

## MASTER

### Development of a simulation environment for modelling multiple factory automation setups

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Department of Industrial Engineering and Innovation sciences  
Operations Management and Logistics - Manufacturing Systems Engineering Track



# Development of a simulation environment for modelling multiple factory automation setups

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**Graduation project** Master thesis report

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# Abstract

This masters thesis document describes the process involved in the design and development of a simulation environment. This environment serves as a platform for modelling systems similar to the factory automation systems (referred to as FAS from here on) supplied by ASMPT to its customers. The developed platform aims to serve as a means for testing different manufacturing setups and make iterative changes to them in order to reach the optimal option. The environment also eliminates the need for setting up an actual physical model for testing, which otherwise would prove to be a very expensive proposition. The simulation environment is developed on the commercial simulation modelling platform, Flexsim. Different layouts for the same test case are designed and tested on the tool and the results are compared on a number of key system performance metrics. The environment requires minimal user intervention, owed to the background logic that automates model inputs and eliminates the need for ground up modelling for every case scenario. The environment is designed by first an investigation into the simulation modelling methodology. Then, the actual physical FAS is analysed and key system parameters are identified. Then, the conceptual model for the tool is produced, which serves as an inspiration for the simulation modelling procedure that follows. Testing and validation of the resulting simulation environment is then carried out by modelling several different test cases. These different test cases are based on varied AGV configurations. The two broad categories modelled and tested on the simulation environment are *traditional and tandem configurations*. Based on the performance metrics, traditional layouts are deduced to be working better than their tandem counterparts for the given system configuration. However, it is also concluded that a more complex and larger system could be better suited to a tandem layout.

# Acknowledgments

This masters thesis marks the end of my tenure as a graduate student of the Industrial Engineering and Innovation Sciences faculty at the Eindhoven University of Technology. My master in Operations Management and Logistics has been a challenging, yet enriching adventure. Moving away from my hometown in India and migrating to another continent proved to be a big change for me and something that I had always been looking forward to. Living in a different country, miles away from the only people you have known all your life and making new friends, seemed like a daunting task at first. However, the international as well as the dutch community I got acquainted with during my time here never really made me miss home as much as I thought I would. The masters in itself was quite demanding from the get go, with all the courses providing interesting challenges in the form of group projects and weekly assignments. Although, the extra emphasis on the application of the course learnings in real life case scenarios and problems, is something that I enjoyed the most and that prepared me well for the challenges of a masters thesis project. The thesis project is pursued at ASM Pacific Technology's Centre of Competency located in Beuningen.

The thesis project proved to be tricky in the beginning due to a number of unknowns and assumptions that had to be made for the development of the solution. This provided a great challenge but also proved to be really enjoyable at the same time as it tested my abilities to think outside of my comfort zone. I would like to thank ASM Pacific Technology for providing me with the opportunity for pursuing my graduation thesis project at their premises. Moreover, I would like to thank my initial supervisor, Ard Willems for introducing me to the company and this project as well as his support for almost the entire duration of the project. I would also like to thanks Guido knippels and Robin van Es for successfully seeing out my project post Ard's departure from the company. All their critical feedback during the thesis documentation phase is highly appreciated. Special thanks for Robin for always being available, be it day or night and being more of a friend than a superior.

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Akshay Pundir  
Eindhoven, January 2020

# Executive summary

## Introduction

This report is a product of a research performed at ASMPT's Centre of Competency located in Beuningen. This masters thesis project comes under the software research group, which is one of the three research groups under the Centre of Competency. The Centre of Competency is responsible for conducting research projects, with ASMPT being their end customer. One of the main issues identified by ASMPT is regarding the testing of the FAS produced by them. This problem forms the theme of this project, where an investigation is done into the area of simulation modelling to *develop a simulation environment for the modelling of the FAS*, similar to the physical setups manufactured by ASMPT.

## Research methodology

The research methodology begins with systematic literature review in the areas of *Simulation modelling and AGV configurations*. This is followed by a detailed investigation into the actual physical FAS, the material flow through the machines and the system parameters associated with the components of the FAS (like the machines, the AGVs, materials and the system input as well as output towers). Conceptual design modelling follows, which is an essential pre-requisite for the design of the simulation environment. The developed simulation environment is then used to model a variety of test cases. A number of different guide path layouts are drafted for a particular test case and compared based on key system performance metrics. The research concludes with a discussion on the validation and verification of the developed simulation environment.

## Results

The key deliverable of this research is the simulation environment, which can be used to model multiple FAS, similar to the ones manufactured by ASMPT. A lot schedule is considered as a test case and tested on the simulation environment. Three different guide path layouts, resembling traditional AGV configurations (as seen in Figures 1, 2 and 3), are developed and compared based on several key performance metrics. These include the makespan of the system (i.e., the time taken to execute the entire lot) as well as utilisation statistics of the AGVs involved. The resulting analysis indicates that the layout with exit lanes, which provides the freedom to the AGVs to take a shorter route back before performing their next operation, has a significantly lower makespan as compared to the other two. Although the utilisation statistic seem to indicate a possible downside to it, with very high utilisation rates for the AGVs in the case of the layout with the exit lanes. This is followed by an investigation into tandem configurations, which are one of the more recent guide path layouts used in MHS design. Another guide path layout is built based on the same lot schedule, which is inspired by a tandem configuration (as seen in Figure 4). The layout is compared with the other traditional options based on the same performance metrics. The developed tandem layout performs worse than its traditional counterparts (as seen in Figure 5). Although, it is also concluded that the system performance of the tandem based layout will

only improve as the system increases in its size and complexity. This concludes the testing phase and indicates that any layout can be developed and tested on the simulation environment.

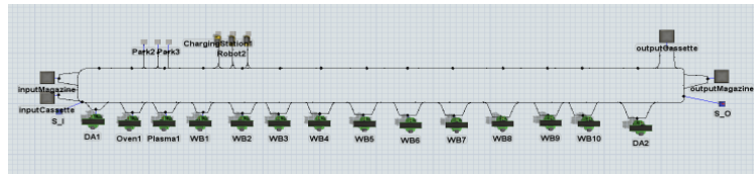


Figure 1: Guide path layout (Option 1)

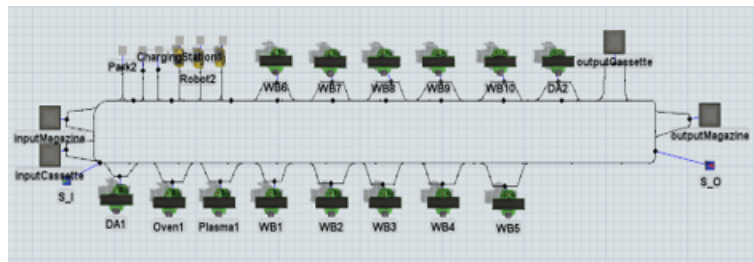


Figure 2: Guide path layout (Option 2)



Figure 3: Guide path layout (Option 3)

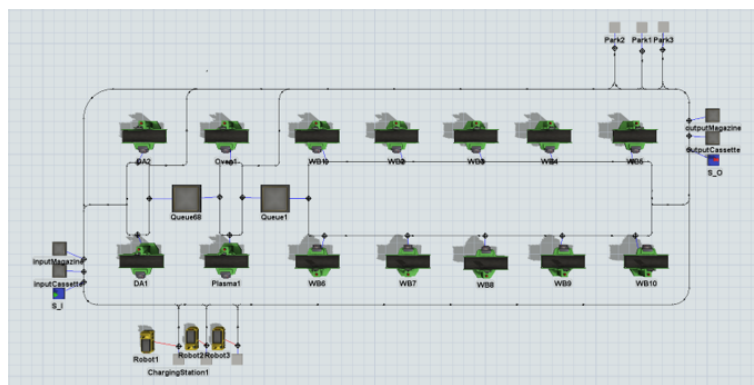


Figure 4: Tandem layout

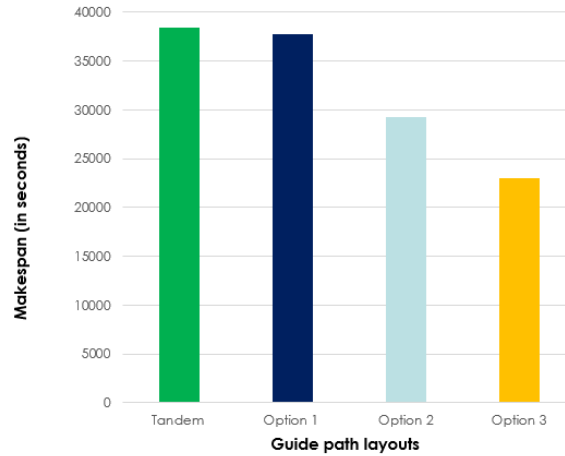


Figure 5: Traditional v/s Tandem (makespan comparison)

## Conclusions and future steps

The research questions established in the beginning of this project are looked back upon and it is concluded that most of them are answered via the developed solution. The system components as well as the AGVs are sufficiently reflected, although further detailing regarding their external appearance could not to be pursued, owed to the limited time frame of this research. Hence, that forms one of the future steps for this research. A number of guide path layouts are designed and evaluated with ease, which indicates that the simulation environment can be used without the need for any pre-knowledge on Flexsim. Dynamic scheduling, which is the ability of the simulation environment to communicate with an external control system and update its inputs in case of exceptions in the system, is also included as one of the future steps for this research. These exceptions can be classified as machine breakdowns, AGV collisions or blockages and material shortages. A further investigation into the area of dynamic scheduling and its implementation onto the simulation environment would greatly aid the objective of making the simulation model as close to reality as possible.

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# List of Abbreviations

1. AGV - Automated Guided Vehicle
2. ASMPT - Advanced Semiconductor Materials Pacific Technology
3. DA AOI - Die Attach Advanced Optical Inspection
4. WIP - Work In Progress
5. WB AOI - Wire Bonder Advanced Optical Inspection
6. FIFO - First In First Out
7. FILO - First In Last Out
8. DE - Discrete Event
9. AB - Agent Based
10. SD - System Dynamics
11. DS - Dynamic Systems
12. ABS - Agent based simulation
13. DES - Discrete event simulation
14. FMS - Flexible manufacturing systems
15. MHS - Material handling systems
16. SMT - Surface mount technologies
17. FAS - Factory automation system
18. MTTF - Mean time to failure
19. MTBF - Mean time between failures

# Chapter 1

## Introduction

Manufacturing excellence has become essential to gain leadership and competitive edge in recent years. Some of the challenges faced by most of the manufacturing industries are the reduction of production costs, continuous improvement of the product quality and shortening the production lead time of the line to deliver a higher throughput[5]. Automated production lines have been the answer to the suggested challenges in more ways than one. With the implementation of automation in an existing production line, a manufacturer can not only reap the benefits of higher production rates, increased productivity, more efficient use of materials, better product quality, improved safety and shorter production lead times, but also improves the line flexibility [6]. Flexibility in an automated production line enables widening of the range of products that can be produced on the line without entirely replacing the stock of the machinery. Flexibility also induces the ability to move with customer needs, respond to competitive pressures and be closer to the market needs [7].

