing me with encouragement and support throughout my years of researching and writing thesis.

Remziye Şirin Uyan
İzmir, 2019

# TEXT OF OATH

I declare and honestly confirm that my study, titled “ANALYSIS OF A DEDICATED FLEXIBLE MANUFACTURING SYSTEM WITH CLOSED LOOP LAYOUT” and presented as a Master’s Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Remziye Şirin Uyan
Signature
…………………………………..

January 2019

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# CHAPTER 1

# INTRODUCTION

A Flexible Manufacturing System (FMS) is a structure of computer controlled semi-independent workstations, which have connection through an automated transportation system. There are many different FMS configurations which vary with the types of components used in the system such as the types of machine tools, types of material handling system, type of storage areas for in-process inventory and the variety of part types to be processed (Tempelmeier, 1993).

This study concerns with a dedicated flexible manufacturing system with closed loop layout. A number of ordered operations are performed on a fixed set of part types. The processing time of each operation is different for each part type. Each operation is assigned and performed on only one machine station for all part types. It is a fixed route for each part through the system. A conveyor is used to move parts between machines. The storage area is local between each machine station. In fact, the system has a unidirectional cyclic design and operates similarly to a dedicated non-homogeneous transfer line.

This kind of production system is used when the same series of operations are performed on the different parts of a final-product whose parts have different size, shape and material. The computers regulate the machines to conform to the changes in size, shape and material if two consecutive parts are of different types. For example, Schneider Electric uses this system for metal coating and related operations in producing medium voltage switching devices. Basic structure of the system is seen in Figure 1.1.

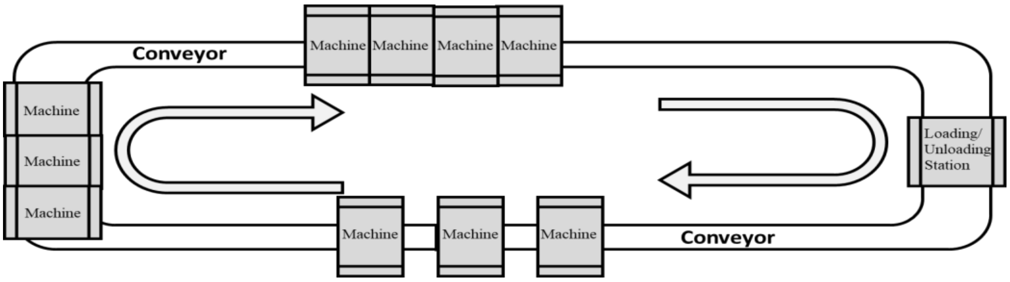


**Figure 1.1**. A Dedicated FMS with Closed Loop Layout

The parts are transported between machines in load-bearing containers i.e. trolleys which are moved by a conveyor system. The speed of the conveyor may vary at different sections on the layout due to technological requirements. The trolleys have different fixtures for different part types. Therefore, there is a specified trolley type associated with each part type. Trolleys accommodate one or more parts simultaneously depending on the structure of its fixture. Accommodation capacity of each trolley type is fixed and predetermined. The machines process the parts in batches accommodated in the trolley without dropping them off.

Unprocessed parts enter in the system when they are loaded at the loading station in the trolleys that are compatible with that part type. The trolley loaded with parts is moved through the system to visit all stations sequentially until the last operation is performed on the last station. When all operations are completed, the trolley then moves forward to complete a closed loop path and arrives back to the loading / unloading station where parts are dropped off. Empty trolley is then loaded again with new unprocessed part(s) of the same type and it continues to revolve in the system (Werner, 2001).

If a machine at a station is busy, the trolley coming from the previous station waits in a local buffer storage area, which has a limited capacity. If the local storage area between two consecutive stations is full, then the trolley cannot leave upstream station and hence blocks it. The station stays blocked until an unoccupied space is available in the buffer storage area in between.

If someone could observe a time-lapse animation of the system, he/she would see a set of trolleys revolving constantly in a closed loop. This set is comprised of different trolley types and hence we can define disjoint subsets each having a number of trolleys from a different type. Since different parts of a product are processed in the system, the number of subsets should be equal to the number of part types and each subset should have at least one element. The cardinalities of the subsets, i.e. the number of elements in each subset of trolleys should be decided. A great number of combinations may be defined as alternative feasible solutions, however, the problem is to find the best combination, in other words to find the best configuration of the system in order to maximize the efficiency.

In this study, we used simulation tool to analyze the system and tried to show how simulation is used to find an optimal solution for the cardinalities of the vehicle subsets. The next chapter explains the operational environment of manufacturing system in detail and gives a clear definition of the problem. Literature review is covered in Chapter 3. An analytical model is proposed for the system in Chapter 4 if the stochastic aspects are ignored. Chapter 5 is devoted to describe the detailed simulation model of the system. Input analysis of the simulation model is given in Chapter 6. Verification and validation is explained in Chapter 7 and then Chapter 8 covers the output analysis of the simulation model. Experiment design of simulation is explained in Chapter 9. The outcomes of the simulation model, OptQuest results, discussions and recommendations are presented in Chapter 10.

# CHAPTER 2

# STATEMENT OF THE PROBLEM

In this chapter, the operational environment and the details of system will be described first and then the definition of the problem will be given.

## 2.1. Operational Environment

Schneider Electric produces industrial switching devices (SD). The production process can be divided into several stages. During the early stages, the parts of the SD are produced separately and then, they go through a process called “Metallization Process”. The last stage is the assembly line in which the parts are combined together and assembled to form the end product, SD.

Metallization process includes some consecutive operations essentially for coating the parts with the layers of special materials. There are two functions of the metallization process. The first one is protection of the surface of the parts from harsh environment conditions such as moisture, dust, chemicals etc. It also includes mechanical protection since the process provides resistance to shocks, which may possibly cause micro cracks and eventual failures and malfunctioning of the parts. The second function is to establish a Faraday cage around the parts by coating it with a conductive (metalized) paint. If the final product is electrically grounded in a proper way, the electrical field generated during the operation of the switchgear is totally kept inside the product, as the metallization layer is fully covering the surface area of the product.

The operations of the Metallization Process are performed on a specially built, carousel like platform, which involves processing machines and conveyor segments connecting the machines. Conveyor segments form a closed layout. The structure of the system is shown in Figure 2.1.

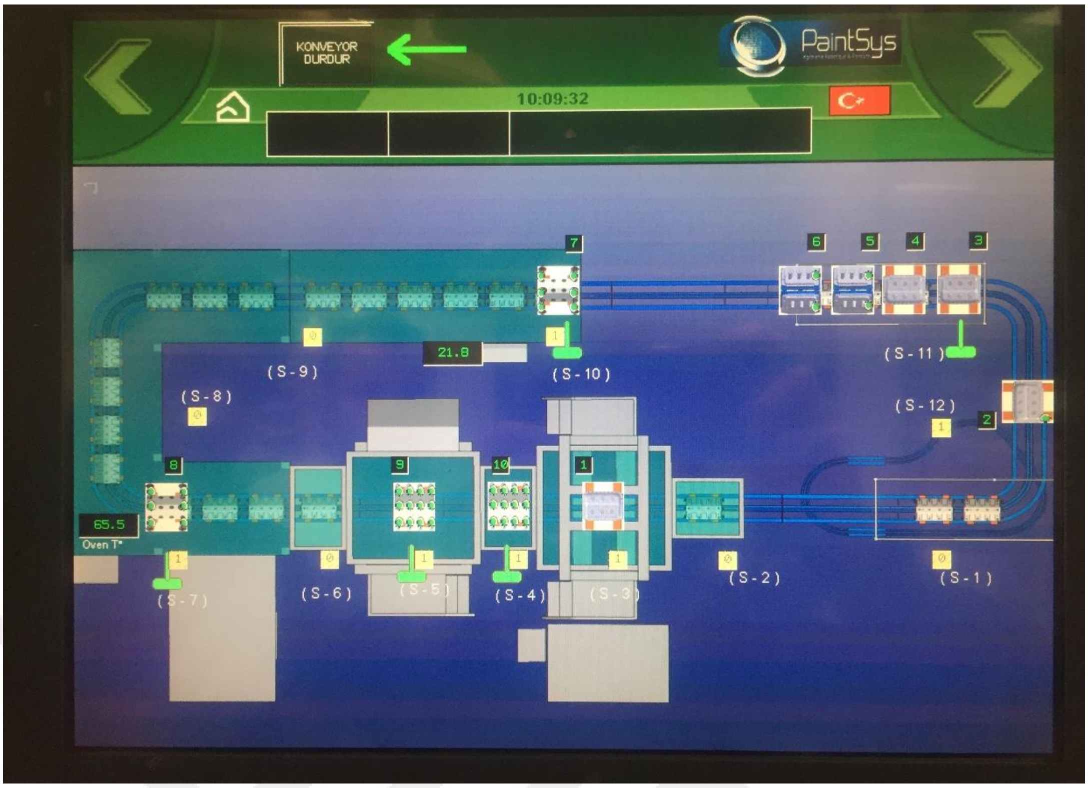


**Figure 2.1.** Layout of Metallization Process

Metallization operations are called Sandblasting, Painting, Flashover, Oven-1, Oven-2, Oven-3 and Cooling. For simplicity, these operations are numbered from one through seven and they are called sequentially as Operation 1, Operation 2 etc. Each operation has performed on a distinct workstation. There is one additional workstation to perform both loading and unloading operations. Therefore, there are nine operations performed on eight workstations.

Five different types of parts are being processed in the metallization process. The parts are then combined and assembled to form a product, i.e., a switching device (SD). The bill of materials (BOM), which is given in Table 2.1, shows the number of parts from each type to produce one unit of end-product.

**Table 2.1.** Bill of Materials for the End Product (SD)

| | **Part 1** | **Part 2** | **Part 3** | **Part 4** | **Part 5** |
|---|---|---|---|---|---|
| **Part/ Finished Product** | 3 | 1 | 1 | 3 | 3 |

Each part type has different operation time on each workstation. Table 2.2 shows the operation times of different part types.

**Table 2.2.** Operation Times of Part Types

| **OPERATION TIMES (seconds)** | | | | | | |
|---|---|---|---|---|---|---|
| **STATION** | **OPERATION** | **Part 1** | **Part 2** | **Part 3** | **Part 4** | **Part 5** |
| **LOADING/ UNLOADING STATION** | Loading | 554 | 401 | 501 | 140 | 140 |
| | Transfer on Conveyor to the Next Station | 40 | 40 | 40 | 40 | 40 |
| | Transfer on Conveyor to the Next Station | 14 | 14 | 14 | 14 | 14 |
| **SANDBLASTING STATION** | Operation 1 | 406 | 371 | 350 | 319 | 387 |
| | Transfer on Conveyor to the Next Station | 14 | 14 | 14 | 14 | 14 |
| **PAINTING STATION** | Operation 2 | 783 | 325 | 293 | 547 | 282 |
| | Transfer on Conveyor to the Next Station | 14 | 14 | 14 | 14 | 14 |
| **FLASHOVER STATION** | Operations 3 | 162 | 162 | 162 | 162 | 162 |
| | Transfer on Conveyor to the Next Station | 8 | 8 | 8 | 8 | 8 |
| **OVEN STATION** | Operations 4-5-6 | 1200 | 1200 | 1200 | 1200 | 1200 |
| **COOLING STATION** | Operation 7 | 26 | 26 | 26 | 26 | 26 |
| | Transfer on Conveyor to the Next Station | 33 | 33 | 33 | 33 | 33 |
| **LOADING/ UNLOADING STATION** | Unloading | 98 | 297 | 232 | 88 | 85 |

Trolleys are driven by accumulating conveyor on this structure. Total number of trolleys in the system is physically constrained to 30. A trolley can accommodate one or more parts of the same type simultaneously depending on the fixture. Accommodation capacity of each trolley type is given in Table 2.3.

**Table 2.3.** Part Capacity of Trolleys Types

| | **Trolley Type (associated with corresponding part type)** | | | | |
|---|---|---|---|---|---|
| | **Type-1** | **Type-2** | **Type-3** | **Type-4** | **Type-5** |
| **Capacity (parts)** | 6 | 1 | 2 | 12 | 12 |

As a summary, all parameters in this operational environment are deterministic. However, it is known that the system suffers random hardware failures, and hence the system has stochastic aspects. There are historical records regarding to occurrence date and time of failures and associated repair times. Those records are processed in the context of input analysis to be used in the simulation model.

## 2.2. Problem Definition

The goal of this study is the throughput analysis of the system, which is described above. The performance is measured by the quantity of end product that can be produced using the parts processed in the system in a given period of time, for example in a week. In other words, performance of the system can be measured by throughput of the system or the number of end product (SD).

Decision variables are the numbers of elements in each subset of trolleys types. In other words, main question will be "how many trolleys should be used from each trolley types?" The objective is to maximize the quantity of end product while ensuring the following technological constraints are not violated.

- Total number of trolleys allowed in the system is limited to 30 due to physical restrictions.
- Each subset of trolleys should have at least one element. In other words, there should be at least one trolley from each type.
- Preemption is not allowed.

In order to show the nature of the problem, the objective function values have been calculated for some feasible solutions of the problem using a deterministic simulation model. The following table shows the results for the period of one week.

**Table 2.4.** Objective Function Values for Particular Feasible Solutions

| Number of Trolleys In Each Trolley Type | | | | | | The Numbers of Parts and Corresponding End Product That Can Be Produced | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type 1 | Type 2 | Type 3 | Type 4 | Type 5 | Total Trolley | Part 1 | Part 2 | Part 3 | Part 4 | Part 5 | SD | Number of Tours |
| 1 | 1 | 1 | 1 | 1 | 5 | 1990 | 331 | 662 | 3972 | 3972 | 331 | 331 |
| 2 | 4 | 2 | 1 | 1 | 10 | 3444 | 1148 | 1148 | 3444 | 3432 | 1148 | 287 |
| 6 | 12 | 6 | 3 | 3 | 30 | 3384 | 1116 | 1116 | 3348 | 3348 | 1116 | 93 |

Each row in the table indicates a different feasible solution to the problem and hence a corresponding scenario for the simulation model. For example, the first row represents a feasible solution the problem since it imposes to use a single trolley for each type, which leads to 5 trolleys in total. Another feasible solution of the problem is represented in the second row, which is to use 2, 4, 2, 1 and 1 trolleys respectively for each trolley type and therefore you have 10 trolleys in total in the system. The simulation model is used to find out how many parts can be produced in each setting (scenario). The outcomes are shown in the corresponding rows of the table. The numbers of end product, i.e., switching device (SD) is calculated by considering the BOM structure. In the last column, the number of completed tours of trolleys is given for each scenario.

It is obvious that a great number of feasible solutions can be listed since there are many feasible combinations of trolley types for each particular number of trolleys in total, which varies between 5 and 30.

Notice that as the number of trolleys in total increases, the number of completed tours decreases. It is natural, since duration of each tour increases as the number of trolleys in total increases in the system. There is a trade-off between the number of completed tours and the number of trolleys in the system.

The numbers of SDs represent the values of objective function. One may instinctively expect that the value of objective function should increase as the number of trolleys in total increases. Indeed, it is true for certain conditions. For example, if we compare a particular combination of trolleys types, which sums up to 10 trolleys to a combination of 5 trolleys in total, it is shown that the first option yields more than 3 times better objective function value (1148 vs 331). However, as the number of trolleys in total increases further, objective function ceases to increase and it begins to decrease at some point and may be fluctuate in between 10 and 30.  In fact, there are a complicated and non-linear relationships exist between the number of trolleys in total, the combinations of trolley types and the duration of tours.

# CHAPTER 3

# LITERATURE REVIEW

There are many articles in the literature regarding to flexible manufacturing systems (FMS) and optimization with simulation. Studies have focused on different topics, such as analysis of the flexible manufacturing system, closed loop layout design and some of them focused on optimizing some performance metrics in the system.

Browne et al. (1984) proposed basic definitions and a classification scheme of flexible manufacturing systems. Koenigsberg and Mamer (1982) defined different types of conveyors, work transporters, workstations, and they proposed a deterministic analytical model (queuing model) to be used in the analysis of classical FMS systems. The objective function is minimizing waiting times and queue size at particular crucial points in the system. However, our system is not a classical FMS, rather a specific variant of FMS. Moreover, we do not need manage a queue.

Dhouib et al. (2009) analyzed the throughput of non-homogeneous transfer line, which has different process times in each machines. The problem settings are similar to our problem. However, its layout is not a closed loop. Each part type is moving through between workstations and when its process on the last machine is finished, it leaves the system. In our closed loop layout, the parts are unloaded after they are done with the last workstation, and then the trolleys are loaded again with the same type of parts and hence sequence of the jobs are determined in a different way in our problem. They proposed different analytical approaches, which delivers approximate solutions. They do not prefer analytical models because they cause significant errors and poor estimate when compared to verified and validated simulation outputs.