With all the pros of such an efficient system, there are certain cons that need to be addressed as well, in order to make the system as reliable as possible. Although a flexible manufacturing system does provide the manufacturer with considerable manufacturing prowess in terms of the higher productivity and ability to respond to the ever changing market demands, it also induces a risk of failure in the system [8]. Components of a typical factory automation setup (referred to as FAS from here on), like the workstations and robots, are quite prone to failures, which can highly influence the performance of the line. When a machine enters a failure status, the number of parts in the upstream buffer tends to increase, while the downstream buffer slowly gets exhausted. If this status persists, the upstream buffer may become full and as a consequence, block the upstream machine(s), which can negatively impact the rate of production. Similarly, the downstream buffer might get empty, which might lead to the downstream machine(s) to get starved as a consequence [9]. Breakdowns of robots and/or the Automated Guided Vehicles (referred to as AGVs from here on) can have similar effects on the system, leading to possible production down-times or lowered production rates. Variability in the process parameters is another one of the important factors to be considered while modelling a factory automated setup. Variability is often used to represent the stochastic effect in a manufacturing system. The most common sources of variability in manufacturing setups are events like machine breakdowns, reworks, batching, product mixes, operator availability and fluctuation in process times and arrival intervals. It is essential for the system variability to be reduced, to improve the system service levels [10].

The goal of this research stems from the challenges offered by an FAS. This research looks into the possibility of capturing the physical FAS in such a way that it eliminates the needs for continuous experimentation with the actual physical hardware.

## 1.1 Company Background

ASMPT (or ASM Pacific Technology), founded in 1975, is the market leader in the manufacturing of equipment for all major steps in the electronics manufacturing process - from carrier for chip interconnection to chip assembly and packaging to Smart machine technologies (referred to as SMT from here on).

The ASM Center of Competency (CoC) is located in Beuningen, the Netherlands, and is responsible for identifying new high-tech innovation opportunities for the full global ASMPT product portfolio. Their product portfolio covers the complete back-end section of the semiconductor equipment market. Moreover, the company offers comprehensive assembly and advanced packaging solutions for its customers in the fields of optoelectronics, electronics, solar energy, automotive and other segments.

In their past year's annual report, ASMPT has identified Industry 4.0 as one of their main focuses going forward as a smart solutions provider. ASMPT has plans to turn into smart digital enterprise, transitioning from their role solely as a hardware machinery supplier to incorporating software solutions in their portfolio as well. This is where this research becomes one of a bigger significance as the research goal delves deep into the area of simulation modelling for testing and optimisation, which is one of key verticals of the Industry 4.0 ideology. Thus, the objectives of this thesis are quite cohesive with the future goals as envisioned by ASMPT [11].

## 1.2 Problem context

As established towards the end of this chapter's introduction, a need for modelling the physical FAS has been identified. Constructing a real-life system for every project can be a challenging task as it might require modifications to the system from time to time in order to arrive at an optimal solution. While trying different configurations of the system would eventually help attain the best possible automation setup, it would also lead to a lot of capital costs to the user in terms of the actual physical hardware that would be required to test a number of scenarios for the same FAS. Not to mention the investment in terms of time spent towards the development of all those scenarios from scratch. As discussed in Section 1.1, ASMPT has plans to transition to a more digitally intensive infrastructure and the above mentioned testing approach doesn't seem to support their objectives. Hence, a need for a dedicated testing platform arises where such automated manufacturing setups can be modelled and tested, while paving way for optimisation studies as well. Such a tool will eradicate the need of any physical testing and will also prove to be a cost effective option.

There are two ways by which a typical factory automation setup can be modelled, namely *analytical modelling or simulation modelling* [12]. An analytical model is a mathematical abstraction of a physical model, that can be extended to address various working conditions based on certain assumptions made about the process. Unfortunately, it becomes inapplicable quickly as the problem grows in size and complexity. In such cases, the next possible option is approximation methods. When even approximation methods become inapplicable in most cases, it becomes inevitable to pursue simulation as the preferred option to model such systems[13].

Simulation is an established method in industry and science, which aims at representing or imitating a real world system over time [14]. In manufacturing, simulation is widely used as a supporting method in *designing, planning, analysing, and optimising manufacturing systems*. It is also worthwhile to note that simulation enables testing of alternative system designs, control strategies and new system elements without actually having to set them up physically or disturbing a real world system [15, 16, 17]. Simulation approaches can also be categorised based on different characteristics [17]. For example, simulation models can either be static (i.e. representing a certain state of the system) or dynamic (i.e. representing development of a system over time). These models can be based on deterministic inputs or include random variables for modelling

stochastic behaviour. The problem in hand for this thesis project deals with the *development of a simulation environment for analysing multiple factory automation scenarios*. The said simulation environment should make it easy to model a production line that consists of a number of machines and material transfer equipment (AGVs). Consequently, the developed model has to be simulated using real world control logic, which will be provided as an input to the system. The simulation environment being discussed here is devised on a simulation tooling and consists of digital copies of a majority of the machines being used in a typical FAS, as well as that of the AGVs. These digital copies are designed to mimic the actual physical equipment in its operations. Once the said simulation environment is developed, the user should be able to model any number of automation setups he/she desires.

### 1.3 Research goal and questions

As established in Section 1.2, the main research goal for this thesis can be formulated as below -

***To develop a simulation environment that facilitates the modelling and analysis of multiple factory automation setups***

To answer the above stated research goal, the following research questions are formulated.

1. *What are the system parameters that capture the components of an FAS?*
2. *How can the machines be modeled so that they effectively mimic the real world system?*
3. AGVs form an essential part of the system as they are responsible for material transfer between the machines. Due to the presence of multiple AGVs in a system, their modelling poses a big challenge. This leads us to our next research question, i.e., *How can the AGVs be modelled so that they effectively capture the behaviour of their real world copies and the rules they operate on?*
4. *How can the host software's operations be mimicked in the simulation environment so as to mirror the control logic as it is available through the actual host software?*
5. The simulation environment is envisioned to deliver a virtual copy of a physical FAS. A number of such virtual copies can be generated based on different system configurations. This problem leads to the genesis of the next research question which is, *how can the different simulation configurations be evaluated in order to select the most suited setup for the customer?*
6. *How can the simulation environment be delivered to the end users so that it can be used with minimal knowledge of the simulation tool?*

The research methodology undertaken to answer the posed research questions as well as satisfy the research goal is explained in Chapter 3. Chapter 8 expands upon how each of these research questions were answered.

### 1.4 Structure of the Report

The structure of the report is as shown in Figure 1.1. Chapters 1 to 4 represent the *problem genesis and proposed solution* part of this report. These chapters contain the introduction, the theoretical background, the methodology as part of the project and the problem investigation. This part dives into the project background and what led to the genesis of this research. This then leads to an investigation on the current developments in the area of simulation modelling as well as AGV configurations, which then inspires the methodology. Followed right after is the *Design* part of this report, which consists of Chapter 5 and 6. Chapter 5 deals with conceptual modelling, where



the ground rules are laid down for eventual simulation model. Chapter 6 is about simulation modelling, where the actual solution, i.e., the designed simulation environment is described in detail. Chapter 7 is about validation and verification of the developed simulation environment. This chapter analyses whether the developed simulator is able to represent the actual physical setup as accurately as defined earlier in Chapter 5. Finally, in Chapter 8, the conclusions and recommendations are presented.

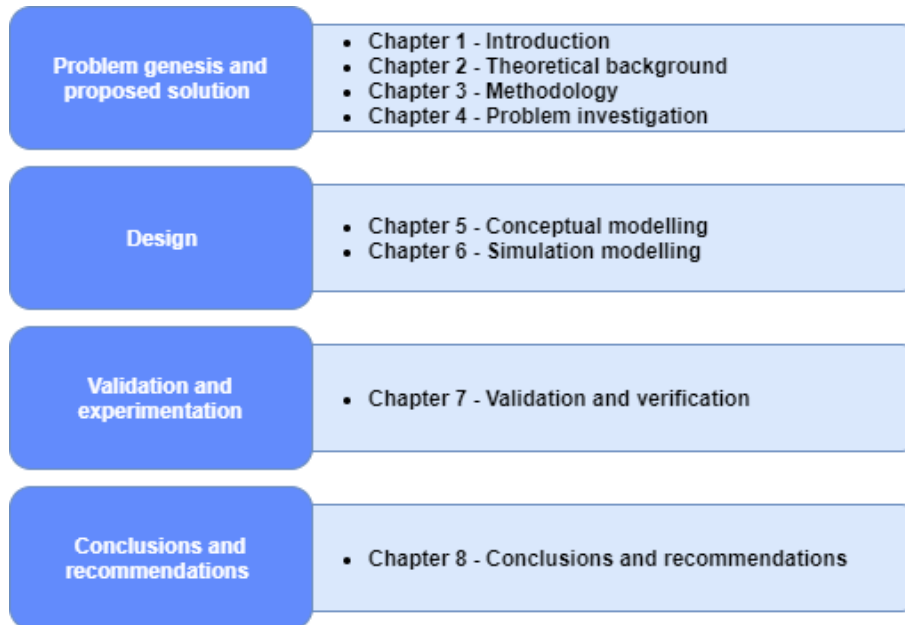


Figure 1.1: Structure of the report

## Chapter 2

# Theoretical background

This chapter establishes the theoretical foundation of this research. The literature review is partly conducted during the preparation phase of this project and partly during the project phase. First, the main takeaways from the systematic literature review done prior to the project phase are discussed. Starting from the broad scope of simulation modelling in manufacturing systems, the research area is narrowed down to the two main topics (Sections 2.1 and 2.2), first of which was a review of the academic literature into modelling of a material handling system (MHS). This subsection discusses the different control strategies for an AGV network and how they differ from one another. This is followed by another study into the simulation modelling methodologies. Finally, the chapter concludes with a brief summary.

Prior to beginning this thesis, a structured literature review was conducted. The broad scope of the review dealt with investigating into the literature that relates closely to the research goal. For this purpose, the research goal was dissected into two major categories. They are as listed below -

1. *AGV configurations*
2. *Simulation modelling methodologies*

The above mentioned categories broadly cover the scientific scope for this research. In order to conduct the systematic literature review, the methodology followed was as issued by Impellizzeri et al. [1]. The steps in this methodology are as shown in Figure 2.1. This methodology has been implemented and the resulting findings have been summarised in the following subsections.



Figure 2.1: Steps in a systematic literature review [1]

The two components that have been identified for successful modelling of any factory automation systems are - the material handling system (the AGVs in our case) and the machines themselves. Hence, first the modelling of MHS will be discussed in subsection 2.1.1 and then the following subsection 2.1.2 discusses the modelling methodologies available for an entire system in itself.

## 2.1 Modelling of an MHS

In order to increase productivity, product quality and system flexibility, automated guided vehicles (AGVs) have been frequently used in manufacturing systems, especially in flexible manufacturing

systems and semiconductor fabrication facilities. The design and operation of AGV systems are highly complex due to their high levels of randomness and large number of variables involved. This complexity makes simulation the perfect technique to study and model such systems. Vis [18] presents a survey of work involving design and control issues of AGV systems in manufacturing, distribution, transshipment and transportation systems. Several simulation-based models are discussed and it is concluded that most of these models can be applied in manufacturing settings. AGV systems play an important role in flexible manufacturing systems since they can be easily modified to respond to changes in the system including changes in the demand, product-mix, and job priorities. Koo and Jang [19] present stochastic models for AGV-based material handling systems. In their study, they focus on vehicle travel time as a fundamental parameter in solving various flexible manufacturing system design problems. Um et al.[20] present a hybrid method that combines simulation-based analytical and optimization techniques for an FMS with AGV systems to satisfy three objectives of minimizing congestion, maximizing vehicle utilization, and maximizing the throughput. Huang et al. [21] develop a simulation model of a real world fab and use a simulation optimization technique to obtain the optimal vehicle allocation. Torres [22] provides a review of several articles concerning the use of simulation for facility layout and MHS design for integrated circuit semiconductor manufacturing industry. Agrawal and Heragu [23] give a review of various approaches for automated material handling in semiconductor manufacturing industries. Some of the reviewed papers involve the use of simulation for analyzing equipment utilization and facility layout.

One of the critical issues in the design of an AGV based material handling system is AGV guide path layout, otherwise known as AGV configurations. Most researchers have particularly centered their attention towards such AGV configurations and have come out with a number of solutions for guided path layout designs. Some of these allow bidirectional flow of AGVs over a guided path without increased complexity of control. The two major categories of such an AGV configuration have been identified as, **Traditional and Non-traditional configuration** (as seen in Figures 2.2 and 2.3). Most of the non-traditional configurations are a derivative of tandem configuration, where a guide path layout is split into loops and each loop is designated a single AGV. In a traditional AGV configuration, any vehicle is allowed to serve any P/D station and all the vehicles operate over the same guided path. As the MHS grows bigger and becomes more complex, a more sophisticated control is required for the traditional AGV configuration. Mahadevan and Narendran [24] introduce a similar configuration, known as a single vehicle loop. Tanchoco and Sinriech [25] propose an optimal single loop configuration. Bozer and Srinivasan [26] propose a newly developed tandem configuration to tackle the control complexities that are faced in the usual traditional configuration. Furthermore, tandem configurations have attracted the attention of more researchers over the years (for example, Choi et al. [27] ; Lin et al [28].; Wang and Hafeez [29]; Dahel [30]; Ross et al. [31]). Bozer and Rim [32] introduce the tandem loop configuration to overcome the shortcomings of a tandem configuration.

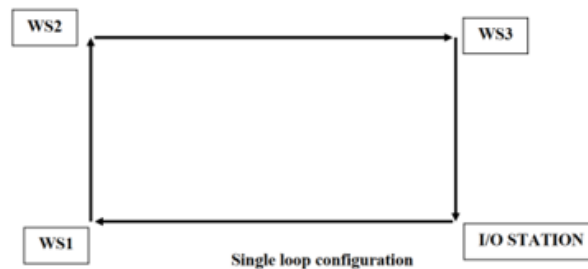


Figure 2.2: Traditional configuration

At present, most of the research is concentrated on the design of an AGV configuration that performs optimally under all operating conditions and also simplifies their control. Choi et. al

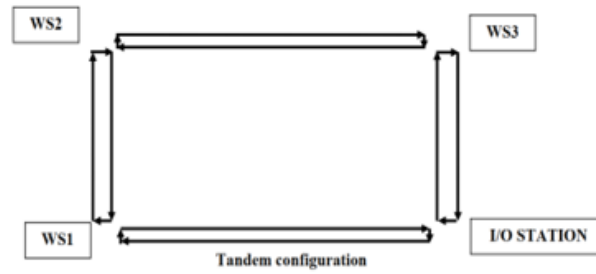


Figure 2.3: Non-traditional (or tandem) configuration

[27] conduct a simulation study to draw a comparison between tandem and traditional configurations. In this research, a number of critical performance attributes like speed of the AGV, number of AGVs in the system and part arrival distribution are taken into consideration while the performance of the system is measured in terms of throughput and flow time of the parts. The resulting analysis reflects upon the fact that AGV speed has a significant affect on the overall system performance. Lin et al. [28] studies a static load routing issue in a tandem configuration. Fazlollahtabar et al. [33] uses a simulation modelling methodology to analyse the role of a tandem configuration based guide path layout on throughput time optimisation. Dahel [30] uses a tandem configuration for the design of cellular manufacturing systems. Ross et al. [31] lead a study that dealt with a comparative study between the performance of tandem, tandem loop and traditional configurations for the same set of system inputs. Wang and Hafeez [29] perform a study on tandem and traditional AGV configurations using generalised stochastic Petri nets. Huang [34] used tandem AGV configuration to solve the problem of material transfer between two stages of a manufacturing process. An optimal transfer point is determined at first, which was then linked through bi-directional tracks. Occena and Yokota [35] design a modified tandem configuration for an AGV based MHS based on Just in time (JIT) manufacturing requirements. This design utilises both unidirectional and bidirectional layout designs. The results show that tandem configuration lends itself better to bi-directional paths. Another design option utilises independent vehicle service paths in a multiple AGV system. The research eventually concludes that a tandem configuration can be easily implemented to a JIT manufacturing environment. Tandem characteristics beneficial to such a system include simplicity of control, lack of congestion and ease of expansion. Tanchoco and Sinriech [25] take a conventional approach to design an optimal single loop (OSL) configuration. The approach uses mixed integer programming to formulate the model for finding out the optimal solution. The number of AGVs in the system vary depending upon the system configuration used and additional AGVs are added to alleviate the performance problem. As compared to a traditional configuration, the OSL performance drops with the increase in the number of AGVs deployed. Eventually, it is concluded that OSL does not perform particularly well under expansion or an upgrade. In another study, Sinriech and Tanchoco [25] specify another kind of guided path sytem design, called segmented flow topology (SFT). Considered carefully, an SFT system exhibits a lot of similarities to a general tandem configuration. Even when not fully connected, an SFT system can be considered as a combination of several tandem sub-systems. The main disadvantage, however, is that such a system requires additional transfer stations.

The following tables (Table 2.1 and 2.2) summarise some of the literature findings on the guided path layout designs as well as touches upon the pros and cons of the three major categories, namely **Conventional, Single-loop and Tandem configurations**. After evaluating the available literature, it can be concluded that non-traditional AGV configurations (like Tandem, Tandem-loop, SFT etc.) are preferred over traditional ones (like single loop). This conclusion is mainly based on the ease of control and better performance metrics provided by the implementation of a non-traditional configuration. As far as this research goes, a comparative study between a singular loop flow and a tandem loop flow (for the same case) has been establish in Chapter 7.

Furthermore, the performance metrics of these layouts are analysed individually.

Table 2.1: Comparison of guide path layouts

Features	Conventional	Single-loop	Tandem
Number of mutually exclusive zones	One zone, fully connected system	One zone, fully connected system	Split system which retains connectivity through transfer buffers, can be non-connected for a special case (SFT)
Number of vehicles per zones	Multiple	Multiple	Single
Operating with bidirectional system	Difficult	Difficult	Simple
Traffic control	Difficult	Easy	Easy
Vehicle scheduling/dispatching	Complex scheduling/dispatching system	Simple	Simple
Congestion (probability)	High	Low	No
Intermediate buffers required (no transfer loads between loops or transfer points)	No	No	Yes

Table 2.2: Advantages and disadvantages of guide path layouts

Guide-path system	Advantages	Disadvantages
<b>Conventional</b>	<ul style="list-style-type: none"> <li>- Flexible in routing</li> <li>- Efficiency achieved by utilizing alternative routes</li> <li>- Shorter travel distances</li> <li>- Tolerance to system failures</li> </ul>	<ul style="list-style-type: none"> <li>- Complicated to control</li> <li>- Congestion, interference problems are likely to happen</li> <li>- Difficulty of expansion</li> </ul>
<b>Single-loop</b>	<ul style="list-style-type: none"> <li>- Simplicity of control</li> <li>- Congestion, blocking, interference problems are reduced in comparison with the conventional system</li> </ul>	<ul style="list-style-type: none"> <li>- Less flexible in routing</li> <li>- Less tolerance to system failures</li> <li>- Vehicle blocking and interference are possible</li> <li>- Extra transport capacity needed</li> <li>- Longer travel for loads</li> <li>- Difficulty of expansion</li> </ul>
<b>Tandem</b>	<ul style="list-style-type: none"> <li>- No vehicle congestion and interference</li> <li>- Simplicity to control</li> <li>- Easy expansion</li> <li>- Effective use of the bidirectional path</li> </ul>	<ul style="list-style-type: none"> <li>- Additional transfer buffers are required</li> <li>- Restriction of one vehicle per zone</li> <li>- Less tolerance to system failures</li> <li>- Some loads are handled by more than one vehicles</li> <li>- Additional time is required to transfer loads at buffers</li> </ul>

## 2.2 Simulation methodology

The case in hand for this thesis is that of a flexible manufacturing system. A flexible manufacturing system usually consists of *machines, an automated material handling system and computer control unit* for system control (as well as the integration of the automated material handling system and machines). The multi-dimensionality of FMS design adds a level of complexity to these problems which makes them beyond the reach of many analytical models and provides a suitable environment for the application of computer simulation. Suresh Kumar and Sridharan [36] study a typical FMS design with a tool-sharing environment. They develop a discrete event simulation model for the purpose of experimenting different scenarios. They use simulation results to develop regression-based meta models to predict the performance of the FMS. Chan [37] use simulation to analyze different routing policies and the effect of changing part mix ratios under both infinite and finite buffer capacity in an FMS.

While most of the simulation studies in the literature address a narrow set of manufacturing problems or single-use application of discrete event simulation, a few authors have been identified, describing the issues associated with development of generic simulation models that can be

reused for a number of applications. Fowler and Rose [38] describe challenges in modeling and simulation of manufacturing systems. They discuss the need for general-purpose architectures for simulation reuse and plug-and-play interoperability as a grand challenge. McLean and Shao [39] discuss the possibility that different simulation analysts obtain different results and reach different conclusions from their case studies. They describe the standardization of case study methodology and development of generic simulation case studies that can produce repeatable results. Akiya et al. [40] propose a framework for building generic simulation models for non-steady process networks. The framework is based on a rule-based queue and resource-task network representation and can be implemented in any simulation software. McLean et al. [41] describe the work done at the National Institute of Standards and Technology (NIST) to develop a generic machine shop simulator. The data-driven simulator can be used in a large number of machine shops. Son et al. [42] describe the use of formal neutral models of simulation components proposed by NIST. They further discuss that libraries of formal neutral models of simulation components would simplify the generation of simulation models and enable reuse of existing models. They also present a discrete-event simulation of a job shop system using a collection of these components. Angelidis et al. [36] introduce a generic simulator incorporating realistic schedules, priority rules, and resource restrictions designed specifically for the simulation of complex assembly lines. In another paper, Kibira and McLean [42] describe the development of a generic simulation model of an assembly plant to be used in distributed integrated manufacturing simulations for automotive manufacturing. Moreover, increasing the versatility of the model, running on neutral data, and integration with supply chain simulation are discussed as future research opportunities.

As explained earlier in *Chapter 1*, simulation modelling has been identified as the preferred approach for tackling the problem in hand. Simulation modelling in itself deals with a wide spectrum of approaches, each of which are more suited for one problem than the other. The four main approaches for modelling a system under a simulated environment are **Discrete event (DE)**, **Agent-based (AB)**, **System dynamics (SD)** and **Dynamic systems (DS)** [43]. SD, DS and DE are traditional approaches, while AB is relatively new. While SD and DS deal mostly with continuous processes, DE and AB are more focused towards modelling systems based in discrete time, i.e. the systems that jump from one time event to another. Another scale on which these approaches as well as the various range of problems, being addressed by simulation modelling, are ranked on is - *Level of Abstraction*. The following figures (Figures 2.5 and 2.4) showcase the same for a number of scenarios (with respect to the application areas and the modelling paradigms) [2].

As can be seen in Figure 2.4, the *Factory Floor* application which resembles the theme of this thesis project requires Low Abstraction level and more details. Also, Figure 2.5 shows that both AB and DE approaches cover the two important requirements of this problem, i.e., the modelling is set in discrete time and the requirement of a low abstraction level (as seen in Figure 2.4). Thus, AB and DE, both seem like the more suited modelling paradigms for this problem, as suggested by the relevant literature [2]. Now, the next question that arises is of their application to this problem. Although AB is discussed in detail in one of the following sections of this chapter, to make the final decision on the modelling approach, certain other factors need to be considered.