Kumar et al. (2015) also studied on the performance analysis of flexible manufacturing systems. They concluded that analytical models are complex and usually nonlinear and therefore they are difficult to solve. They advised to use simulation models since they are more effective to analyze such systems.

Pourbabai (1987) analyzed closed loop material handling performance. Manufacturing system consists of a set of workstations, an inventory system, and a material handling system. Model has developed for analyzing the performance of a manufacturing system consisting of N workstations, one loading station, N unloading stations, and an inventory system linked by conveyors. Incoming parts enter from loading station and recirculate throughout the conveyor, leave the system through the respective unloading station after being processed. Although there are some similarities with our problem settings, there are significant deviations. For example, in that model, the parts have an option to bypass a machine to be processed in others. In our problem, the parts should be processed sequentially in the same order. Furthermore, the parts arrive in a stochastic process, which does not conform to our problem settings. He considered the congestion along conveyors, which refers to the tour time in our model. As usual, a simulation model is used to conduct the analysis.

El-Tamimi et al. (2012) has analyzed the performance measures of classical FMS systems. Study focused on application of Petri nets for measuring performance of FMS. He considers flexible routes for the parts in the system, which indicates a deviation of our problem environment since there is no route flexibility in our model. He used a simulation model. Additionally, the bottleneck technique (an analytical model) has been developed to compare and verify simulation results. Designing optimal FMS for particular requirements is a complex problem and hence it is hard to develop accurate mathematical models to calculate performance measures. Therefore, simulation models are used for numeric modeling technique for analyzing highly complex systems.

Schattka et al. (2016) studied how to improve the resilience of a production system. Study has a method to assess the performance in face of breakdowns and to identify the level of resilience for a production system Due to its modular structure, arbitrary production lines have been analyzed. A simulation model has been employed and optimization procedures are used along with the simulation model. They use genetic algorithm to find the best configuration of the system to maximize the resilience.

Standridge et al. (1988) have used a simulation model for FMS. Study focused on strategic issues like variants of the simulation models to run and analyzing the outputs. In their problem settings, there are a number of machines usually performing different operations, however some of them identical and performs the same operation. The parts may have different routes. In our problem environment, there is only one machine dedicated for each particular operation and the parts have the same route through the machines. The aim of that study is determining the machine mix i.e. the number of machines performing each operation and the number of flexible machines performing any operation.

**Table 3.1** Comparison Tables of Literatures

| **Article** | **Production System** | **Objective Function** | **Solution Methodology** |
|---|---|---|---|
| Koenigsberg and Mamer (1982) | Varied layouts of FMS | Min waiting times, queue size and max the output | Queueing Theory |
| Dhouib et al. (2009) | Non-Homogenous Automated Transfer Line | Max throughput | Optimization via simulation model |
| Kumar et al. (2015) | Closed –loop & routing flexible FMS | Max utilization of machines | Optimization via simulation model |
| Pourbabai (1987) | Closed loop material handling system | Max efficiency of each work station & Min average congestion along every conveyor | G/M/S/K queueing theory (Generally distributed interarrival times, Markovian processing times, S machines, local storage size K) and simulation model |
| El-Tamimi et al. (2012) | Routing and machine flexibility FMS | Max machine utilization & Overall productivity | Petri nets,<br>and<br>simulation model |

|  |  |  |  |
|---|---|---|---|
| Schattka et al. (2016 | Arbitrary production line | Max output | Optimization via simulation model |

Almost all the studies use a simulation model as the basic analysis tool since underlying relationships usually lead to the complicated and nonlinear analytical models. We will follow the same path to demonstrate the analysis of our problem setting, i.e., a dedicated FMS with closed loop layout.

# CHAPTER 4

# ANALYTICAL MODEL

If machine failures ignored, the system can be considered as a deterministic model and therefore an analytical model can be demonstrated. A mathematical model has been developed to find the best composition of the trolleys to maximize throughput of the system. The notation is given as follows.

**Parameters:**

$j$ : index for trolley types, $1 \leq i \leq n$ ,

$B_j$ : quantity of part type *j* needed to manufacture an end-product (shown in BOM)

$A_j$ : number of parts that can be accommodated in the trolley type $j$ (determined by fixture of that trolley)

$R$ : maximum number of trolleys allowed to operate in the system

**Decision Variables:**

$x_j$ : number of type *j* trolleys to be used in the system,
(Each part type is represented by an associated trolley type)

*y* *:* the number of end-product that can be produced in one complete tour of all trolleys

*k* : the number of tours that can be completed in a given period of time

Objective function; $Max. Z = k * y$ (1)

$$\frac{A_j}{B_j} * x_j \geq y, \qquad \forall j = 1,2, \dots\dots, n \tag{2}$$

$$x_j \geq 1, \qquad \forall j = 1,2, \dots\dots, n \tag{3}$$

$$\sum_{j=1}^{n} \mathrm{x}_j \leq R \tag{4}$$

$$k = f\left( \mathrm{x}_1, \mathrm{x}_2, \dots \dots, \mathrm{x}_{n,} \right) \tag{5}$$

$$x_j \ integers, \ \forall\, j = 1,2, \dots \dots, n \tag{6}$$

Notice that the formulation leads to a nonlinear integer-programming problem since the objective function includes a multiplication of two decision variables and each decision variable is restricted to be integers. Furthermore, Equation (5) indicates that the tour time $k$ is a function of $x_j' s$. Although the model (1) –(6) is relatively simple, that function in Equation (5) creates a great deal of complexity and ambiguity and therefore needs to be elaborated. For this reason, let us adopt some additional notation as follows.

$i$ : index for work stations, $0 \leq i \leq m$ ,
Loading/unloading station is denoted by $i = 0$

$V$ : total number of trolleys currently used in the system,

$$V = \sum_{j=0}^{n} x_j$$

$P_{ij}$ : operation time of parts carried in trolley type *j* on station *i*

$g$ : index for conveyor segments between stations.

Since the system is designed as unidirectional cyclic, conveyor segments are represented by a set of ordered pairs of stations,
$\mathrm{G} = \{(0,1), (1,2), (2,3), \dots\dots, (m-1, m), (m, 0)\}$

$T_g$ : transfer time on conveyor segment $g$.

If only one of a particular type of trolley is allowed in the system, in other words, only one $x_j$ is equal to 1,

$C_j$ : total job completion time or the time for completing one tour for trolley type *j* if only one of trolley of type *j* is revolves in the system. It is defined as the sum of all processing and transfer times,

$$C_j = \sum_{i=1}^{m} P_{ij} + \sum_{g \in G} T_g \tag{7}$$

Then the number of tours, $k$, in a given particular duration of production time, $T$, can be defined as follows.

$$k = T \,/\, C_j = \frac{T}{\sum_{i=1}^{m} P_{ij} + \sum_{g \in G} T_g} \tag{8}$$

On the other hand, if only one of each type of trolley is allowed in the system, in other words, each $x_j$ is less than or equal 1, then the number of tours, $k$, is given as follows.

$$k = \frac{T}{Max\,\{\, C_1,\ C_{2,}, \ldots \ldots C_n\}} \tag{9}$$

If more than one trolley from each type is allowed in the system as required in real life application, i.e., $1 \le x_j \le R$ , then the number of tours, $k$, is given as follows

$$k = \frac{T}{Max\left\{\sum_{j=1}^{n} x_j P_{ij},\ \ \forall i = 1,2, \ldots m\right\}} \tag{10}$$

However, the equation above holds in specific conditions, such as if machine blocking does not occur in the system. If machine blocking occurs, new relations should be investigated.

# CHAPTER 5

# SIMULATION MODEL

In this study, ARENA software has been used for creating simulation model. An animation model has also been developed to accompany to the simulation model. The animation model is shown in the below figure.

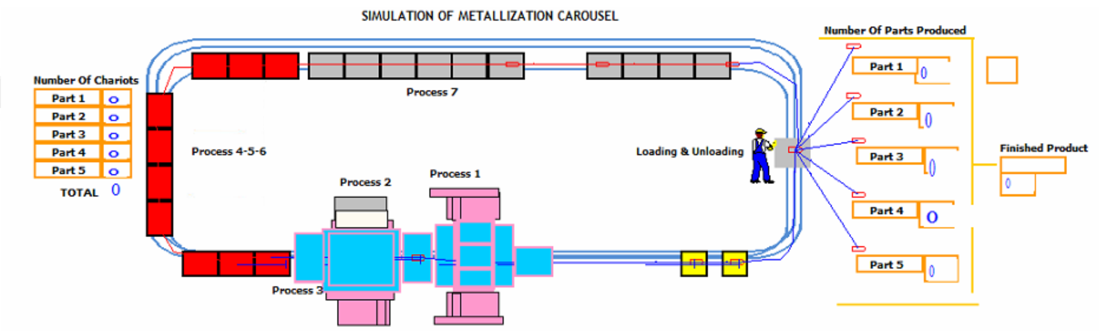


**Figure 5.1** Overview of Animation

Two external files have been used in the model, inputs are received from the first one and outputs of the simulation are written to the second file. MS Excel $^{TM}$ files are being used. The content of input file as follows.

- Processing times of each trolley type at each workstation
- Transferring times between stations
- Loading/unloading times of each type of trolley
- Part accommodation capacity of each trolley type
- Trolley configurations, i.e., the numbers of trolleys from each type

The model has been developed in a flexible structure with sub-models. Sub-models include initialization, loading/unloading processes and operations in stations. As an example, one of sub-model simulates trolleys creation to the system. Some others simulate arrivals of the parts to the loading/unloading station. Each sub-model details are explained in the next subsections. Basic structure of the simulation model is stated in Figure 5.2.

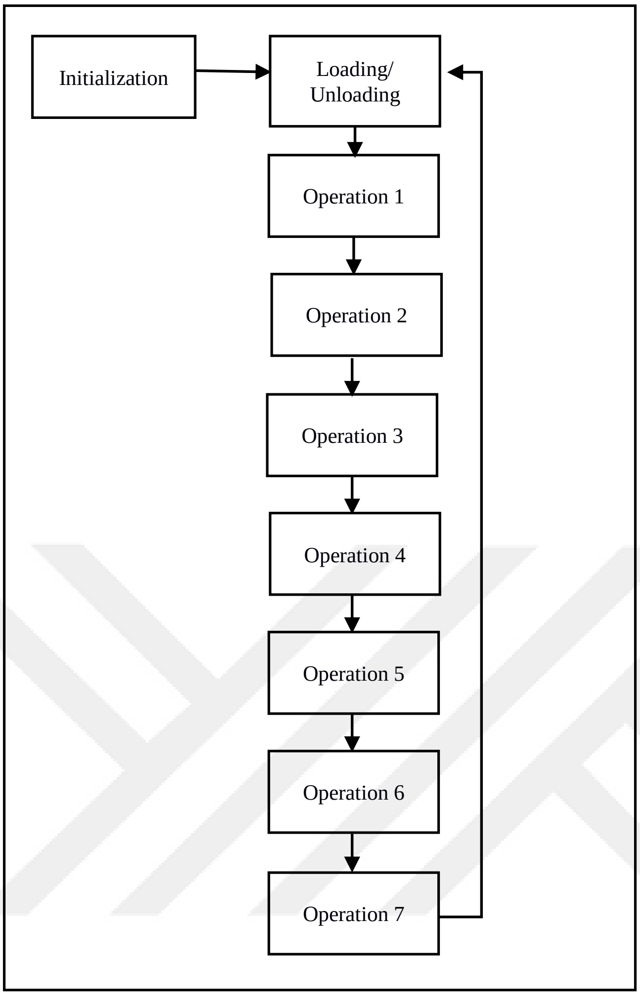


**Figure 5.2.**Basic Structure of Simulation Model

## 5.1. Initialization Process

The first sub-model is initialization. This sub-model describes creation of parts, assignments of parts and initial waiting queue before the first loading. General structure and display of sub-model of initialization process are shown in Figure 5.3 and Figure 5.4.

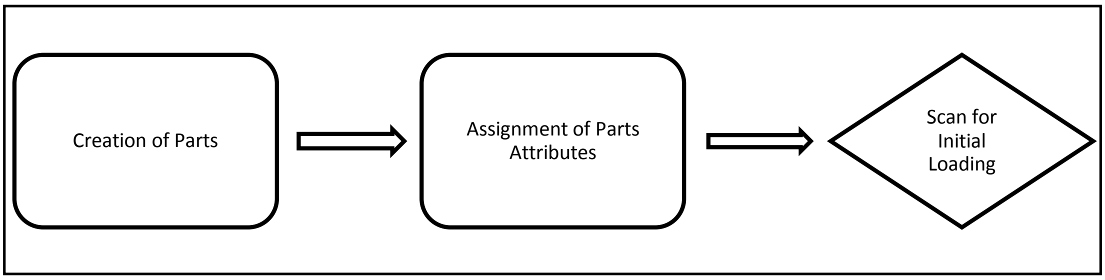


**Figure 5.3.** General Structure of Initialization Sub-Model

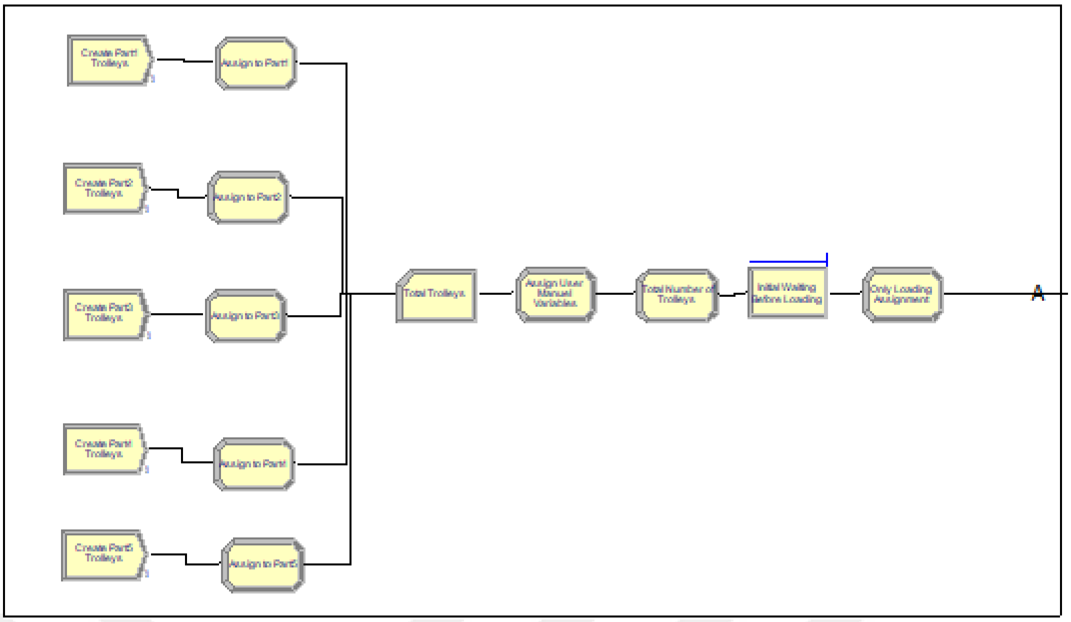
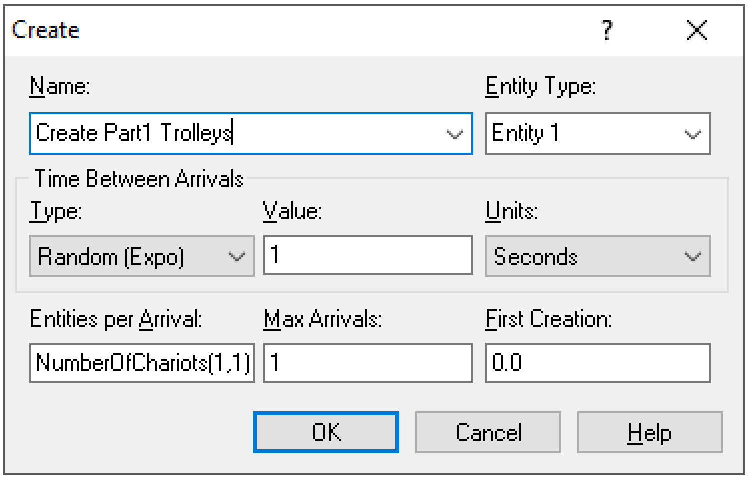


**Figure 5.4.** Display of Initialization Sub-Model

There are five different Create modules in sub-model. Starting with the Create module that will create arriving Part 1, Part 2, Part 3, Part 4 and Part 5 entities. Below Figure 5.5 provides the information required to complete this module. It has been given name to sample module as Part1.

The number of part types into the system is decision variable. It means that entities per arrival for each part type can be decided according by user with not violating system constraints. There is a link between excel file and simulation which is related with quantity of trolleys in the system. The remaining entries have default options.