One of the fundamental differences between ABS and DES lies in the control of the entities that make up a factory automation system. While ABS systems show the *agents* (individual entities that make up a system) to have their own behaviour and classify them as *active* entities, the behaviour of the entities modelled by DES is determined by a central control unit, which classifies them as *passive* [44]. Another one of the key differences is the fact that while DES is built around a system of queues, ABS has no such concept of queues [45]. However, some systems are better suited to be modelled by a combination of the two approaches. This can be achieved by creating a DES system, in which some entities are actually *active* and exhibit self behaviour, while the others can be controlled by a central control unit that acts as a brain for the entire system. This control unit would be responsible for defining the operations of the *passive* entities in the system [46]. Despite their differences, DES and ABS do share certain similarities. Both are stochastic in nature and can use input distributions to model random behaviour. It is important to note here

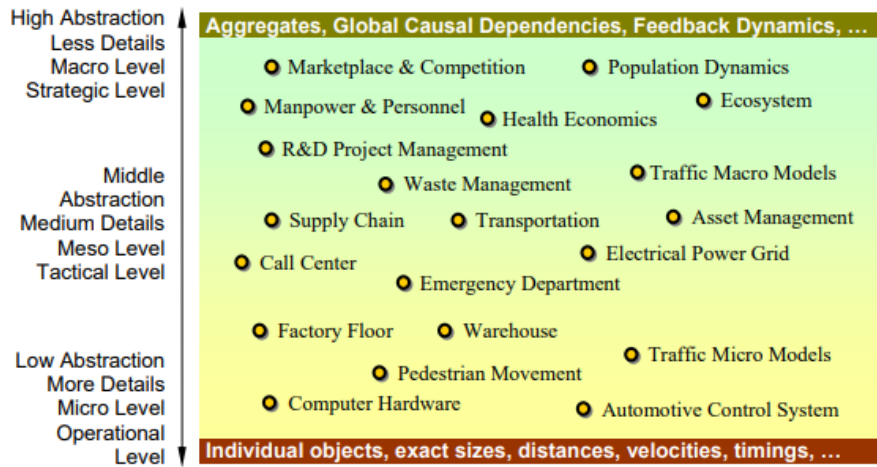


Figure 2.4: Applications of Simulation Modelling on Abstraction Level Scale [2]

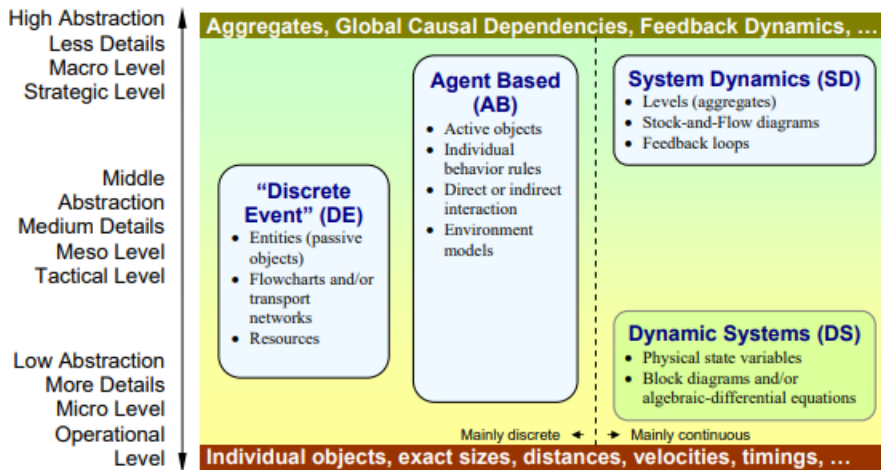


Figure 2.5: Approaches in Simulation Modelling on Abstraction Level Scale [2]

that the systems to be modelled in the simulation environment as part of this project exhibit a very specific similarity with the kind of system that has been explained above.

As explained above, the ABS-DES combined modelling approach can be used to model systems that have both *active* and *passive* entities, and the same can be said about ASMP’s factory automation setups. While the machines are controlled by a host software (the brain of the system as discussed above), the AGVs act as *active* entities and display individual behaviour. The host software has no control over an AGV’s behaviour and only defines the recipe that should be running through the production line. Based on the said recipe, the machines request material and the AGVs deliver it to them. However, the AGVs run independently based on their own scheduling rule and with the aid of an internal control software. Hence, the **ABS-DES combined approach** seems to suit the problem in hand as it can mimic the behaviour of the machines on a DES platform, while aiming to capture the individual behaviour of the AGVs via the agent focused methodology of ABS.

## 2.3 Summary

The main findings of the systematic literature review can be summarised as follows -

1. The literature review was focused on two important aspects concerning the modelling of an FAS, which are modelling of the MHS and the simulation modelling methodology to be used for defining an FAS such as that of ASMPT.
2. A thorough literature study into the area of AGV configurations reveals that non-traditional AGV configurations display better performance metrics compared to their traditional counterparts, given the ease of control, reduced congestion and faster lot execution offered by them. However, an argument can be made about the viability of both kind of layouts depending upon the case in hand. Thus, a number of factors need to be considered before making a decision on which guide path layout is more suited for a certain system.
3. The second study delves in the scientific literature available on simulation modelling methodologies for systems similar to the one produced by ASMPT. The four predominant approaches are SD, DS, AB and DE. AB and DE are identified to be the more relevant ones in the modelling of discrete event systems. After a thorough analysis, it is concluded that a combined DE and AB modelling approach is most applicable for the case in hand. Here, the AGVs are modelled as individual entities as hence can be represented as part as an agent based methodology, where as the machines are modelled under a standard discrete event approach.

The following chapter follows up with the methodology undertaken for the completion of this thesis project. Based on the theoretical review, this chapter explains what steps need to undertaken for the successful attainment of the research goal.





# Chapter 3

## Methodology

In this chapter, the entire project methodology is shown in the form of a block diagram (or a flow diagram). Each block represents a step taken during the project towards fulfilling the final research goal and below each step are the outcome(s) resulting upon implementation of that step. First, the block diagram is shown for the reader's reference and a detailed explanation of each step follows thereafter.

### 3.1 Project steps

The methodology followed is as shown in Figure 3.1. In the following pages, each of these steps as well as their resulting outcomes are described in detail.

1. **Problem statement** - The main research goal in this case concerns the development of a simulation environment for modelling multiple FAS provided by ASMPT to their customers or for internal testing purposes. The sub research questions deal with modelling the critical components of an FAS like **machines, AGVs, systems buffers etc.**
2. **Problem investigation** - This step in the methodology deals with understanding of the actual physical FAS and its critical components. The first objective is to gain an understanding about machines, the buffer stations, the material transfer equipment (AGVs in this case) and other supporting elements that make up the FAS. This is followed by the understanding of the material flow through the machine as well as establishing the attributes of each of the critical components of an FAS. An investigation is also done into the current way of conducting simulation studies within the organisation and how the development of the simulator is going to improve that process. Finally, an analysis into the critical inputs, outputs and constraints with respect to the actual physical FAS concludes this step.
3. **Literature review** - The literature review aims at reviewing and drawing an inspiration from the available scientific work already established in the areas of *simulation modelling for manufacturing systems* and *AGV network design*. These two areas are identified to have significant scientific relevance with respect to this research.
4. **Conceptual model definition** - This step deals with the description of a conceptual model for the simulation modelling to be done later. According to literature, a conceptual model is an abstraction of a simulation model that is based on a real world system [3]. In other words, a conceptual model defines what to model and what not to model. The amount of abstraction depends on the amount of data one has available on the real world system, how much detail is required out of the model and how much time is available to the modeller. Thus, in this step, a conceptual model for a typical FAS is defined. The methodology for defining a conceptual model includes, to first define the objectives of the simulation study, and then to describe the inputs and outputs of the envisioned simulation model. Finally,

the scope and detail of the simulation model is defined (so as to determine the level of abstraction in the model). This concludes the conceptual design discussion and leads us to the development phase of the research.

5. **Data Collection** - Once the conceptual design has been established and the level of abstraction for the model has been defined, the next step deals with the collection of the input data for the simulation model. The input data can either be deterministic or stochastic (represented by a theoretical distribution in case of variability in the data) in nature. The input data collected in this research ranges to everything from processing times for the machines to their buffer capacities. Information on essential AGV parameters like their **speed, acceleration, charging rate, threshold charge levels etc.** is needed to accurately capture the behaviour of those systems within the simulation model. Additionally, supporting information like layout design, floor plans and schedules (that supply the information on how a given lot is processed) also serve as important inputs to the simulation environment. This concludes the *Data collection* step and paves way for the development of the simulator.
6. **Simulator development** - Once a conceptual design is established and all the necessary data has been collected, the next logical step in the methodology is the development of the simulator (also called as the *simulation environment* through this document). There are 2 different aspects to the simulator - modelling the 3D layout (on **FlexSim's 3D modelling interface**) and modelling the simulator logic (on **FlexSim's process flow interface**). The 3D layout modelling interface on FlexSim is where a three dimensional representation of a physical FAS can be achieved. This 3D model provides an animated setup of the actual physical FAS, where the user, with a simple drag and drop operation, can replicate any type of a layout without the need for any post processing. This 3D model is controlled by a process flow, which is basically a custom created model logic that runs in the background, controlling the 3D model while it is being executed. The process flow logic is visually akin to a flow chart where each step has a outcome and all outcomes put together eventually lead to the final result. In this case, the process flow is responsible for processing the schedule (given as an input to the model) and executing the prescribed activities for processing a lot. The 3D model and the process flow, put together, form the generic simulator required as an outcome of this research. Subsequent steps in this part of methodology are to determine how to treat the simulation with respect to the warm up time and the duration of the simulation run. Another important part of setting up the simulator is to also set up **FlexSim's Statistic Dashboard**. The statistics dashboard provides the user the advantage of real time data collection and data monitoring. Post simulation execution, the statistics dashboard can also be use for model analysis and optimisation by studying several key model performance statistics like throughput, utilization rates, battery levels and many more.
7. **Simulation modelling and execution** - Now that the simulator has been developed, a number of different schedules and layouts can be tested on it. In this stage of the research, an example case model is developed, executed and tested against any errors in the model logic and/or data input as well as the errors with respect to the layout design (like network congestion, blockage, possible AGV collisions etc.). Collection of model performance statistics (as listed in the previous step) upon the successful execution of the model, also forms a part of this step.
8. **Model validation** - Model validation deals with checking the accuracy of the model with respect to the real world system. The model is developed for a specific purpose or to fulfill a set of objectives and its validity is determined for that purpose. The purpose here is to simulate multiple FAS and the validation is done based on product flow monitoring. This will be expanded upon in **Chapter 7**.
9. **Model verification** - This step deals with analysing the overall performance of the simulator. Model verification is essential to ensure if the developed simulation model is performing as envisioned in its conceptual design. Model verification can be done in a number of ways

(as described in Chapter 7), but the preferred method in the case of this research would be to run multiple replications of the same model but with varying input parameters and to perform statistical analysis on the resulting performance statistics (as listed in the *Simulator development* section of this methodology). The said statistical analysis deals with the calculation of the **mean, standard deviation, half width, confidence intervals etc.** for the same layout. This analysis would then help in concluding whether the model is performing in accordance with its conceptual design or not.