Name: Create Part1 Trolleys

Entity Type: Entity 1

Time Between Arrivals

Type: Random (Expo)

Value: 1

Units: Seconds

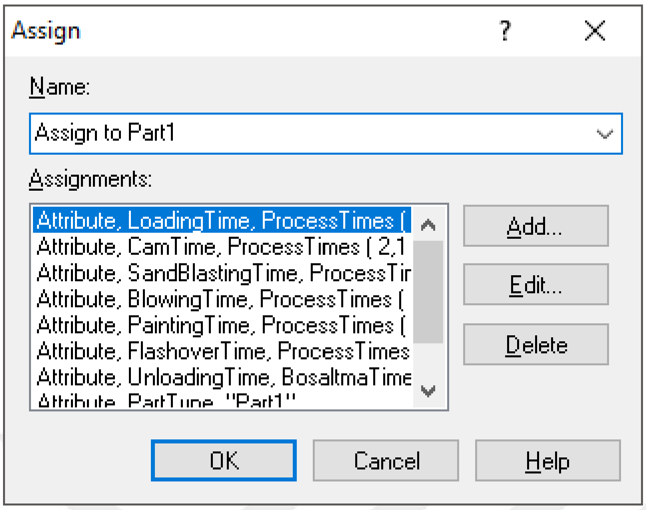
Entities per Arrival: NumberOfChariots(1,1)

Max Arrivals: 1

First Creation: 0.0

**Figure 5.5.** Creation of Part1

Having created arriving parts, we must to assign an attribute for operation times in each stations and specified the part type which is different for each part type. Although five entities are created in the previous module for each arrival, the parts will each be assigned a different value from the different operation times in the assign module. Display of assignment is in Figure 5.6.

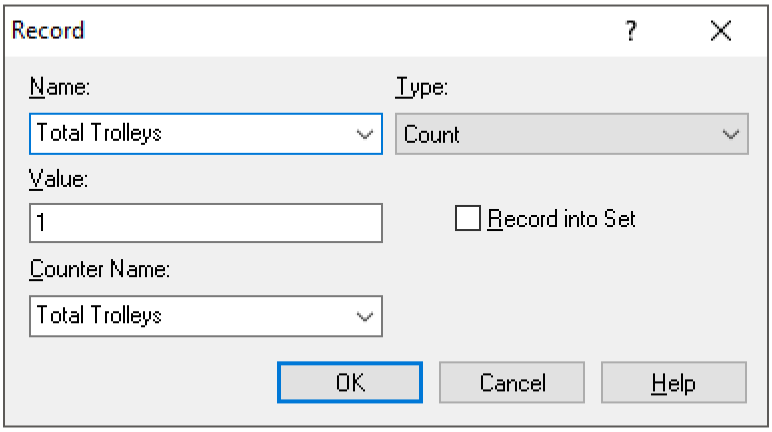


Name:
Assign to Part1

Assignments:
Attribute, LoadingTime, ProcessTimes (
Attribute, CamTime, ProcessTimes ( 2,1
Attribute, SandBlastingTime, ProcessTir
Attribute, BlowingTime, ProcessTimes (
Attribute, PaintingTime, ProcessTimes (
Attribute, FlashoverTime, ProcessTimes
Attribute, UnloadingTime, BosaltmaTime
Attribute, PartType, "Part1"

**Figure 5.6.** Assignment of Part 1

We wanted to collect some statistics as part of simulation output. One of them is total number of trolleys in the system. The record module performs a certain amount of increase or decrease the total number of trolleys quantity in the system, which is shown below Figure 5.7.



Name:
Total Trolleys

Type:
Count

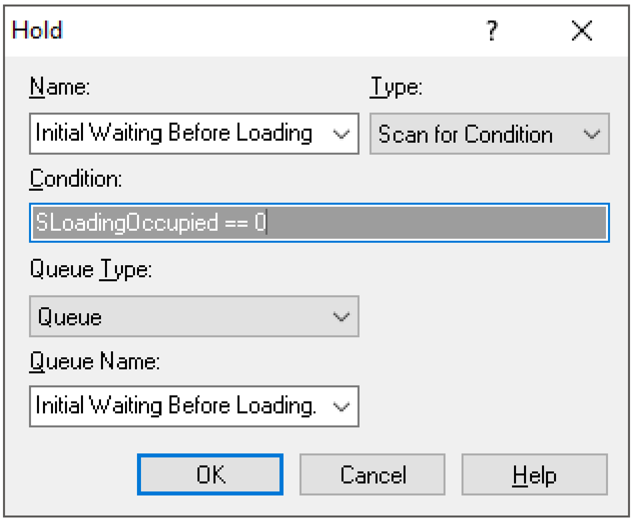
Value:
1

☐ Record into Set

Counter Name:
Total Trolleys

**Figure 5.7.** Counting of Total Number of Parts

The first loading operation is done only once to create the parts into the system. The parts are waiting for the condition that is availability of queue for loading operation to start the flow. After initial loading, same trolleys are starting to be used in this closed loop carousel. In this below Figure 5.8 shows that the Hold module condition for initial loading. This module will hold the parts in a queue to wait for a condition which is next operation is ready for operation to become true (scan).



Name: Initial Waiting Before Loading

Type: Scan for Condition

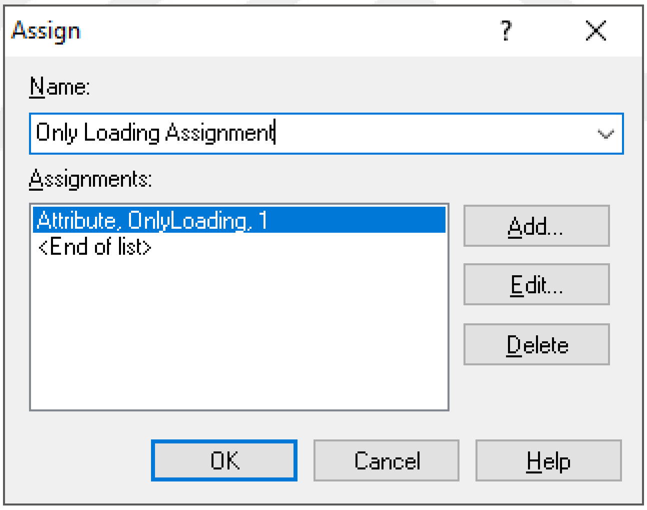
Condition: SLoadingOccupied == 0

Queue Type: Queue

Queue Name: Initial Waiting Before Loading.

**Figure 5.8.** Initial Loading Waiting Condition Hold Module

The system performs loading and then unloading operations. Since the process is done at the same location, we need to identify a binary distinctive feature like 1 for loading and 0 for unloading. We must to assign an attribute for loading and unloading operations in loading/unloading station, which you can see in Figure 5.9.



Name: Only Loading Assignment

Assignments:
Attribute, OnlyLoading, 1
<End of list>

**Figure 5.9.** Assignment of Loading Availability

## 5.2. Loading/Unloading Processes

The second sub-model describes loading/unloading processes. This manufacturing system has currently only one station for both loading/unloading operations. Loading operation has to wait for completion of unloading operation and vice versa. Each operation is performed at only one station for all part types.

In current situation, there is only one worker works in the loading/unloading station. At this point, an alternative option occurs to speed up performance of the system.

Unloading operation location can be changed depending on the number of workers in the system. If there is one worker, loading/unloading operation is completed in the same loading/unloading station otherwise, unloading operation is completed in the last buffer storage area and loading is done in the same loading/unloading station. Below Figure 5.10 and Figure 5.11 show that loading/unloading process according to the number of workers.

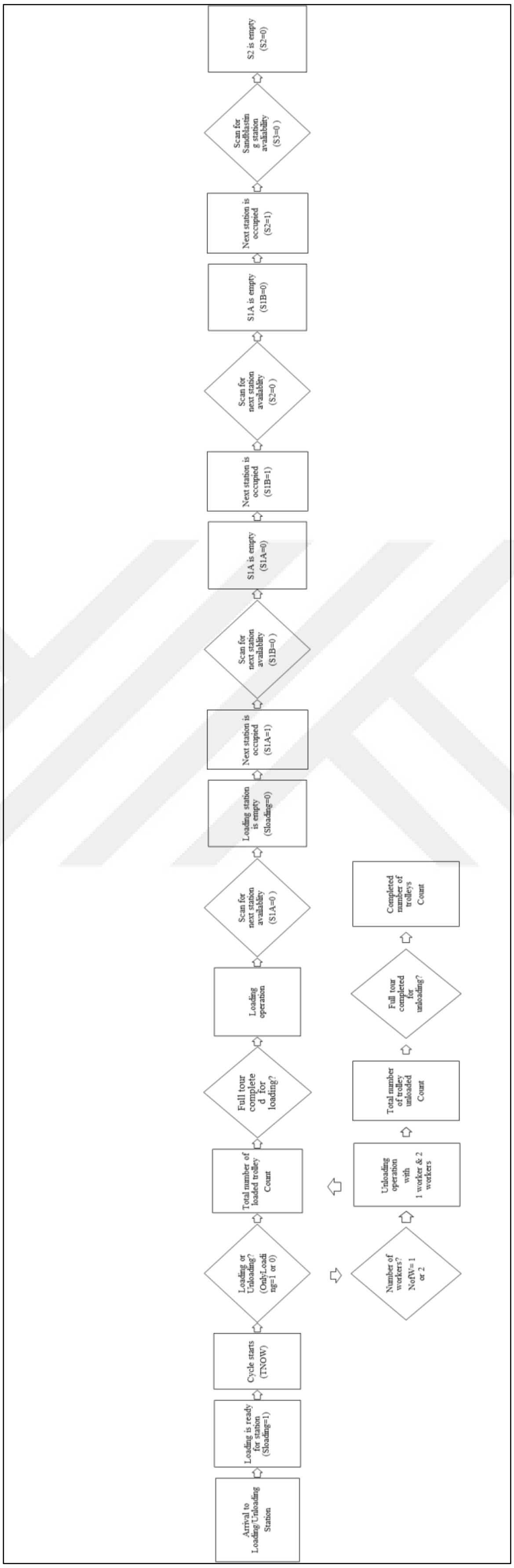


**Figure 5.10.** General Structure of Loading & Unloading Operation

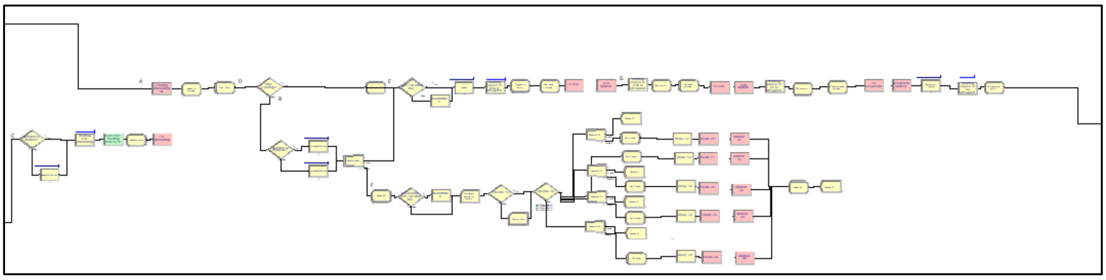


**Figure 5.11.** Simulation Model of Loading/Unloading Operation

### 5.2.1 Loading Process

After completion of initialization process, parts flow start for the first loading operation. The entities arrive to loading station and occupation is done for loading purpose. The ARENA variable TNOW shows the current time of simulation, which in this case is the time the part started their operations in the closed loop carousel and recorded as Start Time in assign module.

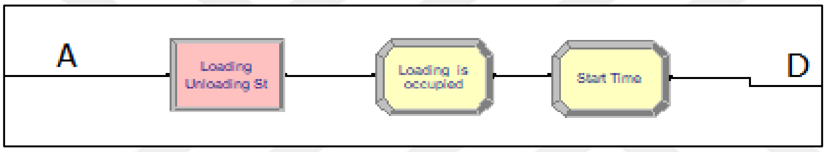
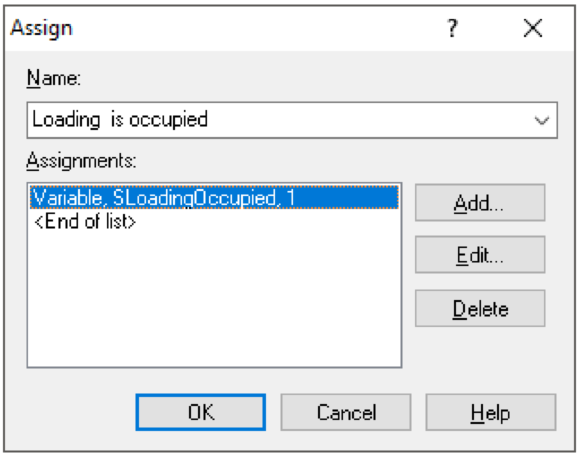


**Figure 5.12.** Loading Station Occupation Model

For the arrived parts, which are ready for being processed, we have to assign a variable for having the operation details about loading whether to see station is occupied or empty. Therefore, we need to identify a binary distinctive feature to perform all sequential operations starting with the loading operation which is incremented by a part entity when it enters that area and decremented by a part when it leaves the area. Display of assignment is below Figure 5.13.



Loading is occupied

Variable, SLoadingOccupied, 1
<End of list>

**Figure 5.13.** Assignment of Loading Operation Occupation

After waiting for condition to see the loading/unloading availability, Decide module is used to model this structure. The aim is directing the operations depending on the different conditions. The simulation model and the data for decide module is shown in Figure 5.14 and Figure 5.15.

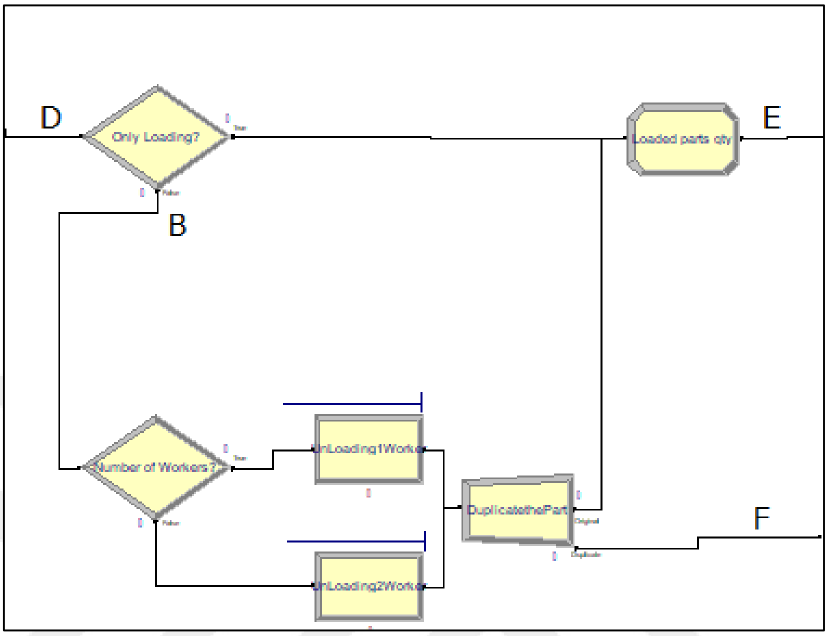
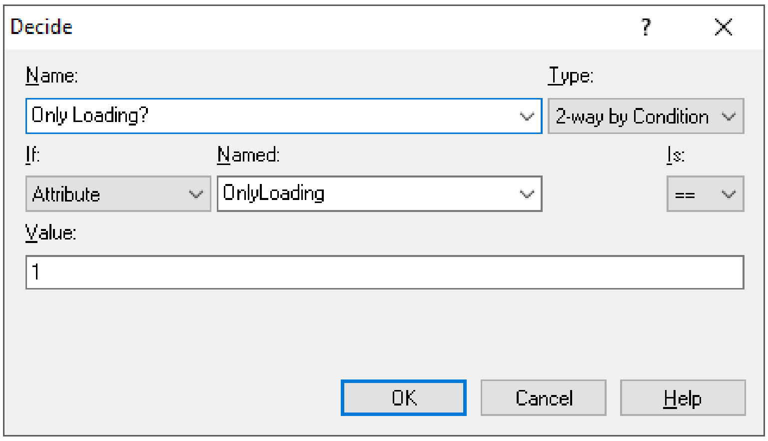


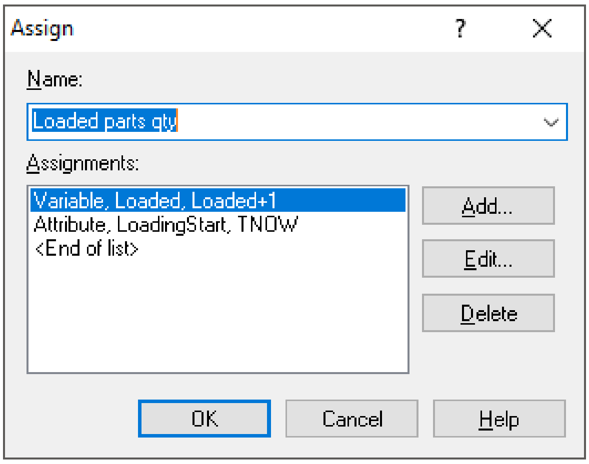
**Figure 5.14.** Decision of Loading / Unloading Operations Model



Name: Only Loading?
Type: 2-way by Condition
If: Attribute
Named: OnlyLoading
Is: ==
Value: 1

**Figure 5.15.** Decision Condition for Loading/Unloading Operations

Having the ready parts for loading, loading/unloading station is occupied for only loading purpose and then the parts are moving forward for loading operation. We recorded total number of loaded parts in the system as a variable, and for each loading operation start time as an attribute and Figure 5.16 is shown below.