10. **Experimentation** - Once it has been validated that the conceptual model has been rightly transitioned into simulation modelling, the simulator can be used to experiment different layouts and schedules. In the case of this research, one of the literature study areas dealt with a deep dive into available AGV configurations. This was investigated upon and tested on the developed simulator to see how the system performance varies with a change in the line layout and/or AGV allocation strategies (refer Chapter 2 for more on AGV configurations and Chapter 7 for system performance comparison). Another part of this step is the testing of the different schedules on the developed simulators. The schedules can differ in the **quantity of products to be processed, the number of machines, the number of AGVs used and the number of system buffers**. So testing these schedules so as to ensure that the simulator executing them properly is also part of the *experimentation* step.
11. **Result and analysis** - This part of the methodology deals with reporting the key performance indicators coming out of the simulator, that signal how efficient the line and its components are in their operations. These performance indicators can be studied, which can then pave way for an optimisation study on the line. Based on these results, an argument can be made on whether the same lot can be executed with lesser number of machines, or if material transfer can be done with a lesser quantity of AGVs, or if lesser number of charging stations can be used to charge the same number of AGVs etc.
12. **Discussion and conclusion** - This penultimate stage of the research deals with looking back onto the research goal established in the beginning of the project and how it has been achieved by the developed solution. The research questions are reflected upon and it is seen if they have been satisfactorily answered or not. A discussion on the unsatisfied objectives forms the future scope for this research.
13. **Documentation** - This is the ultimate step of the methodology which deals with the documentation of all the essential information pertaining to this research. The document is drafted in an orderly fashion, starting from the *Problem genesis* and ending at the *Conclusions and discussions*.

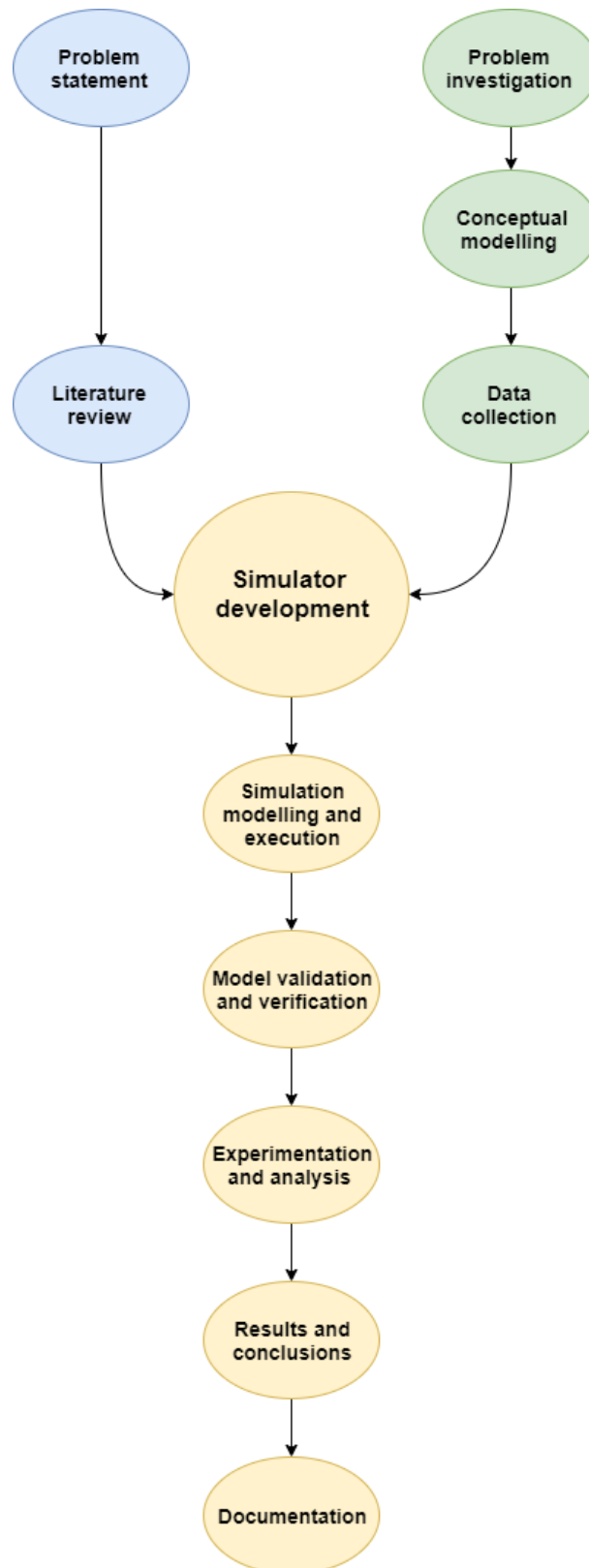


Figure 3.1: Project methodology

## **3.2 Summary**

This section makes an attempt at describing the exact events that took place for the duration of this research, that lead to the drafting of this research methodology. The research deals with the development of a simulation environment for testing purposes (both at customer sites and within ASMP) and the methodology lists all the crucial steps undertaken for the successful attainment of that goal. The following chapter discusses one of the important steps in the methodology that deals with problem investigation. In this chapter, the physical FAS setup is discussed. The discussion pertains to the machines and the robots in its majority, but the material flow across the line is also analysed as well the process dependencies between the machines that influence it.



# Chapter 4

## Problem investigation

The goal of the problem investigation is to discuss how the actual physical FAS is laid out, to identify how the material flow takes place through the line and understand the inputs, outputs and constraints associated with it. Answers to the second and third research questions (*How can the machines be modeled so that they effectively mimic the real world system and how can the AGVs be modeled so that they effectively capture the behaviour of their real world copies and rules they operate on?*) are provided by capturing the current situation of the FAS at ASMPT. First, a brief discussion on the project background is initiated, via a discussion on the typical FAS produced by ASMPT. Second, the nominal process flow is explained and a discussion on the general process flow within the machine follows. Finally, the chapter concludes with a brief summary and partial conclusions.

### 4.1 Typical factory automation setup

This section aims to provide background information to the reader about the typical automation set ups at ASMPT Customer production sites and workshops. Furthermore, the dynamics of the process and the interactions between the machines is discussed, as well the parameters that go into modelling a particular factory automation setup has been explained.

As explained earlier, ASMPT specialises in providing entire end to end solutions in the semi-conductor equipment market. Although the company specialises in separate solutions for each stage of the electronics manufacturing process, the focus is now being shifted to entirely automated production lines that can be sold to the customer as a complete solution. A typical factory automation setup is as shown below in Figure 4.1.

As can be seen in the figure below, the setup consists of a number of different machines with their individual functionality, working in unison to form a completely automated setup. This setup provides the customer with a turnkey solution to their manufacturing needs. Figure 4.1 consists of row-wise distribution, consisting of multiple machines. **Row 1** consists of the Die attach (AD8312SD), Oven (MD609HD), DA AOI, and Plasma. All the machines have internal buffers, that help to accommodate for the built up WIP, before the AGV comes to collect the job and transfer it to one of the downstream machines. Moving on, **rows 2 and 3** consists of Wire bonder (Aero) alone. **Row 4** again consists of a combination of machines, identical to row 1, but having different functionality. Here, we have a WB AOI, Aero gauge, plasma and Mold (IDEALmold 3G) machine. These machines are also equipped with internal buffers (as seen in Row 1). **Row 5** consists of the control room, which serves as the station for the line operator to monitor the line. In addition to all the machines, there are the material storage towers and a certain amount of material logistics equipment (AGVs in this case). The AGVs are responsible for facilitating the material movement between the machines and also has its own buffer (for carrying multiple units at a time).



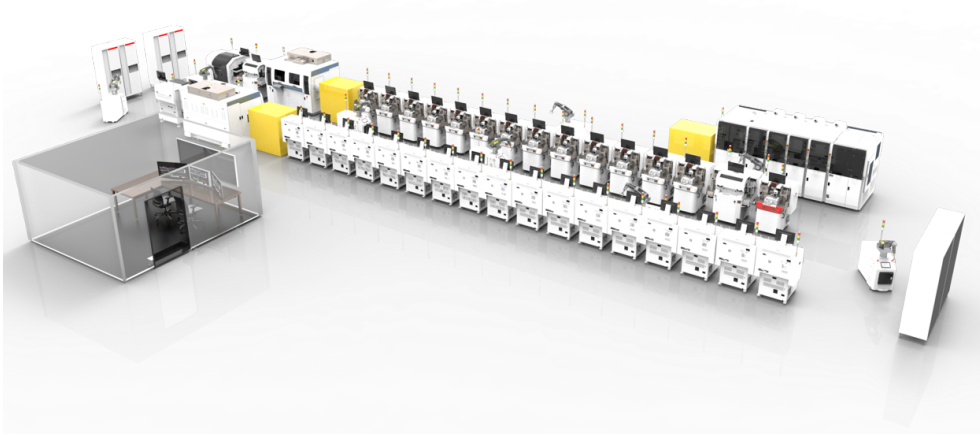


Figure 4.1: A typical Factory Automation Setup in ASM customer workshop

#### 4.1.1 Normal material process flow (Example case)

Now that a generic factory automation setup has been explained, one of the provided example cases, which has to be tested in the simulation environment, will be discussed. Figure 4.2 shows the material flow of one of the factory automation setups to be considered as an example case.

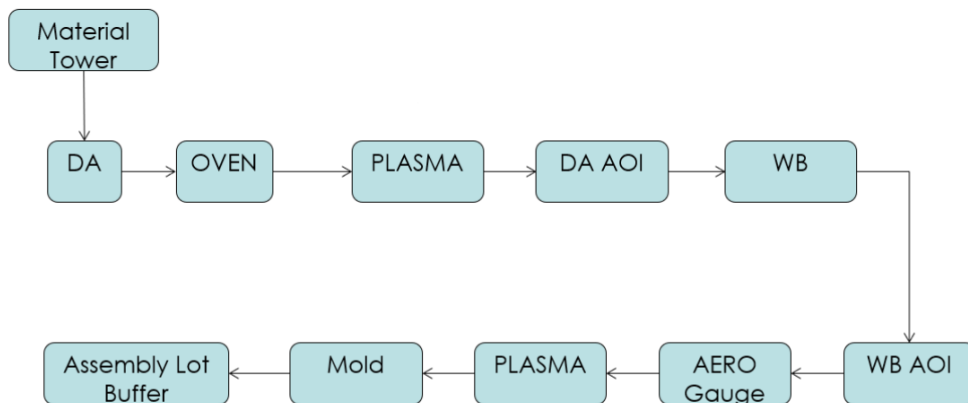


Figure 4.2: Normal material process flow (example case)

As can be seen in the figure below, the material flow through the various stages of the process has been shown. The operations at each stage and functions of the machines is not of any importance in the context of this thesis. Therefore, this has not been discussed here.

However, what is interesting for the scope of this thesis here are the system parameters for this process. For that discussion, the system can be categorised into **six** main components, namely **machines, system input, system output, charging station, material and AGVs**. It is important to note that all times are reported in **seconds** and all quantities (like buffer capacity, workstation holding quantity etc.) are reported in **units**. The configuration parameters (for each of the six components) have been identified as follows -

1. **Machine** - The configuration parameters identified for the component "Machine" are as follows -
  - (a) Processing time - How long does it take for the machine to process one material type. All processing times are deterministic in nature.
  - (b) Buffer Quantity - Buffer capacity of the machine. This is variable and depends on the type of machine.
  - (c) Workstation quantity - The amount of units that can be processed at the machine at a time. This is variable and also depends on the type of machine.
  - (d) Process input and output - The input(s) that come into the machine (a machine can have a single input or multiple inputs from multiple sources). The output from the machines are usually singular in nature. There is always one finished article as a result of an operation on any machine.
  