Name:
Loaded parts qty

Assignments:
Variable, Loaded, Loaded+1
Attribute, LoadingStart, TNOW
<End of list>

**Figure 5.16.** Assignment of Loaded Parts Count and Loading Start Time Recording

The loading process is starting with the decide module that is shown below Figure 5.17. This module controls the condition whether the loaded parts completed their tours or not. If the parts completed their tour, then system records each tour time between loading operations.

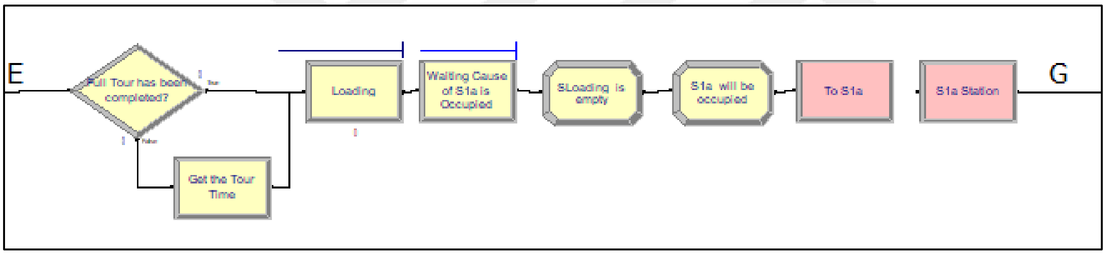
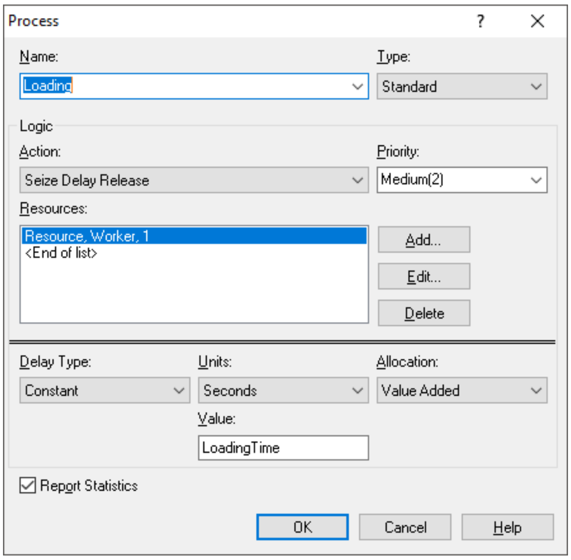


**Figure 5.17.** Loading Operation Simulation Model

There is a link between excel file and simulation which have loading times of parts. Process module indicates that the worker1 will be allocated and the delay operation will be performed. The worker1 is then released after completion of loading operation. Figure 5.18 shows that loading operation process module in the loading/unloading station.



Name: Loading
Type: Standard

Logic

Action: Seize Delay Release
Priority: Medium(2)

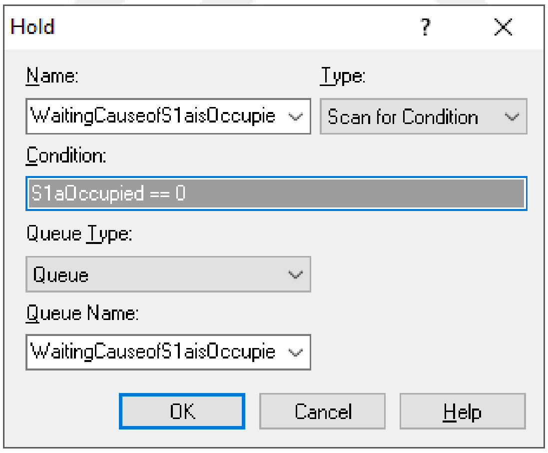
Resources:
Resource, Worker, 1
<End of list>

Delay Type: Constant
Units: Seconds
Allocation: Value Added
Value: LoadingTime

☑ Report Statistics

**Figure 5.18.** Loading Operation Process Module in the Loading/Unloading Station

After loading, parts are moving forward to be processed sequentially in this layout. Therefore, beginning with this module, all operations will hold the parts in the queue until the condition, which is given at first to be true; the parts will remain at the module until the next station queue is available for processing. Figure 5.19 shows that the Hold module condition for next station queue availability.



Name: WaitingCauseofS1aisOccupie
Type: Scan for Condition
Condition: S1aOccupied == 0
Queue Type: Queue
Queue Name: WaitingCauseofS1aisOccupie

**Figure 5.19.** Waiting Condition for Next Station Hold Module

The parts that complete their loading operation start moving forward with trolleys for processing to the next stations. There are three buffer storage areas before arriving to the stations where the parts will be processed.

First of all, next station queue availability condition that will be evaluated to keep the entity at the module. If there are no waiting parts in the next station (condition=0), parts leave from the module it means that the previous station is empty and the next station will be full (condition=1). The flow continues until parts pass through three-buffer storage area and arrive to the station for Operation 1. Below Figure 5.20 shows the module.

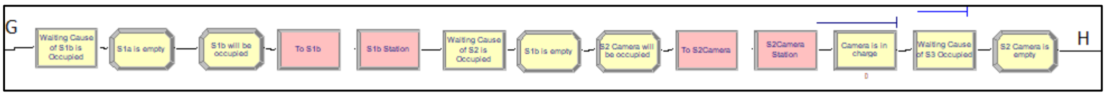


**Figure 5.20.** Buffer Storage Area Model after Loading Operation

### 5.2.2. Unloading Process

#### 5.2.2.1 Unloading Operation in Loading/Unloading Station

Each parts which complete their operations in each station start to wait for a final operation, unloading. Unloading operation may vary according to the number of workers. Let me explain this situation with more detail. Below Figure 5.21 shows that unloading operations in the loading/unloading station.

The unloading process start with the decide module that is shown below. This module controls the condition whether the number of worker in the system is 1 or 2.

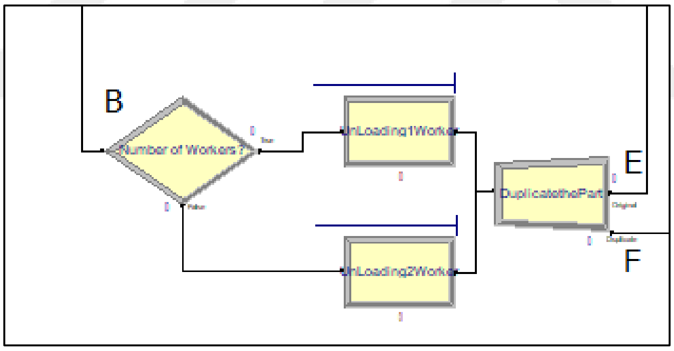
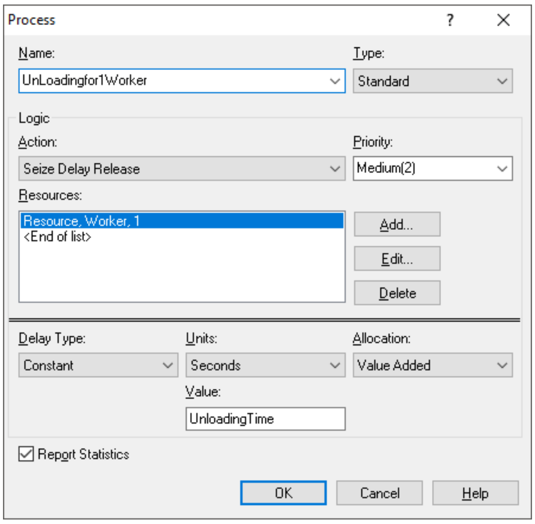


**Figure 5.21.** Unloading Operation in the Loading/Unloading Station Model

If there is one worker in the system, unloading is completed in the same (loading/unloading) station.

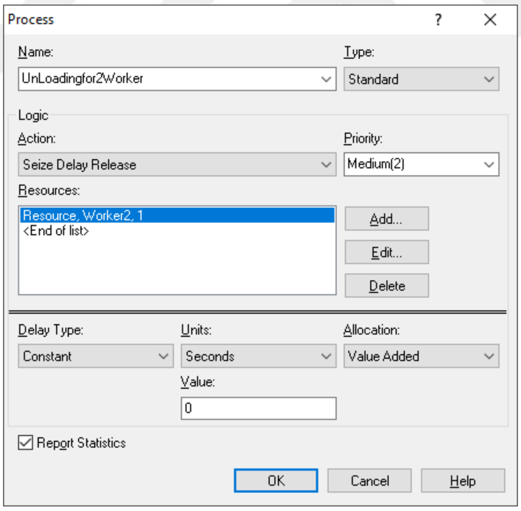
There is a link between excel file and simulation which are unloading times of parts. Process module indicates that the worker1 will be allocated and the delay operation will be performed. The worker1 is then released after completion of unloading operation. Figure 5.22 shows that unloading operation process module for one worker in the loading/unloading station.



Name: UnLoadingfor1Worker
Type: Standard
Logic
Action: Seize Delay Release
Priority: Medium(2)
Resources: Resource, Worker, 1
<End of list>
Delay Type: Constant
Units: Seconds
Allocation: Value Added
Value: UnloadingTime
☑ Report Statistics

**Figure 5.22.** Unloading Operation for One Worker in the Loading/Unloading Station

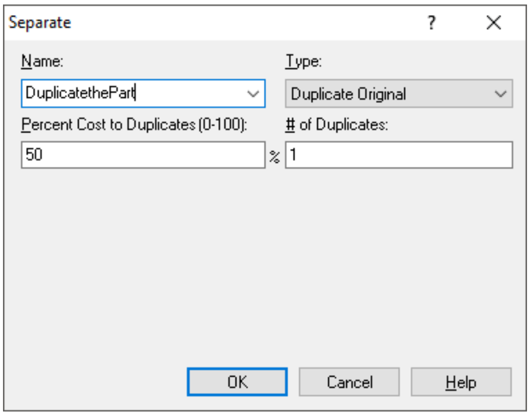
If there are two workers are working in the system, unloading operation is completed in the last buffer storage area thus unloading time in loading/unloading station will be 0. The process modules have variety due to above reasons. Figure 5.23 shows that unloading operation process module for two workers in the loading/unloading station.



Name: UnLoadingfor2Worker
Type: Standard
Logic
Action: Seize Delay Release
Priority: Medium(2)
Resources: Resource, Worker2, 1
<End of list>
Delay Type: Constant
Units: Seconds
Allocation: Value Added
Value: 0
☑ Report Statistics

**Figure 5.23.** Unloading Operation for Two Worker in the Loading/Unloading Station

After all these operations, the parts are moving through to the loading operation are duplicated to collect some statistics. This module can be used to take the original entity and make one identical duplicates as stated below Figure 5.24.



Name: DuplicatethePart

Type: Duplicate Original

Percent Cost to Duplicates (0-100): 50 %

# of Duplicates: 1

**Figure 5.24.** Duplication of Part to Calculate Some Statistics

#### 5.2.2.2 Unloading Operation in the Last Buffer Storage Area

Unloading operation is completed in the last buffer storage area if there are two workers in the system therefore loading/unloading station will perform only loading operation. The unloading process starts with the decide module that is shown below. (Figure 5.25) This module controls the condition whether the number of worker in the system is one or two.

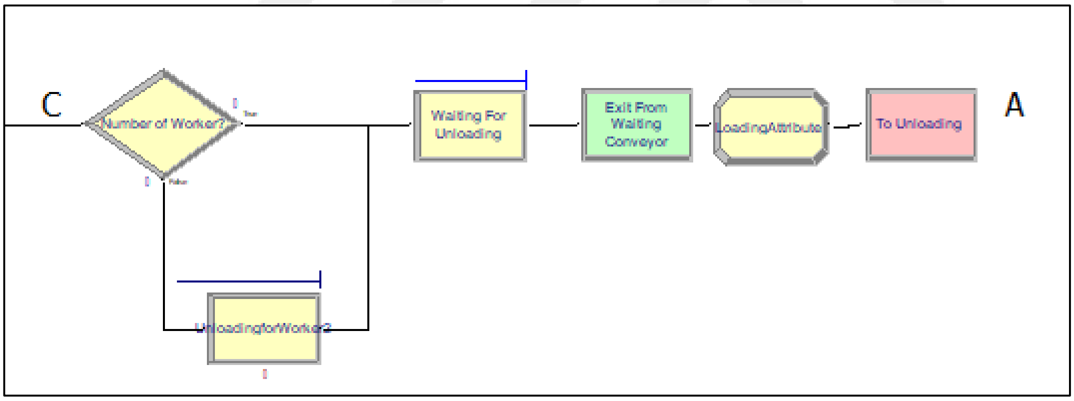
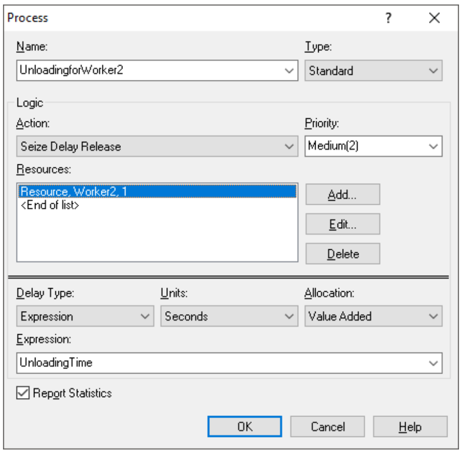


**Figure 5.25.** Unloading Operation in the Last Buffer Storage Area with Two Workers Simulation Model

If there is one worker in the system, parts are moving directly to the loading/unloading station and wait for unloading condition.

There is a link between excel file and simulation which are unloading times of parts. Process module indicates that the worker2 will be allocated and the delay operation will be performed. The worker2 is then released after completion of unloading operation. Below Figure 5.26 shows that unloading operation process module for two workers in the last buffer storage area.



Process

Name: UnloadingforWorker2

Type: Standard

Logic

Action: Seize Delay Release

Priority: Medium(2)

Resources:

Resource, Worker2, 1
<End of list>

Delay Type: Expression

Units: Seconds

Allocation: Value Added

Expression: UnloadingTime

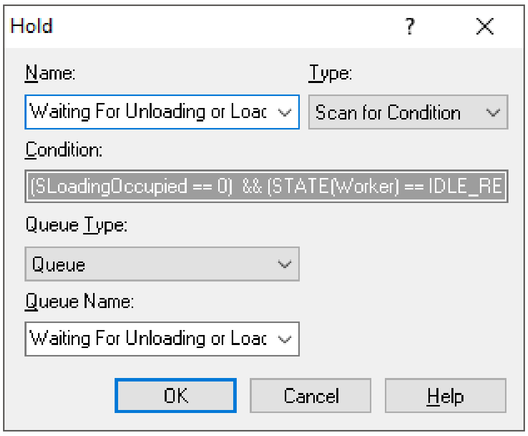
☑ Report Statistics

**Figure 5.26.** Unloading Operation for Two Worker in the Last Buffer Storage Area

When then parts complete unloading operation, they have to move forward to the initial station for loading operation because of the layout of the system. In this below Figure 5.27 shows that the Hold module condition has two different option.

The first one is one worker option. Hold module keeps the parts in a queue to wait for a specified condition which is loading/unloading station is ready for unloading operation to become true (scan).

The second one is two workers option. This module scan for condition for state of worker because of unloading operation has been completed before the parts arriving to the loading/unloading operation and only loading operation performing in the next station.



Hold

Name: Waiting For Unloading or Loac

Type: Scan for Condition

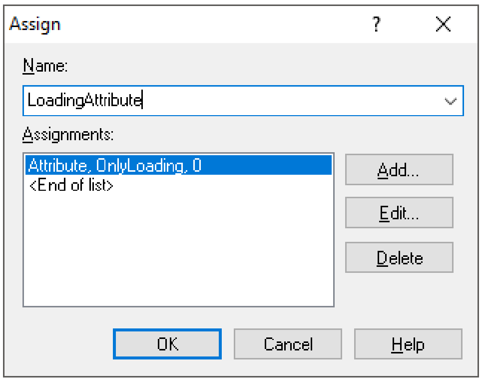
Condition: (SLoadingOccupied == 0) && (STATE(Worker) == IDLE_RE

Queue Type: Queue

Queue Name: Waiting For Unloading or Loac

**Figure 5.27.** Waiting Condition for Unloading/Loading Hold Module

Since the process is done at the same location for the 1 worker option, a binary distinctive value is assigned to identify loading and unloading operation. Figure 5.28 below shows that reassignment of “OnlyLoading” value.


Assign

Name: LoadingAttribute

Assignments:

Attribute, OnlyLoading, 0
<End of list>

**Figure 5.28.** Assignment of Unloading Availability

After completion of unloading operation, number of unloaded parts are counted and unloading tour completion is controlled by decision module then all statistical calculations are made.

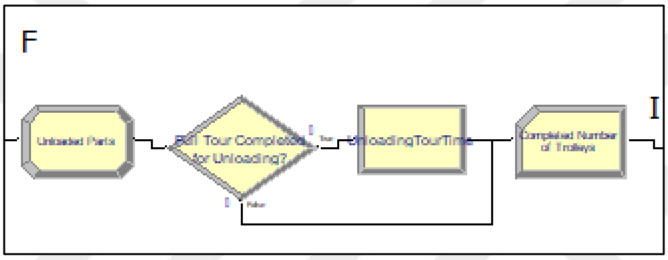
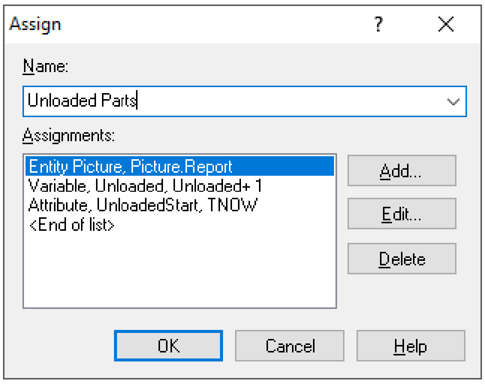


**Figure 5.29.** Unloading Operation Completion Control and Recording Some Statistical Values

Total number of unloaded parts in the system and each unloading operation start time are calculated, that Figure 5.30 is shown below.


Assign

Name: Unloaded Parts

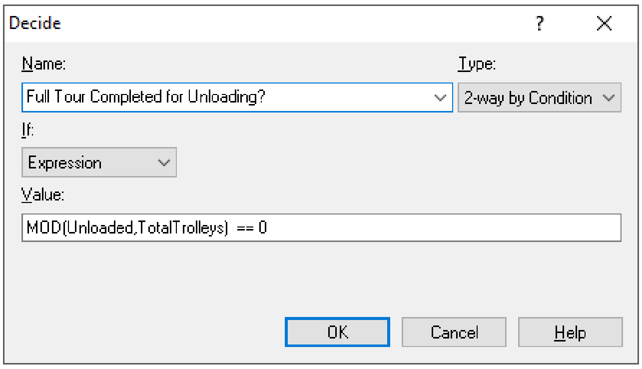
Assignments:

Entity Picture, Picture.Report
Variable, Unloaded, Unloaded+ 1
Attribute, UnloadedStart, TNOW
<End of list>

**Figure 5.30.** Assignment of Unloaded Parts Count and Unloading Start Time Recording

Parts are controlled for the condition whether complete their unloading tour or not. If the parts complete their tour, then system records each tour time between unloading operations and completed number of trolleys to display number of output in the system.

Figure 5.31 shows module details.



Decide

Name: Full Tour Completed for Unloading?

Type: 2-way by Condition

If: Expression

Value: MOD(Unloaded,TotalTrolleys) == 0

**Figure 5.31.** Controlling of Unloading Tour Completion

The trolleys that complete their tours into the system have to remove the parts from the system. Firstly, part type is checked because the number of part loaded in the trolley is different from each other. Then, number of output part types are calculated with assigned variables. Finally, the main product (SD) quantity is calculated with using the output part quantity dividing by the BOM quantity and then the entity is disposed from the system.

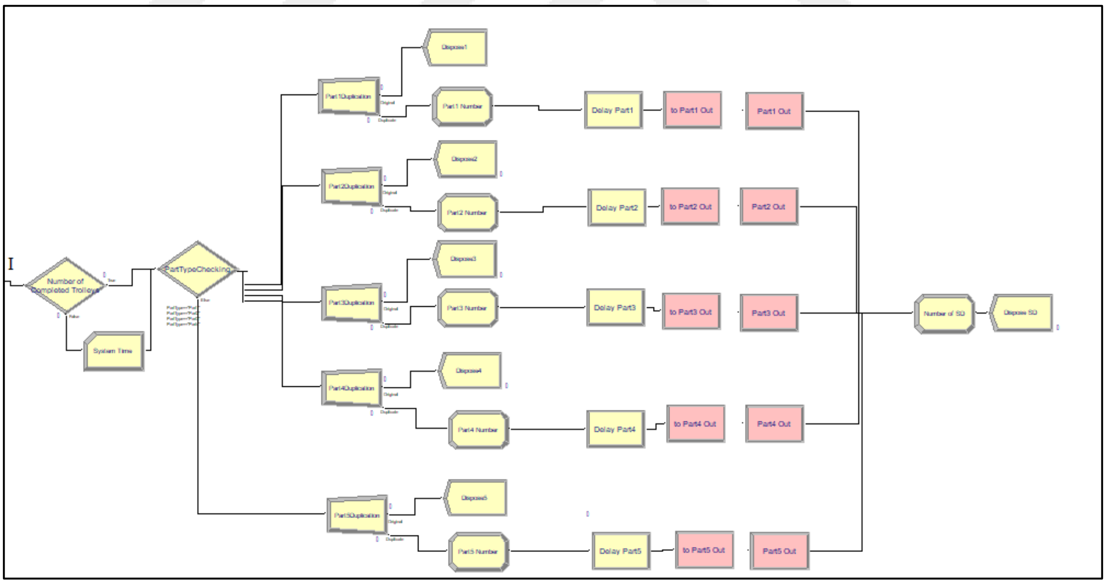


**Figure 5.32.** Calculation of SD and Part Type Quantity

## 5.3. Operations in Stations

The next four sub-models are related with processing of parts in each station. These sub-models describe operation of parts and waiting queue before moving forward to the next station for another processing. The common general structure of the sub-models is shown in Figure 5.33.

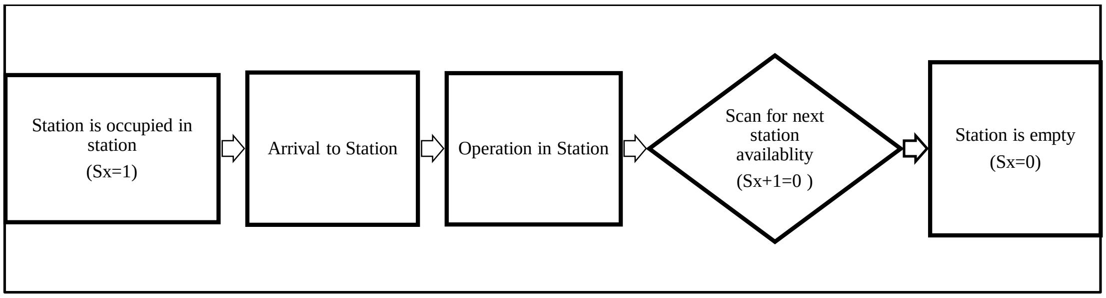


**Figure 5.33.** General Structure of Operations Sub-Models

The ARENA modules inside Sub-Model related to first operation is shown in Figure 5.34.

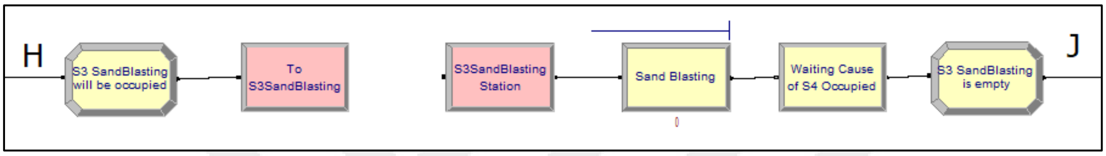
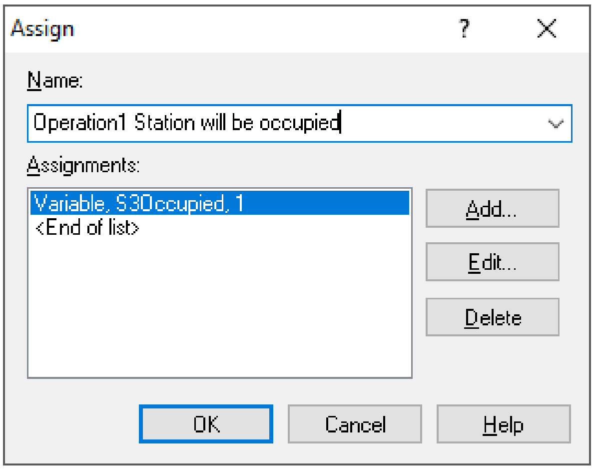


**Figure 5.34.** Display of Operation1 Sub-Model

For the arrived parts, which are ready for being processed, we have to assign a variable for having the operation details whether to see station is occupied or empty. Therefore, we need to identify a binary distinctive feature to perform all sequential operations which is incremented by a part entity when it enters that area and decremented by a part when it leaves the area. Display of assignment is below Figure 5.35.

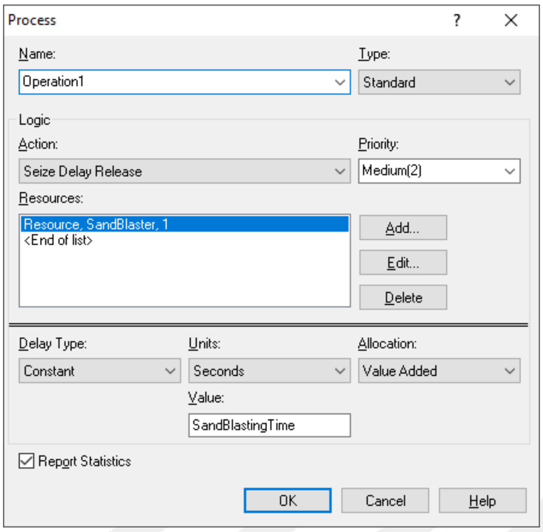


Name:
Operation1 Station will be occupied

Assignments:
Variable, S3Occupied, 1
<End of list>

**Figure 5.35.** Assignment of Operation1 Occupation

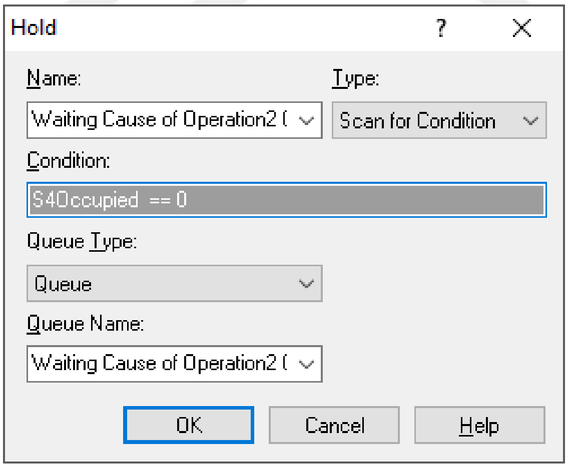
There is a link between excel file and simulation which have operation times of parts. Process module indicates that the machine will be allocated and the delay operation will be performed. The machine is then released after completion of loading operation. Figure 5.36 shows that operation1 process module in the station.



Name: Operation1
Type: Standard
Logic
Action: Seize Delay Release
Priority: Medium(2)
Resources:
Resource, SandBlaster, 1
<End of list>
Delay Type: Constant
Units: Seconds
Allocation: Value Added
Value: SandBlastingTime
☑ Report Statistics

**Figure 5.36.** Operation1 Process Module

Parts are moving forward to be processed sequentially in this layout. All operations will hold the parts in the queue for given condition to be true, the parts wait at the module until the next station queue is available for processing. In this below Figure 5.37 shows that the Hold module condition for next station queue availability.



Name: Waiting Cause of Operation2 (
Type: Scan for Condition
Condition: S4Occupied == 0
Queue Type: Queue
Queue Name: Waiting Cause of Operation2 (

**Figure 5.37.** Operation1 Waiting Condition Hold Module

The parts which are completed their operation leave the module immediately it means the previous station is empty and the next station will be full (condition=1). The flow continues until parts complete all 7 operations and arrive to the last buffer storage area before unloading.

## CHAPTER 6

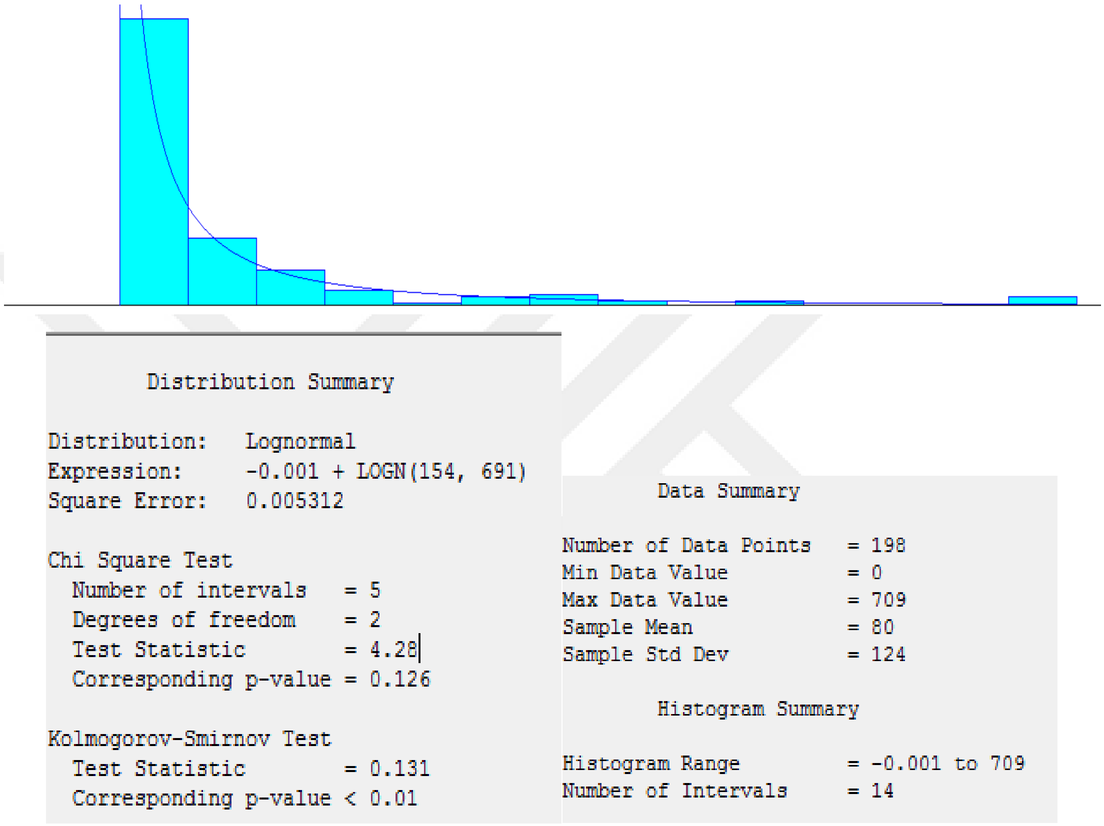
## INPUT ANALYSIS

The machines in the production system are subject to random failures. There is a real set of historical records regarding to occurrence date & time of failures and associated repair times. Time span of data spreads at least three years. Table 6.1 shows sample records from real data.