2. **System input (material tower)** - Defines the starting point of the process flow and acts as the source for the supply of material to be processed in the line. The following parameters are included in the system input -
  - (a) Material Type - The material type in the system input. The materials used in the line are predominantly of three different types, i.e. **magazine, cassette and lead frame box**. While modelling the simulator, these three are the only ones that have been taken into consideration with respect to machine buffer capacity, system input/output capacity as well as the AGV carrying capacity. There are several consumables used in the line, but they are usually add-ons compared to the three materials mentioned above. Moreover, these consumables are usually found in the AGV buffer than at the system input. The system input is loaded with the required material (as per the lot schedule) by one of the line workers and its replenishment (whenever needed) is also done by them.
  - (b) Cycle Time - The time taken for loading the material from storage position to the exchange port for the robot (an exchange port is a load/unload port within the material tower), from where an AGV can receive material for transferring it to one of the downstream machines.
  - (c) Quantity per cycle - How much material is transported to the exchange port per cycle.
  - (d) Capacity - How much material can be accommodated by the system input.
  - (e) Number of load/unload ports available - Number of ports available in the system input (material tower) for material transfer to and from an AGV.
  
3. **System output (material tower)** - Defines the ending point of the process flow and acts as the drain or the sink (exit point for finished goods) for the line. The following parameters are included in system output -
  - (a) Material Type - The material type in the system output. The materials coming out of the line are predominantly the magazines. This is can also be seen in Figure 4.6, where a typical die attach process is shown. As can be seen, the inputs are wafer cassette (or a cassette in our case), lead frame box and some consumables (like glue, collect etc.) as well an empty magazine. The output (at the system output) is the same magazine, but with the processed product inside it. As an exception, there are several cases in some of the tested schedules where cassettes also end up at the system output. These cases occur either due to the presence of process interdependence in the line (refer 4.3 for more information), which means that these cassettes can again be retrieved from the system output back into the line. Otherwise, the cassettes are mere outputs of the line and are eventually taken out of the system output by a designated personnel, that unloads the processed lot from the system output.

- (b) Cycle Time - The time taken for unloading the material from exchange port to storage position in the system output.
4. **Robot** - The following is the list of configuration parameters for the robot -
    - (a) Loading time - Time robot takes to pick one material from one position and to place it at another position.
    - (b) Min power - Lowest power of the robot.
    - (c) Max power - Highest power of the robot.
    - (d) Capacity - Carrying capacity of the robot (its buffer capacity). The robot places the material in its buffer in an  $m*n$  fashion, where  $m$  is the number of storage rows the robot has and  $n$  is the amount of material that can be placed in it. The storing in the buffer/taking out of the buffer can be done by the following options - **FIFO/-FILO/Random**.
    - (e) Velocity - Speed of the robot (unit - m/sec).
    - (f) Charging speed - Speed at which the robot can get its battery replenished (unit - %/sec)
    - (g) Consumption idle - Power consumption speed when robot is idle. (unit = %/sec)
    - (h) Consumption motion - Power consumption speed when robot is moving. (unit = %/sec)
  5. **Charging station** - This component has only one essential parameter (that has to be looked into with respect to the lot schedule) - Robot ID (that specifies which specific robot can charge at the station).
  6. **Material** - Flow of a particular container is essential to be defined, i.e. which sequence of operations is followed by the material. An operation is defined as a single step performed by a single machine. So the flow yields a sequence of machines. Such a flow can be retrieved from the lot schedule, which serves as an input to the simulator.

Apart from the system parameters discussed above, another important aspect of the process flow that needs to be considered while modelling the machines is the **process dependence amongst them**. The process flow seen in Figure 4.2 is uni-directional and exhibits singular dependence between the machines and the rest of the environment. Figure 4.3 shows another example case where the dependence between the machines and the rest of the components (for example the material tower and mobile robot) can be seen.

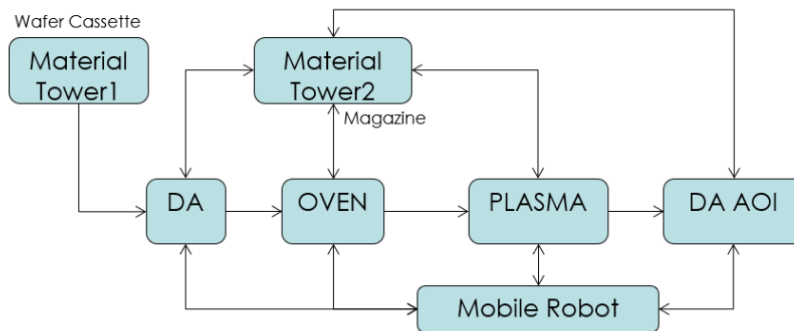


Figure 4.3: Process dependence among machines (example case)

As can be seen from the figure above, a machine displays high levels of dependence with its environment. The process flow depicts singular as well as bi directional flow between different components of the system. The single directional flow indicates that the preceding machine gives

an input to its successor, whereas the bidirectional flow indicates that there is a two way exchange between the machines/other components. Considering the Die Attach machine as an example, the machine receives magazines with lead frames in them and returns empty magazines back to the material tower. All kinds of material transfer is aided by the AGVs. Lets consider an example case where we have two machines, namely A and B. B succeeds A in the process hierarchy. In a typical process flow -

1. A's output can be one of the input sources of B. This means that B can have multiple input sources. For example, the Die attach machine (DA as seen in 4.3) has input from both material tower 1 (for the die from the wafer cassette) and material tower 2 (Lead frame from the magazine).
2. B's input can be from a number of sources. Even though the material input is provided by the AGV, the sources can be multiple, i.e. either the another machine, the material tower or even an AGV (in case of consumables which are supplied by a dedicated AGV). It is important to note here that the term *multiple input sources* signifies the source of the material. The material transfer across any point in the line is always achieved via an AGV, but the source of that material can be either a machine, an AGV or a material tower (as explained above).

### 4.1.2 General material flow within the machine

The previous subsection provided insights into the process flow in general, the various process parameters of each of the components of an automation system and also the process dependence between the different components. Now , the focus will shift to the machine component and the material flow within them. Figure 4.4 and 4.5 show the two variants of material input systems for the machine component of the factory automation system.



Figure 4.4: Single input material flow

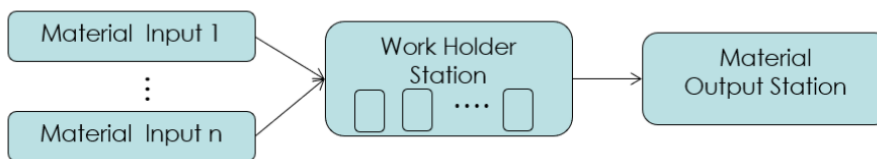


Figure 4.5: Multi input material flow

As can be seen in the figures 4.4 and 4.5, the following observations can be made about the general material flow within a machine component -

1. **Input material can be of multiple kinds/varieties** - For example, if the Die Attach process (as seen in figure 4.6) is considered, input materials include wafer, magazine, lead frame box, glue and collect.
2. **Work holder station can hold more than one work pieces at a time** - For example, the oven has 4 chambers for curing, while the die attach has a single work holder station.
3. **Input and output stations can be the same** - In some dual bond head systems, magazine input station can also work as output station and vice versa.

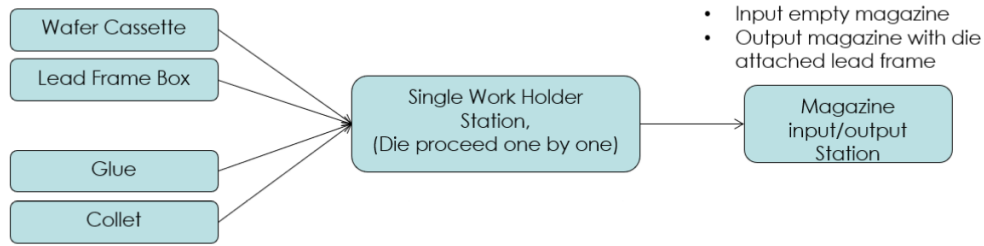


Figure 4.6: Example (Die attach process)

Since the general material flow within a machine has been established now, it is also important to know the factors that could effect the on-time capability of such machines. The following have been recognised as some of those factors that could induce variability in the process -

1. Machine unscheduled downtime
  - (a) Warning
  - (b) Error
  - (c) Requesting the operator to change consumables that can not be filled by an automation system yet, such as *Wire, glue, ejector pin and collect*.
2. Machine waiting for material
  - (a) Input material or output material are in process
    - i. *Case 1* - Material is not available yet in the system.
    - ii. *Case 2* - Material is available, but awaiting transfer.

Usually variability can also be induced into a manufacturing line via the randomness in the process times of machines/other components. Although this variability is ignored in this case due to the presence of deterministic times for all process parameters in the line (For example, process times of the machines, load/unload times of the AGVs etc.), which ensures that the simulation leads to the same results on every run that is made on the developed simulator. This leads to an issue with the simulation verification (more on this will follow in Chapter 7).

## 4.2 Summary

The discussion on the material flow concludes this chapter. Now that a general understanding of a typical FAS and its components has been established, their critical parameters have been discussed, and the sources of variability in the process have been identified, the next logical step is the design of a conceptual model. This will be expanded upon in the following chapter and will pave way for the design and development of the simulator.

## Chapter 5

# Conceptual modelling

Conceptual modelling is one of the most important aspects of a simulation project. The design of such a model has an impact on all parts of a simulation study, such as the data requirements of the model, the level of detail as well the pace at which the model can be developed, the validity of the model as well as how much confidence can be placed in the model results. A well defined conceptual model can significantly enhance the chances of the simulation study being a success [3].

Law [47] states that there is a severe lack of literature on the topic of conceptual modelling, despite its paramount importance leading up to a simulation study. Robinson understands one of the key reasons is owed to the fact that conceptual modelling is considered more of an "art" than a "science", which makes hard to define methods and procedures. This means that art of conceptual modelling is usually learnt largely by experience.

Robinson defines conceptual modelling as the process of *"creating a conceptual model that is used to understand the problem definition, determine the modelling and general process objectives, identifying the model inputs and outputs as well as identifying the model contents (scope, level of detail and assumptions)"*. A graphical representation of the same can be seen in Figure 5.1. This chapter aims to elaborate upon the aspects that need to be taken into consideration for the design of the simulation environment, as defined by Robinson[48]. The level of abstraction, the scope and the input and outputs concerning the models developed on the simulation environment are discussed in the following subsections.

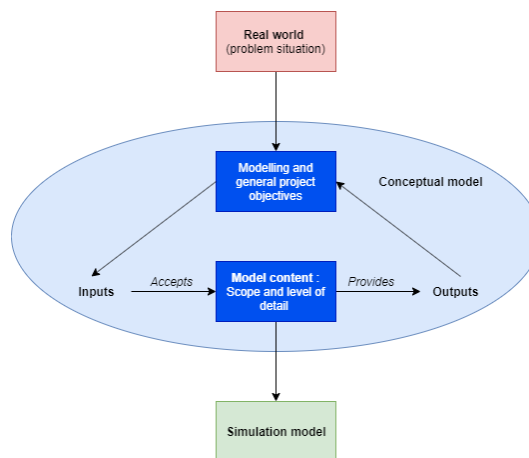


Figure 5.1: Framework for defining a conceptual model (Robinson [3])

## 5.1 Modelling objectives

As can be seen in 5.1, one of the first steps in conceptual modelling is the definition of the modelling and the general objectives with respect to the project. In the case of this project, the main objective concerns the **Development of a simulation environment for testing and development of ASMPPT's FAS(s)**. The other objectives concerned with this subject are that the developed simulation environment should be able to -

1. Facilitate the testing of multiple FAS layouts.
2. Facilitate the testing of multiple lot schedules.
3. Generate statistics on the process parameters like WIP, utilization rate, throughput etc.
4. Facilitate communication between an external scheduler that can make dynamic changes to the schedule in the event of an exception (like machine breakdowns, AGV collisions, material shortage etc.)