**Table 6.1.** Sample Failure Records

| Index | Date and Time of the Failure (A) | Time of Recovery (B) | Repair Time (hours) (B-A) | Times Between Failures (hour) $A_{i+1} - A_i$ |
|---|---|---|---|---|
| 1 | 04.04.2013 15:30 | 04.04.2013 17:30 | 2,0 | |
| 2 | 04.06.2013 12:00 | 04.06.2013 14:00 | 2,1 | 829,7 |
| 3 | 06.06.2013 10:30 | 06.06.2013 12:30 | 2,1 | 31,0 |
| | … | … | … | … |
| i | 08.01.2014 10:00 | 08.01.2014 11:00 | 1,0 | 33,7 |
| j | 10.01.2014 07:30 | 10.01.2014 09:00 | 1,5 | 30,3 |
| | 13.01.2014 09:00 | 13.01.2014 09:30 | 0,5 | 33,0 |
| | 14.01.2014 16:00 | 14.01.2014 16:30 | 0,5 | 20,7 |
| | 17.01.2014 17:00 | 17.01.2014 17:30 | 0,5 | 48,7 |
| | … | … | … | … |
| | 12.03.2016 19:30 | 12.03.2014 23:30 | 4,0 | 6,3 |
| | 13.03.2016 10:00 | 13.03.2014 10:30 | 0,5 | 9,7 |
| | … | … | … | … |
| | 14.03.2017 10:00 | 14.03.2014 10:30 | 0,5 | 9,3 |
| | 15.03.2017 12:00 | 15.03.2014 15:30 | 3,5 | 13,3 |

Those records are processed in the context of input analysis. The first analysis is related to “times between failures (uptime)” and second analysis is about repair times (downtime) of the corresponding failures. The “input analysis” tool of ARENA software is used to find the best probability distributions for uptime and downtime statistics. Figure 6.1 and Figure 6.2 shows the details of the analysis and resulting best probability distributions found for uptimes (times between failures) and repair times respectively. Chi-Square tests indicate that both tests statistics and corresponding p-values are in acceptable regions with respect to 95% confidence level, and hence the distributions can be used in the simulation model.



```
        Distribution Summary

Distribution:   Lognormal
Expression:     -0.001 + LOGN(154, 691)
Square Error:   0.005312

Chi Square Test
  Number of intervals   = 5
  Degrees of freedom    = 2
  Test Statistic        = 4.28
  Corresponding p-value = 0.126

Kolmogorov-Smirnov Test
  Test Statistic        = 0.131
  Corresponding p-value < 0.01
```

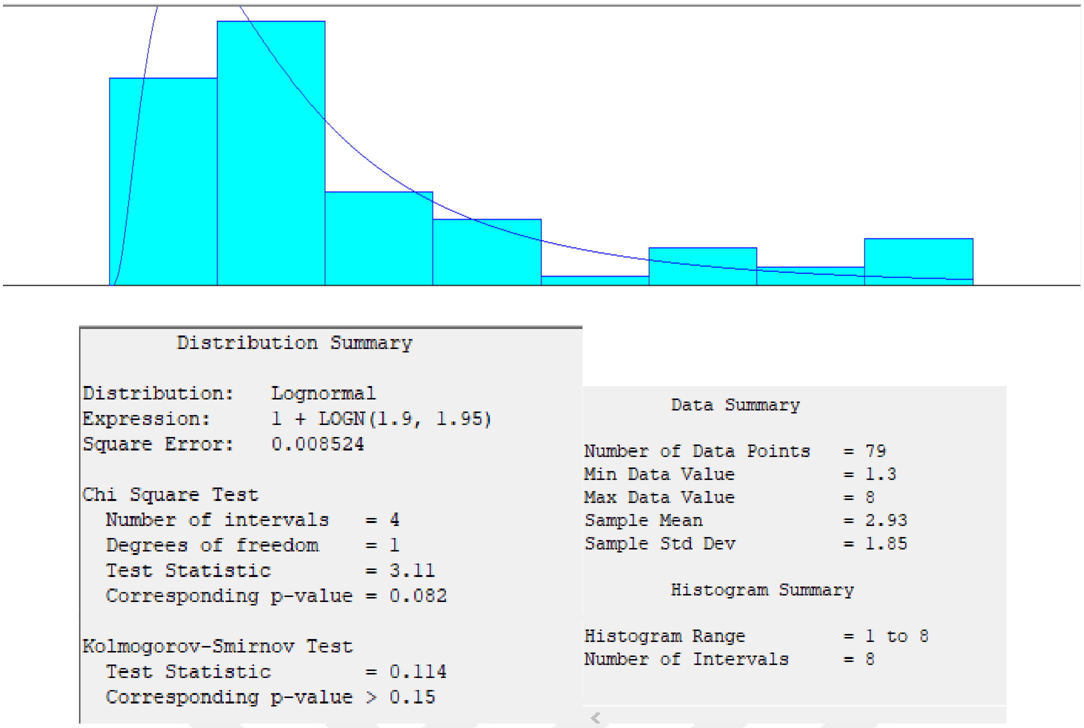
```
        Data Summary

Number of Data Points   = 198
Min Data Value          = 0
Max Data Value          = 709
Sample Mean             = 80
Sample Std Dev          = 124

        Histogram Summary

Histogram Range         = -0.001 to 709
Number of Intervals     = 14
```

**Figure 6.1.** Distribution Fitting for Uptime Data



```
        Distribution Summary

Distribution:   Lognormal
Expression:     1 + LOGN(1.9, 1.95)
Square Error:   0.008524

Chi Square Test
  Number of intervals   = 4
  Degrees of freedom    = 1
  Test Statistic        = 3.11
  Corresponding p-value = 0.082

Kolmogorov-Smirnov Test
  Test Statistic        = 0.114
  Corresponding p-value > 0.15
```

```
        Data Summary

Number of Data Points    = 79
Min Data Value           = 1.3
Max Data Value           = 8
Sample Mean              = 2.93
Sample Std Dev           = 1.85

        Histogram Summary

Histogram Range          = 1 to 8
Number of Intervals      = 8
```

**Figure 6.2.** Distribution Fitting for Downtime Data

# CHAPTER 7
# VERIFICATION & VALIDATION

In simulation studies, verification and validation process should not be underestimated. Without passing verification and validation processes, a simulation model cannot be said credible and reliable. Verification is related to building the model correctly. It is used to compare the computer representation and the conceptual model. The questions are “does the model perform as intended?  Is the model programmed correctly?”

Tests have been conducted using the ARENA software-debugging tool for each sub-module in the process of the model development. Firstly, only a single part is allowed to enter into the system and solitary part flow is observed through the system. The same observations are carried for each other part types. Furthermore, especially the part interactions are investigated carefully. The system tested for many different values of part configurations and processing times. The aim is to create wide variety of different situations where the model logic might fail. A detailed animation model has been developed to accompany the simulation model. It allowed us to track the flow of parts and to view the activities that occurs within the system.

On the other hand, building a correct model is the focus of validation process. It is used to check if the model has accurate representation of the real system. The question is whether the model expresses and accurately reproduces the actions of the real world system.

The outcomes of the simulation model should be compared to the observations on the real system. The real system is observed for a while when a particular configuration of trolley types is on action. Numbers of produced parts of each type are counted during a shift in which no failure is encountered. The corresponding number of end product is calculated.  Then the simulation model had been run for the same configuration. The simulation model concluded the same amount of end product is produced in the same duration of time. Actual and simulated numbers of SD are compared in Table 7.1.

**Table 7.1.** Comparison of Actual System and Simulation Model

|  | Number of Trolleys by Type |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  | Type 1 | Type 2 | Type 3 | Type 4 | Type 5 | Number of Trolleys in Total | Number of SD Produced |
| ACTUAL | 2 | 4 | 2 | 1 | 1 | 10 | 12 |
| SIMULATION | 2 | 4 | 2 | 1 | 1 | 10 | 12 |

# CHAPTER 8

# OUTPUT ANALYSIS

Designing replications, computing and presenting the statistics in graphical or textual format are concern of the output analysis. It focuses on the analysis of simulation results.

In output analysis, first of all it is required to distinguish whether the system terminating or non-terminating. The model under study is currently a terminating simulation since there are two shifts a day and the system starts to work from scratch at the beginning of each day in actual system. However, it may be non-terminating simulation if the facility works in three shifts, i.e., 24 hours a day. In both cases, identifying the “warm-up” period is crucial. Therefore, we begin with detecting the warm-up period of the simulation response.

## 8.1. Warm-Up Period

It is required to decide how long we should run the simulation to identify the point at which the response of the model has reached to steady-state with respect to the performance metric. The performance is measured by the quantity of end-product that can be produced using the parts processed in the system in a given period of time.

The period between the beginning of the simulation and the critical point at which the response of the model attains steady state is called “warm up period”. The response of the system in this period is usually increasing due to the bias imposed by the starting conditions. Besides, the response may fluctuate because of the variations in stochastic inputs. After a sufficiently long time, the response of the model begins to converge a particular value or oscillates regularly around a particular value, and it is said to be in steady state.

Inıtially we assume that a simulation length of 72 days would be sufficiently long to observe steady state of the system. To test the adequacy of our assumption, the simulation of the system was run between 1-100 days for different scenarios. The scenarios correspond to different combinations of trolley types in a particular number of trolleys in total (between 5 and 30). The outcomes are plotted and illustrated in Figure 8.1 and Figure 8.2.

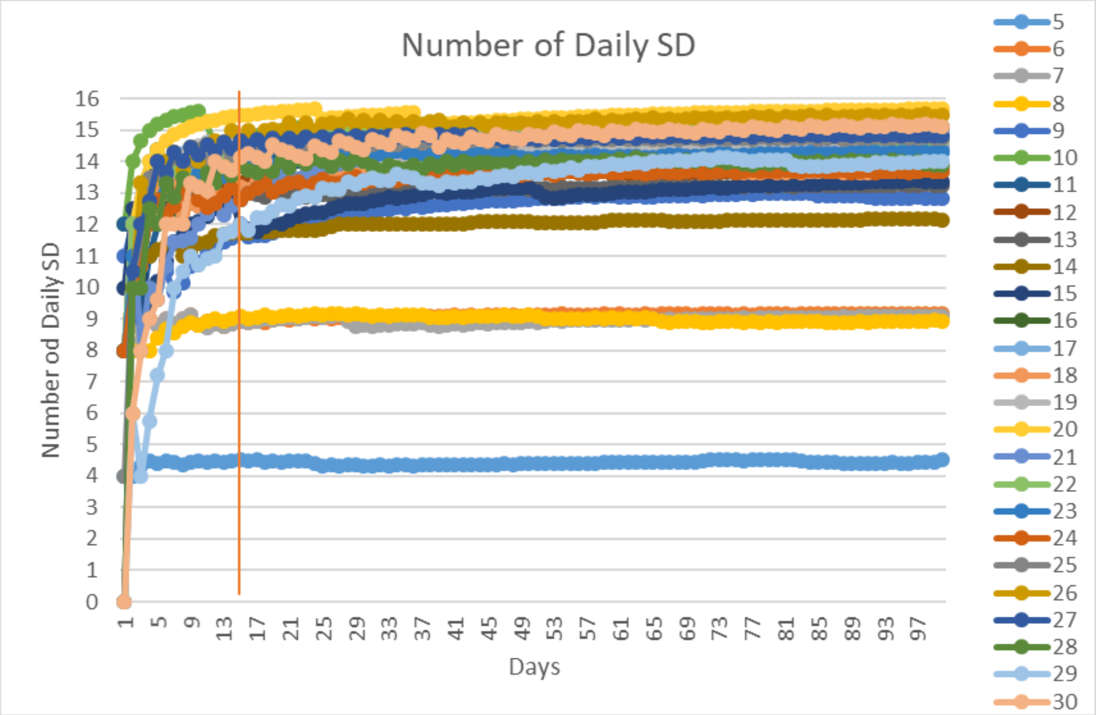


**Figure 8.1.** Number of SD for One Shift-One Worker between 1-100 days

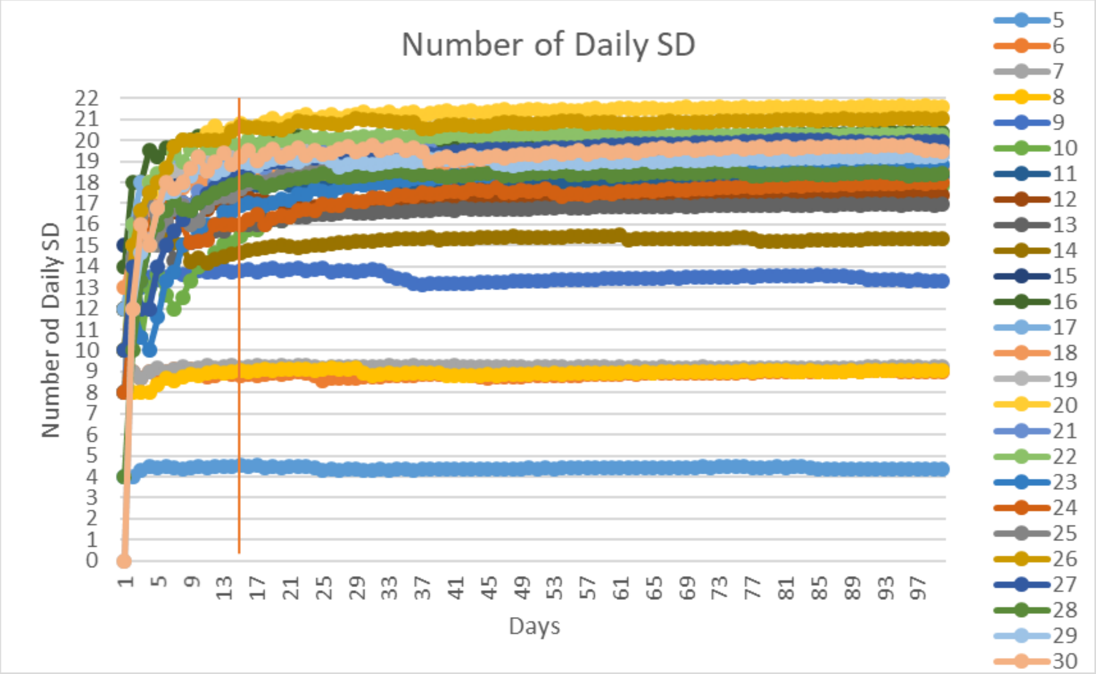


**Figure 8.2.** Number of SD for One Shift-Two Workers between 1-100 days

Outcomes indicate that in the beginning of simulation, until nearly 7 days, the simulation response in increasing trend reflecting the bias of initial conditions. There is some variability between 7 and 14 days, but after day 15, the response seem to be stable. Therefore, our assumption for determining a run length of 72 days is valid.

## 8.2. Output Analysis of Terminating Simulation

For each scenario, the number of replications of the model is set to be 10 initially. Confidence intervals have been established for each scenario based on initial 10 replications.

$$CI = \overline{X(n)} \pm t_{n-1,\ 1-\frac{\alpha}{2}} * \sqrt{\frac{Std^2(n)}{n}}$$

Table 8.1 points out the confidence intervals for the number of SDs for some of the scenarios.

**Table 8.1.** Confidence Intervals for the Number of SDs (n=10)

| Number of Shifts | Number of Worker | Total Num. of Trolley | Distribution of Trolleys (pcs) | | | | | CI for the Number of SDs |
|---|---|---|---|---|---|---|---|---|
| | | | Part 1 | Part 2 | Part 3 | Part 4 | Part 5 | |
| 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | 321,9±5,87 |
| 1 | 1 | 6 | 1 | 2 | 1 | 1 | 1 | 645,4±10,32 |
| 1 | 1 | 7 | 2 | 2 | 1 | 1 | 1 | 656,8±6,81 |
| … | … | … | … | … | … | … | … | … |
| 1 | 1 | 30 | 6 | 12 | 6 | 3 | 3 | 1082,8±9,49 |
| 1 | 2 | 5 | 1 | 1 | 1 | 1 | 1 | 330,7±2,26 |
| 1 | 2 | 6 | 1 | 2 | 1 | 1 | 1 | 662±4,96 |
| 1 | 2 | 7 | 1 | 2 | 2 | 1 | 1 | 653,4±4,82 |
| … | … | … | … | … | … | … | … | … |
| 1 | 2 | 30 | 6 | 12 | 6 | 3 | 3 | 1402,8±22,53 |

As it can be seen on the table, the half-widths of confidence intervals vary depending on the scenarios (configuration of trolleys). In order to standardize the widths of CI, the concept of “relative error” is used. The relative error is defined as the division of half width by the average of CI. (Kelton and Law, 2000). The estimates of relative errors are stated in Table 8.2.

**Table 8.2.** Estimated Relative Errors

| Number of Shifts | Number of Worker | Total Num. of Trolley | Distribution of Trolleys (pcs) | | | | | Relative Error |
|---|---|---|---|---|---|---|---|---|
| | | | Part 1 | Part 2 | Part 3 | Part 4 | Part 5 | |
| 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | % 1,8 |
| 1 | 1 | 6 | 1 | 2 | 1 | 1 | 1 | % 1,6 |
| 1 | 1 | 7 | 2 | 2 | 1 | 1 | 1 | % 1,0 |
| … | … | … | … | … | … | … | … | … |
| 1 | 1 | 30 | 6 | 12 | 6 | 3 | 3 | % 0,9 |
| … | … | … | | | | | | … |
| 2 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | % 0,9 |
| 2 | 1 | 6 | 1 | 2 | 1 | 1 | 1 | % 0,9 |
| 2 | 1 | 7 | 2 | 2 | 1 | 1 | 1 | % 0,9 |
| … | … | … | … | ... | ... | … | … | … |
| 2 | 1 | 30 | 6 | 12 | 6 | 3 | 3 | % 3,6 |
| … | … | … | … | … | … | … | … | … |
| 1 | 2 | 5 | 1 | 1 | 1 | 1 | 1 | % 0,7 |
| 1 | 2 | 6 | 1 | 2 | 1 | 1 | 1 | % 0,7 |
| 1 | 2 | 7 | 1 | 2 | 2 | 1 | 1 | % 0,7 |
| … | … | … | … | … | … | … | … | … |
| 1 | 2 | 30 | 6 | 12 | 6 | 3 | 3 | % 1,6 |
| … | … | … | | | | | | … |
| 2 | 2 | 5 | 1 | 1 | 1 | 1 | 1 | % 0,5 |
| 2 | 2 | 6 | 1 | 2 | 1 | 1 | 1 | % 0,6 |
| 2 | 2 | 7 | 1 | 2 | 2 | 1 | 1 | % 0,7 |
| … | … | … | … | … | … | … | … | … |
| 2 | 2 | 30 | 6 | 12 | 6 | 3 | 3 | % 1,0 |

The highest relative error in that table is observed in the two shifts- 1 worker- 30 trolleys configuration.

## 8.3. Calculation of Required Number of Replications

The estimates of relative errors shown in Table 8.2 calculated from 10 replications. Our intention is to get relative errors as small as % 0.1, so we need to make more replications and therefore it is need to calculate the required number of replications.

Relative error concept has been proposed in Kelton and Law (2000) and implemented in a simulation model by Ozturk (2012). If the estimate $\overline{X(n)}$ is in the formula $\frac{|X(n)-\mu|}{|\mu|} = \delta$ , then it can be said that $\overline{X(n)}$ has relative error of "$\delta$ ". If we conduct many replications of a simulation model until the half-width of the confidence interval divided by $|\, X(n) \,|$ is less than or equal to $\delta$ $(0 < \delta < 1)$. This ratio is an estimate of the actual relative error. Then :

$$
\begin{aligned}
&1-\alpha \approx P\,(\tfrac{|X(n)-\mu|}{|X(n)|} \leq \tfrac{halfwidth}{|X(n)|}) \\
&\leq P\,(|X(n)-\mu| \leq \delta * |X(n)| && (\tfrac{half\ width}{|X(n)|} \leq \delta) \\
&= P\,(|X(n)-\mu| \leq \delta * |X(n)-\mu+\mu|) && \text{(add, subtract } \mu) \\
&\leq P\,((|X(n)-\mu| \leq \delta * (|X(n)-\mu| + |\mu|)) && \text{(triangle equality)} \\
&= P\,((1-\delta) * |X(n)-\mu| \leq \delta * |\mu|)) && \text{(algebra)} \\
&= P\,(\tfrac{|X(n)-\mu|}{|\mu|} \leq \tfrac{\delta}{1-\delta}) && \text{(algebra)}
\end{aligned}
$$

Consequently, the relative error of $\overline{X(n)}$ would be at most $\delta \,/\, (1-\delta)$ with a probability of $1-\alpha$. Rather than desired $\delta$, we get a relative error as $\delta \,/\, (1-\delta)$, since we estimate $|\mu|$ by $|\overline{X(n)}|$

$$
\begin{aligned}
&\frac{|X(n)-\mu|}{|\mu|} && \xrightarrow{\quad estimator \quad} && \frac{halfwidth}{|X(n)|} \\
&\frac{|X(n)-\mu|}{|\mu|} \leq \frac{\delta}{1-\delta} && \xrightarrow{\quad estimator \quad} && \frac{halfwidth}{|X(n)|} \leq \delta \\
&\frac{|X(n)-\mu|}{|\mu|} \leq \delta && \xrightarrow{\quad estimator \quad} && \frac{halfwidth}{|X(n)|} \leq \frac{\delta}{1+\delta} = \delta'
\end{aligned}
$$

$$\text{since } \frac{\delta'}{1-\delta'} = \frac{\frac{\delta}{1+\delta}}{1-\frac{\delta}{1+\delta}} = \frac{\frac{\delta}{1+\delta}}{\frac{1}{1+\delta}} = \delta$$

Using fixed number of replications (n), it has been constructed a confidence interval. We have to obtain relative error of $\delta$ and it is an expression for $n_r(\delta)$ approximate number of replication which is stated by

$$n_r(\delta) = Min\left\{ i \geq n\text{: } \frac{t_{i-1,1-\frac{\alpha}{2}} * \frac{Std(n)}{\sqrt{i}}}{X(n)} \leq \acute{\delta} \right\} \text{ where } \acute{\delta} = \frac{\delta}{1+\delta} \text{ is the adjusted relative error}$$

$nr$ $(\delta)$ is the smallest approximate integer $i$ satisfying $i \geq Std^2(n)\left[\frac{z_{1-\frac{\alpha}{2}}}{\partial' * \acute{X}(n)}\right]^2$

If $n_r(\delta) > n$ and if it is required to make $[n_r(\delta) - n]$ times additional replication in simulation, then the estimate $X(n_r)$ based on all $n_r(\delta)$ replications should have a relative error of approximately $\delta$.

Previously, confidence intervals and estimated relative errors have been calculated with the results of 10 replications. Below example shows the required number of replications calculation of the highest relative error (i.e. 2 workers 1 shift 30 trolleys).

$X(10)$ = 1898.8 (Table 8.1)
$Std(10)$ = 96.57
$\delta$ = 0.001
$\alpha$ = 0.05

$$i \geq Std^2(n)\left[\frac{z_{1-\frac{\alpha}{2}}}{\partial' * \acute{X}(n)}\right]^2 = (96.57)^2\left[\frac{1{,}96}{\frac{0.001}{1+0.001} * 1898.8}\right]^2 \geq \cdots \approx 2484 \text{ replication}$$

It is understood that if additional 2474 replications is done, then desired relative error of 0.001 can be reached for the estimation of $X(2484)$ based on all 2484 replications.

## 8.4. Simulation Outputs with New Number of Replication

Simulation model has been run with recalculated number of replication for each total trolleys configuration with the same run length 72 days. Calculated relative errors are stated below Table 8.3.

**Table 8.3.** Relative Errors after Recalculated Number of Replications

| Number of Shifts | Number of Worker | Total Num. of Trolley | Distribution of Trolleys (pcs) | | | | | Relative Error |
|---|---|---|---|---|---|---|---|---|
| | | | Part 1 | Part 2 | Part 3 | Part 4 | Part 5 | |
| 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | % 0.1 |
| 1 | 1 | 6 | 1 | 2 | 1 | 1 | 1 | % 0.1 |
| 1 | 1 | 7 | 2 | 2 | 1 | 1 | 1 | % 0.2 |
| … | … | … | … | … | … | … | … | … |
| 1 | 1 | 30 | 6 | 12 | 6 | 3 | 3 | % 0.3 |
| … | … | … | | | | | | … |
| 2 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | % 0.2 |
| 2 | 1 | 6 | 1 | 2 | 1 | 1 | 1 | % 0.2 |
| 2 | 1 | 7 | 2 | 2 | 1 | 1 | 1 | % 0.2 |
| … | … | … | … | ... | ... | … | … | … |
| 2 | 1 | 30 | 6 | 12 | 6 | 3 | 3 | % 0.1 |
| … | … | … | … | … | … | … | … | … |
| 1 | 2 | 5 | 1 | 1 | 1 | 1 | 1 | % 0.3 |
| 1 | 2 | 6 | 1 | 2 | 1 | 1 | 1 | % 0.3 |
| 1 | 2 | 7 | 1 | 2 | 2 | 1 | 1 | % 0.4 |
| … | … | … | … | … | … | … | … | … |
| 1 | 2 | 30 | 6 | 12 | 6 | 3 | 3 | % 0.2 |
| … | … | … | | | | | | … |
| 2 | 2 | 5 | 1 | 1 | 1 | 1 | 1 | % 0.3 |
| 2 | 2 | 6 | 1 | 2 | 1 | 1 | 1 | % 0.3 |
| 2 | 2 | 7 | 1 | 2 | 2 | 1 | 1 | % 0.3 |
| … | … | … | … | … | … | … | … | … |
| 2 | 2 | 30 | 6 | 12 | 6 | 3 | 3 | % 0.2 |

It is seen that relative errors are smaller than the initial results when the number of replications is 10. Although the relative errors are around the targeted value % 0.1, there are some calculated relative errors are still greater than % 0.1. The reason of that deviation is due to the assumption of unchanging standard deviation found initially.

However, relative errors are quite small and it is safe to use the outcomes of the model with replication numbers $n_r(\delta)$.

# CHAPTER 9
# DESIGNING SIMULATION EXPERIMENTS

In simulation models, they have many input factors, and determining which ones have a significant impact on performance measures (responses) of interest can be a difficult task. In this study, the step of designing simulation experiment has started with a special approach. The approach was designed to change one factor at a time. Each configuration for all input factors were evaluated and defined as a different scenario. The best configuration was chosen according to the responses. Table 9.1 shows how experiments were made to find effective settings for selected shift and number of worker option.

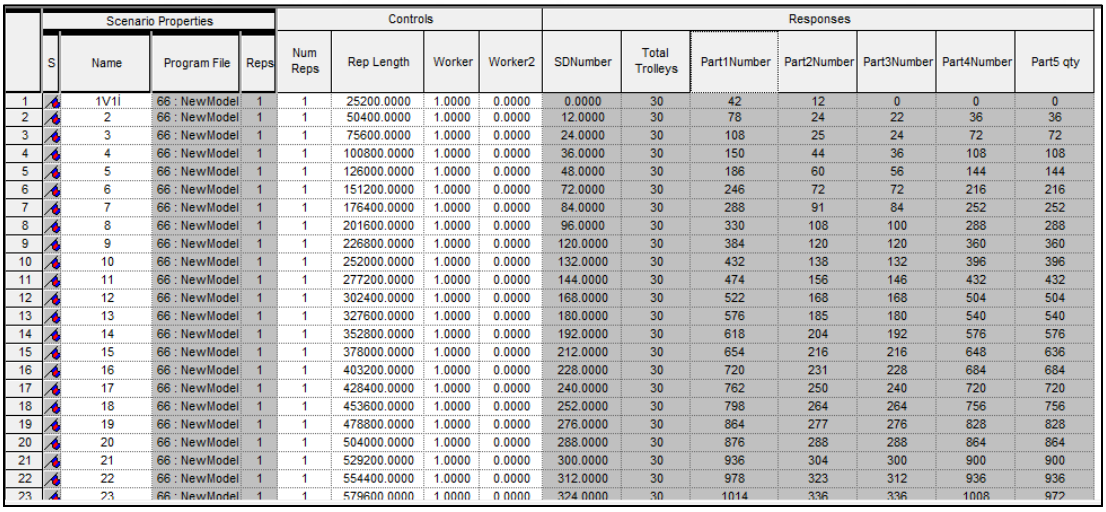
**Table 9.1.** Designing Configuration of Simulation for 72 Days for One Worker & One Shift

| **SCENARIO** | Number of Trolleys In Total | Part1 | Part2 | Part3 | Part4 | Part5 | Avg SD |
|---|---|---|---|---|---|---|---|
| | **5** | **1** | **1** | **1** | **1** | **1** | **322** |
| | 6 | 2 | 1 | 1 | 1 | 1 | 322,3 |
| | **6** | **1** | **2** | **1** | **1** | **1** | **650,2** |
| | 6 | 1 | 1 | 2 | 1 | 1 | 323,5 |
| | 6 | 1 | 1 | 1 | 2 | 1 | 323,10 |
| | 6 | 1 | 1 | 1 | 1 | 2 | 322,90 |
| | **7** | **2** | **2** | **1** | **1** | **1** | **650,60** |
| | 7 | 2 | 1 | 2 | 1 | 1 | 327,20 |
| | 7 | 2 | 1 | 1 | 2 | 1 | 324,80 |
| | 7 | 2 | 1 | 1 | 1 | 2 | 325,30 |
| | 7 | 1 | 2 | 2 | 1 | 1 | 648,90 |
| | 7 | 1 | 2 | 1 | 2 | 1 | 645,80 |
| | 7 | 1 | 2 | 1 | 1 | 2 | 650,50 |
| | 7 | 1 | 1 | 2 | 2 | 1 | 323 |
| | 7 | 1 | 1 | 2 | 1 | 2 | 328,40 |

|  | Number of Trolleys In Total | Part1 | Part2 | Part3 | Part4 | Part5 | Avg SD |
|---|---|---|---|---|---|---|---|
|  | 7 | 3 | 1 | 1 | 1 | 1 | 326 |
|  | 7 | 1 | 3 | 1 | 1 | 1 | 650,40 |
|  | 7 | 1 | 1 | 3 | 1 | 1 | 328,30 |
|  | 7 | 1 | 1 | 1 | 3 | 1 | 328,50 |
|  | 7 | 1 | 1 | 1 | 1 | 3 | 323,20 |

ARENA has a tool called “Process Analyzer” that helps evaluating many scenarios simultaneously. The process analyzer is focused on comparison of models and used under the assumption of the simulation model is completed, validated, and configured appropriately.

The alternatives are called scenarios in Process Analyzer and it is needed to specify input parameters that are called “controls”. Performance metrics are called “responses” for each scenario. Process Analyzer makes enable us to create, run and compare scenarios. Figure 9.1. shows how sample scenarios are evaluated simultaneously.



|  | Scenario Properties |  |  |  | Controls |  |  |  | Responses |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | S | Name | Program File | Reps | Num Reps | Rep Length | Worker | Worker2 | SDNumber | Total Trolleys | Part1Number | Part2Number | Part3Number | Part4Number | Part5 qty |
| 1 |  | 1V1İ | 66 : NewModel | 1 | 1 | 25200.0000 | 1.0000 | 0.0000 | 0.0000 | 30 | 42 | 12 | 0 | 0 | 0 |
| 2 |  | 2 | 66 : NewModel | 1 | 1 | 50400.0000 | 1.0000 | 0.0000 | 12.0000 | 30 | 78 | 24 | 22 | 36 | 36 |
| 3 |  | 3 | 66 : NewModel | 1 | 1 | 75600.0000 | 1.0000 | 0.0000 | 24.0000 | 30 | 108 | 25 | 24 | 72 | 72 |
| 4 |  | 4 | 66 : NewModel | 1 | 1 | 100800.0000 | 1.0000 | 0.0000 | 36.0000 | 30 | 150 | 44 | 36 | 108 | 108 |
| 5 |  | 5 | 66 : NewModel | 1 | 1 | 126000.0000 | 1.0000 | 0.0000 | 48.0000 | 30 | 186 | 60 | 56 | 144 | 144 |
| 6 |  | 6 | 66 : NewModel | 1 | 1 | 151200.0000 | 1.0000 | 0.0000 | 72.0000 | 30 | 246 | 72 | 72 | 216 | 216 |
| 7 |  | 7 | 66 : NewModel | 1 | 1 | 176400.0000 | 1.0000 | 0.0000 | 84.0000 | 30 | 288 | 91 | 84 | 252 | 252 |
| 8 |  | 8 | 66 : NewModel | 1 | 1 | 201600.0000 | 1.0000 | 0.0000 | 96.0000 | 30 | 330 | 108 | 100 | 288 | 288 |
| 9 |  | 9 | 66 : NewModel | 1 | 1 | 226800.0000 | 1.0000 | 0.0000 | 120.0000 | 30 | 384 | 120 | 120 | 360 | 360 |
| 10 |  | 10 | 66 : NewModel | 1 | 1 | 252000.0000 | 1.0000 | 0.0000 | 132.0000 | 30 | 432 | 138 | 132 | 396 | 396 |
| 11 |  | 11 | 66 : NewModel | 1 | 1 | 277200.0000 | 1.0000 | 0.0000 | 144.0000 | 30 | 474 | 156 | 146 | 432 | 432 |
| 12 |  | 12 | 66 : NewModel | 1 | 1 | 302400.0000 | 1.0000 | 0.0000 | 168.0000 | 30 | 522 | 168 | 168 | 504 | 504 |
| 13 |  | 13 | 66 : NewModel | 1 | 1 | 327600.0000 | 1.0000 | 0.0000 | 180.0000 | 30 | 576 | 185 | 180 | 540 | 540 |
| 14 |  | 14 | 66 : NewModel | 1 | 1 | 352800.0000 | 1.0000 | 0.0000 | 192.0000 | 30 | 618 | 204 | 192 | 576 | 576 |
| 15 |  | 15 | 66 : NewModel | 1 | 1 | 378000.0000 | 1.0000 | 0.0000 | 212.0000 | 30 | 654 | 216 | 216 | 648 | 636 |
| 16 |  | 16 | 66 : NewModel | 1 | 1 | 403200.0000 | 1.0000 | 0.0000 | 228.0000 | 30 | 720 | 231 | 228 | 684 | 684 |
| 17 |  | 17 | 66 : NewModel | 1 | 1 | 428400.0000 | 1.0000 | 0.0000 | 240.0000 | 30 | 762 | 250 | 240 | 720 | 720 |
| 18 |  | 18 | 66 : NewModel | 1 | 1 | 453600.0000 | 1.0000 | 0.0000 | 252.0000 | 30 | 798 | 264 | 264 | 756 | 756 |
| 19 |  | 19 | 66 : NewModel | 1 | 1 | 478800.0000 | 1.0000 | 0.0000 | 276.0000 | 30 | 864 | 277 | 276 | 828 | 828 |
| 20 |  | 20 | 66 : NewModel | 1 | 1 | 504000.0000 | 1.0000 | 0.0000 | 288.0000 | 30 | 876 | 288 | 288 | 864 | 864 |
| 21 |  | 21 | 66 : NewModel | 1 | 1 | 529200.0000 | 1.0000 | 0.0000 | 300.0000 | 30 | 936 | 304 | 300 | 900 | 900 |
| 22 |  | 22 | 66 : NewModel | 1 | 1 | 554400.0000 | 1.0000 | 0.0000 | 312.0000 | 30 | 978 | 323 | 312 | 936 | 936 |
| 23 |  | 23 | 66 : NewModel | 1 | 1 | 579600.0000 | 1.0000 | 0.0000 | 324.0000 | 30 | 1014 | 336 | 336 | 1008 | 972 |

**Figure 9.1.** Process Analyzer Example

# CHAPTER 10
# RESULTS AND DISCUSSION

## 10.1. Simulation Outcomes

Average number of SD that can be produced using the parts processed in the system in 72 days' period in the simulation model is our performance measure. Figure 9.1 and Figure 9.2 show the average number of SDs in scenarios.