## 5.2 Input and output

The input and output for the simulation model can be determined using the objectives set out in the previous sub sections. The output of the model needs to provide the user with sufficient information so as to enable him/her to analyse the system and check whether it is the best possible solution to execute a certain lot. This analysis can then lead to further optimisation studies to be conducted and proposals, that can be presented to the prospective customer as a business case.

Therefore, the output(s) of the simulation model needs to be able to facilitate the execution of the above stated objectives. These can be the key performance indicators of the system like utilization, work in process, process lead time etc. Most of the input parameters are deterministic and can not be changed. In figure 5.2, the simulation model to be designed for this project is shown. Starting from the left, the input parameters concerning the different components of an FAS (the machines, system input and output towers and the AGVs). These inputs are then fed to the simulation model, where these process parameters are used to churn out output (as known as the key performance indicators of a system). The values of these parameters can then facilitate an analysis into the model, which can then work as a feedback loop to the input stage again. As seen in the figure, this can continue until the user has achieved a satisfactory model performance, given the inputs and the constraints to the model.

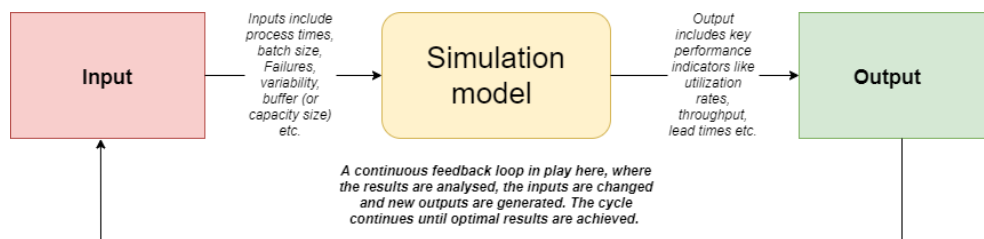


Figure 5.2: Perceived simulation modelling skeleton based on the conceptual design

### 5.2.1 Input

A few of the input measures to the model are as seen in figure 5.2. Change in these factors lead to different model behaviour and different performance statistics. All the involved input parameters are as follows -

1. **Arrival rate** - This concerns the products being processed in the simulation model. In the case of this research, all the products are first loaded onto the system input tower as per the lot schedule, before their processing even starts. This means that if there are 40 products that have to be processed in a given lot, then all 40 are loaded onto the system input tower. Hence, in the case of a simulation model pertaining to this research, the products are all generated at the same time. Hence, the arrival rate stands irrelevant.
2. **Capacity** - This concerns all components of the simulation model, i.e., the machines, the system input and output towers as well as the AGVs. Capacity defines how many products can be carried/stored by a particular component of the FAS for a certain time period, before they have to be transferred to the next stage in the process.
3. **Processing times** - This concerns the machines as well as the AGVs in a simulation model. The processing times of the machines are quite simply the time taken to process a product or batch. These times can either be deterministic or stochastic (represented by a mathematical distribution). In the case of this research, all machines have a deterministic processing time.
4. **Batch size** - This concerns the machines in the simulation model. Batch size defines how many products can be processed by a machine at the same time. These values are fixed and deterministic in nature. In the case of the AGVs, the processing times are represented by the amount of time taken by them to load/unload products, to and from their storage buffer. These times are deterministic as well.
5. **Variability** - As already explained in Chapter 4, there are a number of sources that can induce variability in a FAS. Machine downtime, material unavailability and many other such factors form the possible sources of variability. Stochastic distributions for the input parameters can also induce variability in the system. However, in the case of this research, due to the deterministic nature of the input parameters, no variability could be induced into the simulation model. Due to this reason, variability has been excluded from the scope of simulation modelling in this research.
6. **Failures** - Also known as mean time to repair (downtime) or mean time to failure (uptime). These parameters describe the failures occurring at a machine or an AGV. Mean time to repair represents the average time a failure lasts whereas mean time to failure represents average time between two consecutive failures. Due to unavailability of data, failures have been excluded from the scope of simulation modelling in this research.

### 5.2.2 Output

A number of key performance statistics are generated as an output of the simulation model. A few of them are as listed below -

1. **Product flow** - This flow is in the form of a Gantt chart. It shows how a particular product flows through the simulation model and where it is at a particular instance in the simulation. This product flow gantt is a means for validation of the simulation model.
2. **Utilization** - This output parameter is defined for both the machines as well as the AGVs. This parameter defines the probability that a station is busy or not. The utilization states are split into a number of different categories based on the component under consideration. More on this will be expanded upon in 6.
3. **Lead time** - This output parameter can be defined as the amount of time taken to process the whole lot on the simulation model. The lead time is calculated from the moment the lot arrives in the simulation to the moment the last product of the lot is deposited in the system output.



### 5.3 Scope and level of detail

Once the input and output of the model have been determined, the next logical step in the conceptual modelling cycle is the inclusion of the scope and the level of detail in the simulation model. The scope and level of detail help in determining the boundaries and the depth of the model. Table 5.1 shows the parameters selected to be in the scope of the research, whereas the table 5.2 defines the level of details for those parameters.

Table 5.1: Scope of the model

Subject	Include/exclude	Justification
Physical layout	Include	Relevant for AGV configuration experimentation.
Labor	Exclude	All the transfer tasks are achieved by the AGVs. Workers are not involved in any operations, apart from replenishing the consumables. Hence, out of scope.
Machines	Include	Important part of the FAS.
Failures	Exclude	Data not available.
AGVs (MHS)	Include	Important part of the FAS.
Products	Include	Important part of the FAS.
Production schedule	Include	Specifies the processing steps for all the products in a lot. Important input to the simulation model.
Storage	Exclude	Not relevant for the modelling objectives

Table 5.2: Level of detail in the model

Subject	Details	Include/exclude	Comments
Machines	Capacity Processing times Breakdowns Set up times	Include Include Exclude Exclude	Data available, deterministic values Data available, deterministic values Data not available Data not available
AGVs	Speed Acceleration Capacity Minimum power Maximum power Load time Unload time	Include	Data available, deterministic values
Product	Types of products	Include	Type of products are important for accurate modelling of the FAS.
Physical layout	No. of machines involved No. of AGVs involved Factory floor layout	Include Include Exclude	Data available Data available Data not available, layouts are constructed based on a literature review on the available AGV configurations for an FAS.
Production schedule	Processing steps	Include	Defines the sequence of operations performed to execute a lot. Multiple schedules available for testing on the developed simulation environment.

## 5.4 Variability

Variability forms a key aspect of the conceptual design phase for the simulation environment. It defines the extent to which the models developed on the conceived simulation platform are subject to customisation. There are certain aspects with respect to the simulation environment that remain static, irrespective of the case in hand and they define the extent to which variability is exercised on the simulation environment. The more there is a need for customisation to the models developed on the simulation environment, the lower is its associated variability. A lower variability suggests that the user has an easier task of model development and testing on their hands. The table 5.3 defines the variable and static parameters for the simulation environment.

Table 5.3: Variability in simulation modelling

Model development and execution attributes	
Static (no customization needed)	Variable (changes with every model)
1) AGV parameters (Speed, acceleration, charge/discharge rates, buffer capacity etc). 2) Processing of the lot schedule. 3) Machine parameters (processing times, buffer capacities etc). 4) System input/output capacities.	1) 3D layout model of the FAS (including all components like machines, AGVs and system input/output towers). 2) Guide path layout for the AGVs. 3) Statistics dashboard (for reporting the key performance indicators for the FAS).

After referring to the table above, it can be seen that all the system parameters are static as well as the processing of the lot schedule, that forms the most essential input to the simulation environment. Variability is induced during model development while designing the model layout and setting up the statistical dashboard. This only makes sense as experimentation with the layout as well as the various AGV configuration forms a part of the testing practices, which in turn paves way for optimisation studies. Furthermore, the statistics dashboard can differ from one user to the other based on what results they wish to focus on, hence it can not be standardised. The standardisation of the input parameters for the system components ensures that the user spends the least possible time and effort on model inputs and more on testing and improvements.

## 5.5 Process flow diagram

The conceptual model is designed using the defined input parameters, output parameters, scope as well as the level of detail for the model. The resulting conceptual model is as seen in figure 5.3. The conceptual model is used to lay the ground rules for the resulting simulation model and can be used as a reference to check whether the simulation model behaves as intended. The conceptual model is split into two areas of control, one for the user and the other for the simulation model itself. The modelling begins with the user building up the 3D model, including the guide path layout for the AGV movement. Next, the input parameters are fed into the designed simulation model. After that, the user selects the speed as well as the run time of the simulation. In the case of this research, the model run time is determined by the lot that has to be processed on it. Hence, the model terminates as soon as the entire lot schedule is exhausted. The simulation begins with lot schedule being read into the simulation model and the products being generated at a system input as a result of it. Next, there is a check on the availability of a Robot (or an AGV). If available, the designated robot is prompted to receive the product from the system input and load it on to its internal buffer. The next step in the model is to check for the machine availability. If the machine is not available, the product would wait in the robot buffer, while it goes around executing its other tasks. As soon as the machine becomes available, the robot moves onto loading the product on the machine. The machine processes the product (or products). Once, the product has been processed, it is either transferred to its designated robot (as per the schedule). Else, it is kept in the internal buffer of the machine before it can be picked up by a robot again. This

process continues until the processing is completed on the last machine. Upon the completion of all processing steps, the robot takes the product and stores it in the system output tower. This same cycle is repeated for all products, unless the lot schedule (which was used as an input initially) is exhausted. This signals the end of the simulation. There are several key performance indicators and system statistics like utilization rates, throughput, AGV charging rates, product flow gantt etc. that are recorded while the simulation runs. These parameters are documented, analysed and used to facilitate optimisation studies on the current setup. Once the changes to be made are recognised, the model is adjusted accordingly and the entire cycle starts again from the user input stage.