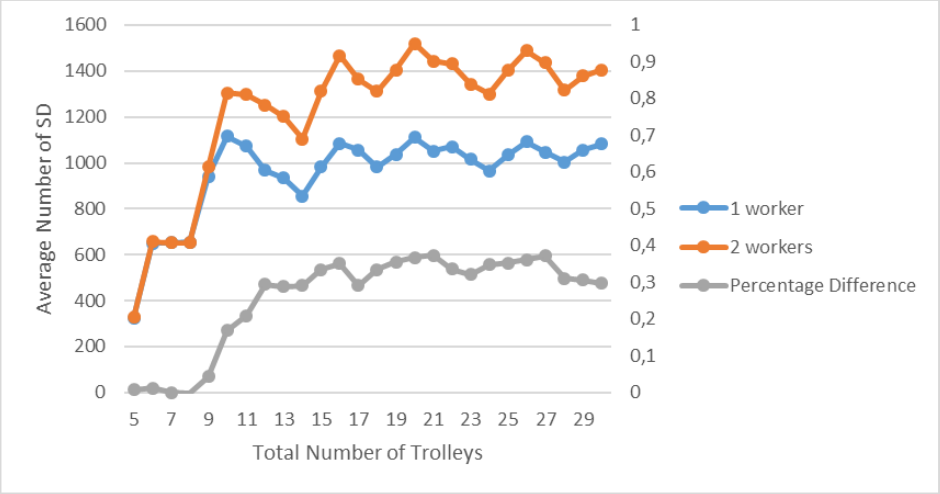


**Figure 10.1.** Average Number of SD for One Shift 5-30 Trolleys

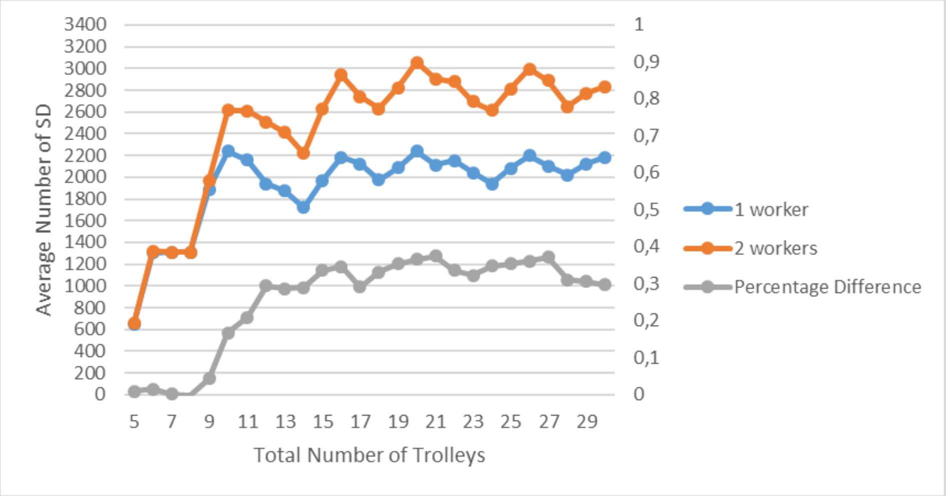


**Figure 10.2.** Average Number of SD for Two Shifts 5-30 Trolleys

The values that are shown in the Figures indicate the average number of produced SDs in 72 days' length. Additionally, percentage difference has been calculated between the number of output for each worker. It is shown in Table 9.1 that two workers option can help to increase output number average 25%.

**Table 10.1.** Max Number of SDs Produced in Different Scenarios

| Shift | Worker | Max Number of SDs Produced (in 72 Days) | Number of Trolleys | Distribution of Trolleys (pcs) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Part 1 | Part 2 | Part 3 | Part 4 | Part 5 |
| 1 | 1 | 1116 | 10 | 2 | 4 | 2 | 1 | 1 |
| 1 | 2 | 1519 | 20 | 4 | 8 | 4 | 2 | 2 |
| 2 | 1 | 2240 | 10 | 2 | 4 | 2 | 1 | 1 |
| 2 | 2 | 3055 | 20 | 4 | 8 | 4 | 2 | 2 |

The simulation of manufacturing system has been run after the recalculated number of replications then construction of confidence intervals and calculation of relative errors have been done for performance measure. Table 9.2 shows the summary of outputs about the average number of SD.

**Table 10.2.** Comparison of Outputs

| Shifts | Worker | Trolleys | Old Number of Replication | | | | New Number of Replication | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | N | Avg. | Half Width | Relative Error | N | Avg. | Half Width | Relative Error |
| 1 | 1 | 5 | 10 | 321,9 | 5,8 | % 1,82 | 634 | 325,1 | 0,38 | % 0,1 |
| 1 | 1 | 6 | 10 | 645,4 | 10,3 | % 1,60 | 490 | 648,9 | 0,85 | % 0,1 |
| 1 | 1 | 7 | 10 | 656,8 | 6,8 | % 1,04 | 212 | 652,9 | 1,51 | % 0,2 |
| … | … | | … | … | … | … | … | … | … | … |
| 1 | 1 | 30 | 10 | 1082,8 | 9,4 | % 0,88 | 154 | 1082,6 | 3,17 | % 0,3 |
| … | … | | … | … | … | … | … | … | … | … |
| 2 | 1 | 5 | 10 | 651,1 | 5,7 | % 0,88 | 154 | 651,5 | 1,15 | % 0,2 |
| 2 | 1 | 6 | 10 | 1298,4 | 12 | % 0,92 | 170 | 1303,2 | 2,09 | % 0,2 |
| 2 | 1 | 7 | 10 | 1313 | 11,2 | % 0,86 | 148 | 1310,2 | 2,72 | % 0,2 |
| … | … | | … | … | … | … | … | … | … | … |
| 2 | 1 | 30 | 10 | 1898,8 | 69,8 | % 3,64 | 2494 | 2181,8 | 1,13 | % 0,1 |
| … | … | | … | … | … | … | … | … | … | … |
| 1 | 2 | 5 | 10 | 330,7 | 2,3 | % 0,68 | 98 | 327,8 | 0,96 | % 0,3 |

**Table 10.2.** Comparison of Outputs (continued)

| Shifts | Worker | Trolleys | Old Number of Replication | | | | New Number of Replication | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | N | Avg. | Half Width | Relative Error | N | Avg. | Half Width | Relative Error |
| 1 | 2 | 6 | 10 | 662 | 4,9 | % 0,75 | 115 | 656,6 | 2,12 | % 0,3 |
| 1 | 2 | 7 | 10 | 653,4 | 4,8 | % 0,74 | 112 | 653,4 | 2,42 | % 0,4 |
| … | … | | … | … | … | … | … | … | … | … |
| 1 | 2 | 30 | 10 | 1402,8 | 22,5 | % 1,61 | 494 | 1404,8 | 2,19 | % 0,2 |
| … | … | | … | … | … | … | … | … | … | … |
| 2 | 2 | 5 | 10 | 661 | 3,5 | % 0,53 | 63 | 657,3 | 1,69 | % 0,3 |
| 2 | 2 | 6 | 10 | 1326,4 | 8,5 | % 0,64 | 88 | 1322,5 | 3,85 | % 0,3 |
| 2 | 2 | 7 | 10 | 1311,7 | 8,7 | % 0,67 | 94 | 1312,6 | 3,7 | % 0,3 |
| … | … | | … | … | … | … | … | … | … | … |
| 2 | 2 | 30 | 10 | 2830 | 28,7 | % 1,01 | 203 | 2831,4 | 5,47 | % 0,2 |

It is obvious that half-widths are all much smaller and relative errors highest value in table is % 0.5.

## 10.2. Tools for Optimization via Simulation

Study area of optimization via simulation models deals with finding possible sets of model specifications lead to optimal performance metrics. ARENA software has a tool for optimization by automating the search for an optimal strategy, which is called “OptQuest”. This linear combination procedure, suggested in connection with the scatter search methodology, is more general than the so-called “linear, arithmetical, average or intermediate” crossover in the genetic algorithm literature. (April, 2003). In this study, OptQuest is used to find the best scenario in our problem environment. Table 9.3, Table 9.4, Table 9.5 and Table 9.6 show the comparisons of best scenarios proposed by OptQuest and actual simulation outcomes.

**Table 10.3.** Best Scenarios - Comparisons OptQuest & Simulation Outputs- One Shift & One Worker

| Simulation Outputs | | | | | | | OptQuest Outputs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Part1** | **Part2** | **Part3** | **Part4** | **Part5** | **Total Trolley** | **SD** | **Part1** | **Part2** | **Part3** | **Part4** | **Part5** | **Total Trolley** | **SD** |
| 2 | 4 | 2 | 1 | 1 | 10 | 1116 | 5 | 10 | 5 | 3 | 3 | 26 | 1102 |
| 4 | 8 | 4 | 2 | 2 | 20 | 1110 | 5 | 10 | 5 | 3 | 4 | 27 | 1094 |
| 5 | 10 | 5 | 3 | 3 | 26 | 1092 | 6 | 12 | 6 | 3 | 3 | 30 | 1092 |
| 3 | 6 | 3 | 2 | 2 | 16 | 1085 | 5 | 10 | 6 | 3 | 3 | 27 | 1088 |
| 6 | 12 | 6 | 3 | 3 | 30 | 1082 | 5 | 9 | 5 | 3 | 3 | 25 | 1086 |

OptQuest recommends that the best configuration would be attained by using 26 trolleys in total. The numbers of trolley types should be 5, 10, 5, 3 and 3 respectively. Corresponding number of SDs that can be produced is 1102. On the other hand, actual simulation experiments recommend a different solution as the best configuration. It states that it is the best to use 10 trolleys in total with the numbers of trolley types as 4, 2, 2, 1 and 1 respectively. Corresponding number of SDs would be 1116. The mismatch between the results of OptQuest and actual simulation experiments has been investigated. First, the best configuration (2-4-2-1-1) recommended by simulation experiment has been checked and confirmed in the simulation model. Then the same configuration is forced in QptQuest to be considered and it is found that resulting number of SDs is 1110. It seems that QptQuest may miss some competent alternative solutions as seen this example, and therefore it is better to be cautious when using it. However, for other environments whose comparisons are given in the following tables, the configuration recommendations of both simulation outcomes and Optquest are compatible with each other although the numbers of SDs are different.

**Table 10.4.** Best Scenarios - Comparisons OptQuest & Simulation Outputs -One Shift & Two Workers

| Simulation Outputs | | | | | | | OptQuest Outputs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Part1** | **Part2** | **Part3** | **Part4** | **Part5** | **Total Trolley** | **SD** | **Part1** | **Part2** | **Part3** | **Part4** | **Part5** | **Total Trolley** | **SD** |
| 4 | 8 | 4 | 2 | 2 | 20 | 1519 | 4 | 8 | 4 | 2 | 2 | 20 | 1465 |
| 5 | 10 | 5 | 3 | 3 | 26 | 1487 | 4 | 8 | 4 | 2 | 3 | 21 | 1444 |
| 3 | 6 | 3 | 2 | 2 | 16 | 1466 | 4 | 8 | 4 | 5 | 2 | 23 | 1438 |
| 4 | 9 | 4 | 2 | 2 | 21 | 1442 | 4 | 8 | 4 | 3 | 2 | 21 | 1437 |
| 5 | 10 | 6 | 3 | 3 | 27 | 1436 | 4 | 8 | 4 | 3 | 3 | 22 | 1433 |

**Table 10.5.** Best Scenarios - Comparisons OptQuest & Simulation Outputs Two Shifts & One Worker

| Simulation Outputs | | | | | | | OptQuest Outputs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Part1 | Part2 | Part3 | Part4 | Part5 | Total Trolley | SD | Part1 | Part2 | Part3 | Part4 | Part5 | Total Trolley | SD |
| 2 | 4 | 2 | 1 | 1 | 10 | 2240 | 2 | 4 | 2 | 1 | 1 | 10 | 2196 |
| 4 | 8 | 4 | 2 | 2 | 20 | 2238 | 2 | 4 | 2 | 1 | 2 | 11 | 2192 |
| 5 | 10 | 5 | 3 | 3 | 26 | 2199 | 2 | 4 | 2 | 2 | 1 | 11 | 2192 |
| 3 | 6 | 3 | 2 | 2 | 16 | 2184 | 3 | 6 | 3 | 3 | 2 | 17 | 2178 |
| 6 | 12 | 6 | 3 | 3 | 30 | 2182 | 4 | 8 | 4 | 4 | 3 | 23 | 2176 |

**Table 10.6.** Best Scenarios - Comparisons OptQuest & Simulation Outputs Two Shifts & Two Workers

| Simulation Outputs | | | | | | | OptQuest Outputs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Part1 | Part2 | Part3 | Part4 | Part5 | Total Trolley | SD | Part1 | Part2 | Part3 | Part4 | Part5 | Total Trolley | SD |
| 4 | 8 | 4 | 2 | 2 | 20 | 3055 | 4 | 8 | 4 | 2 | 2 | 20 | 2937 |
| 5 | 10 | 5 | 3 | 3 | 26 | 2996 | 5 | 10 | 5 | 3 | 3 | 26 | 2916 |
| 3 | 6 | 3 | 2 | 2 | 16 | 2942 | 4 | 8 | 4 | 2 | 3 | 21 | 2892 |
| 4 | 9 | 4 | 2 | 2 | 21 | 2906 | 4 | 8 | 4 | 3 | 2 | 21 | 2881 |
| 5 | 10 | 6 | 3 | 3 | 27 | 2887 | 5 | 10 | 5 | 3 | 4 | 27 | 2880 |

## 10.3. Discussion and Recommendation

Simulation model was run for 72 days for all scenarios to collect accurate data. Actually, company focuses on to see daily max SD quantity for different shifts and worker’s configurations. Therefore, the outcomes were scaled down to show performance metrics indicating daily estimates.  Table 10.7 shows daily estimates of performance metrics.

**Table 10.7.** The Best Configuration of Output SD in Daily Basis

| **Simulation Outputs** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Shift** | **Worker** | **Part1** | **Part2** | **Part3** | **Part4** | **Part5** | **Total Trolley** | **Daily SD** |
| 1 | 1 | 2 | 4 | 2 | 1 | 1 | 10 | 15 |
| 1 | 2 | 4 | 8 | 4 | 2 | 2 | 20 | 21 |
| 2 | 1 | 2 | 4 | 2 | 1 | 1 | 10 | 31 |
| 2 | 2 | 4 | 8 | 4 | 2 | 2 | 20 | 42 |

Currently company is producing 12 SD in daily basis but under increasing demand, they are trying to solve the capacity issue of metallization line to meet customer needs. They are changing their shifts or number of workers to produce SD according to customer demand manually without any systematical analysis. This analysis will help them to see all production options for changing needs.

Their goal is able to produce 30 SD daily with increasing demands of customers for next year and they wonder to see whether can reach to these capacity to meet demands. Using the outcomes of simulation, it seems that they can reach to these capacity for using two shifts-one worker option Additionally, this study also helps them to see they have capacity to produce 42 SD per day under two workers-two shifts option without any investment in case of a %25 increase in customer demand.

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