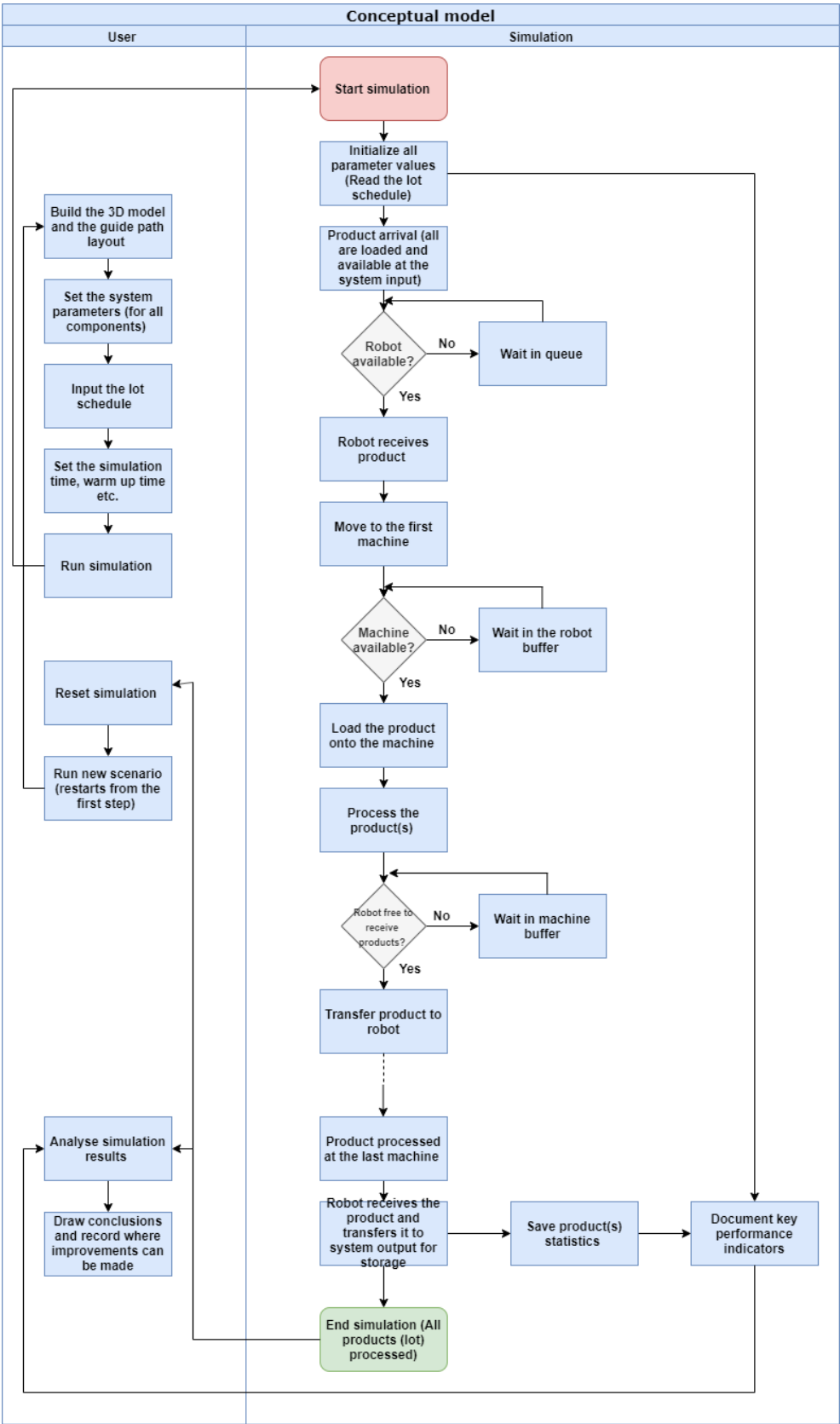


Figure 5.3: Conceptual model

## 5.6 Summary

This chapter discusses conceptual modelling, an important prerequisite towards defining a simulation model. This discussion is carried out based on the findings of Robinson [3]. First the objectives of the simulation model are defined. This leads to the determination of the input and output parameters for the simulation model. Based on the inputs, a discussion is initiated on the variability aspect related to the simulation environment and the developed models. Then we move onto defining the scope and level of detail for the model. This eventually results in a conceptual model. This conceptual model is used as an input to the design and development of the simulation environment, which is discussed in the following chapter.

## Chapter 6

# Simulation modelling

This chapter discusses the simulation modelling procedure. It starts with a brief discussion about the selected simulation tool. Then, based on the selected simulation process (as discussed in Chapter 2, as well as keeping the defined conceptual model in consideration, the simulation environment is created and discussed. The objective of the simulation environment is to enable the modelling and testing of multiple FAS. The simulation models developed on the said environment are virtual copies of the actual physical FAS and are aimed to exhibit the same behaviour to the defined level of abstraction.

### 6.1 Simulation tool

Flexsim is an object oriented software environment that is used to develop, model, simulate, visualise, monitor dynamic flow process activities and systems. The visualisation is possible via tree view, 2D, 3D, and virtual reality animation. Flexsim has several applications, which include modelling systems in manufacturing, warehousing, material handling processes, and semiconductor manufacturing to name a few [49]. This software is currently being used within ASMPT for several simulation projects. A comparative study between FlexSim and other available commercial tools and software packages supporting simulation modelling is done as part of the preparation phase for this research (as listed in Figure 1). *AnyLogic*, *Arena* and *Plant Simulation* are shortlisted alongside FlexSim for the development of the simulation environment. Since the company is already accustomed to FlexSim, this forms a strong case (amongst several other reasons) for the use of the said software as the preferred modelling tool for this research.

As discussed earlier in this report, the simulation environment comprises of a combination of the simulator logic (that is developed on Flexsim's process flow interface) and the 3D model of the FAS (that is developed on Flexsim's 3D modelling interface). The model layout can be accomplished by selecting objects from the library with a simple click and drag operation and placing them in the layout window. The layout window has a 3D spatial view. The process is repeated until the entire layout is completed [49]. The 3D modelling interface as well as one of the example case developed on it are as shown in Figures 6.1 and 6.2 respectively.

As can be seen in Figure 6.1, on the left side, there is a dedicated panel which has a collection of 3D objects that are commonly found in a manufacturing environment. The modelling interface offers everything from equipment to storage racks to material handling systems to even people. For very specific objects, there is an option within the software where solid edge files of an equipment can be imported and hence, a new resource can be created as a result.

After importing all the 3D objects onto the layout window, the next step concerns with the design of the guide path layout. Usually, this layout is constructed based on the factory floor plans, wherein the decision on preferred AGV configuration can be made based on the available floor space. In the case of this research, these floor plans were not made available. Hence, the

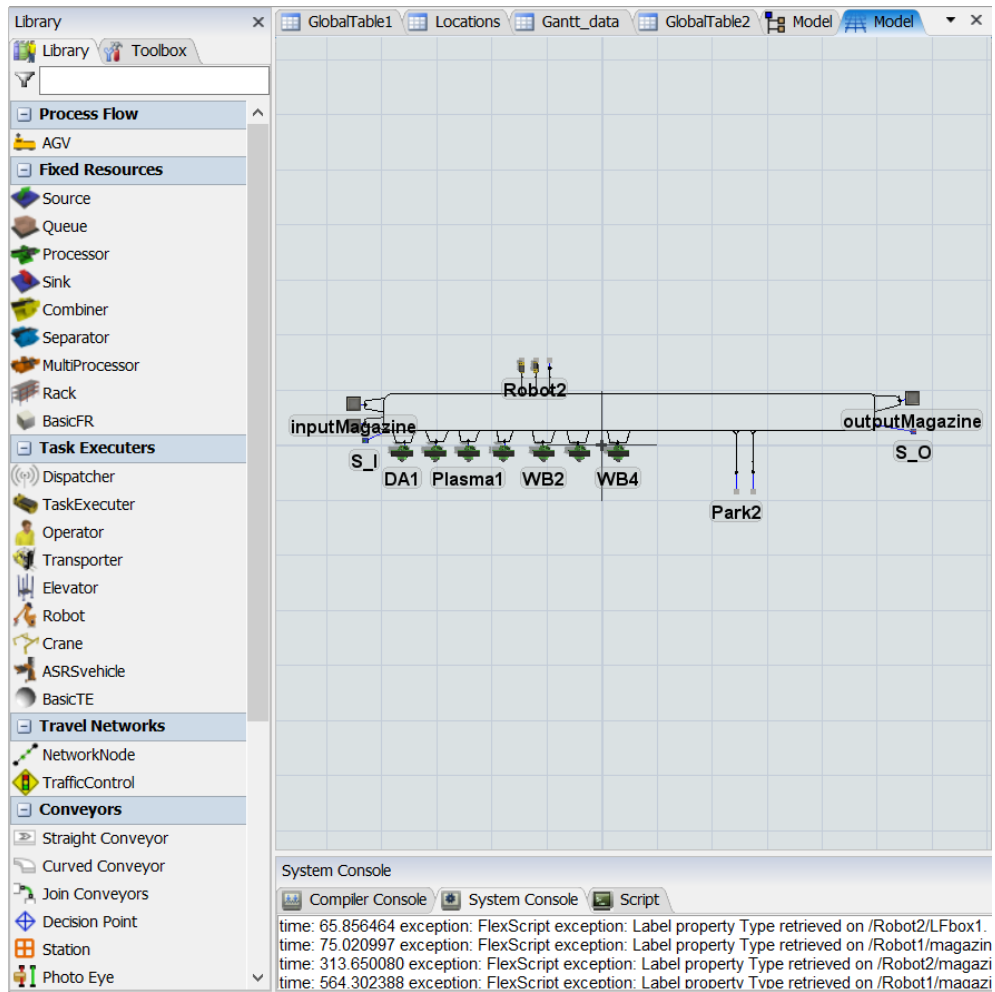


Figure 6.1: Flexsim's 3D modelling interface

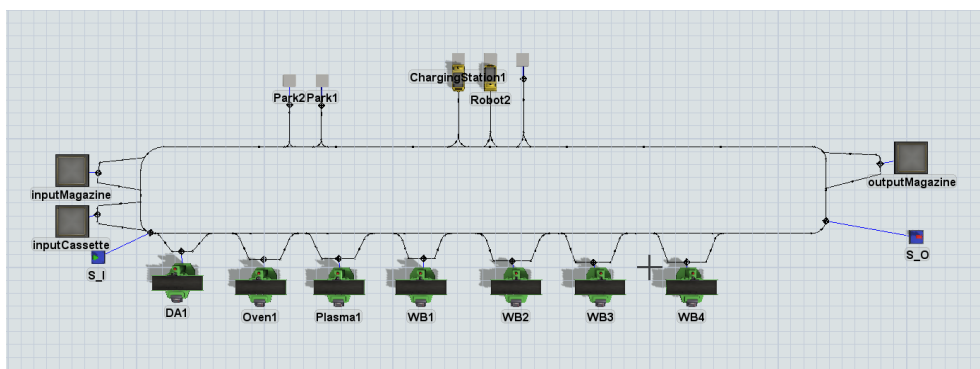


Figure 6.2: 3D model (Example case)

information obtained on the AGV configurations in the literature study done for this research is used as input to construct the guide path layout(s). The guide path layouts can easily be constructed using the components of the AGV category in the 3D modelling library. Once the

model has been constructed as required, the next step deals with the modelling of the simulator logic that controls the 3D model.

## 6.2 Simulation environment

Before beginning a discussion on the simulation environment and modelling of its background logic, it is essential to understand one of the key inputs to the simulation environment, the lot schedule. Figure 6.3 shows a snapshot of the said schedule. Apart from the input parameters mentioned in the previous chapters, the lot schedule is an essential input as well. As explained earlier, the AGV based MHS (as in the case of this research) is responsible for all the material transfer between the machines. The lot schedule specifies the location of the robot and the tasks to be executed by it.

Task_Type	Robot_ID	Information	Column1	_1	_2	_3
1	Robot1	ChargingStation1				
2	Robot1	ChargingStation1				
1	Robot2	inputCassette1_M				
1	Robot1	inputMagazine1_M				
3	Robot1	inputMagazine1	2 Magazine	inputMagazine1,0,1	Robot1,1,1	
3	Robot2	inputCassette1	1 Cassette	inputCassette1,0,1	Robot2,1,1	
1	Robot1	DA1_R				
1	Robot2	DA1_M				
3	Robot2	DA1	1 Cassette	Robot2,1,1	DA1,1,1	
3	Robot1	DA1	2 Magazine	Robot1,1,1	DA1,3,1	
1	Robot2	inputMagazine1_M				
1	Robot1	ChargingStation3				
2	Robot1	ChargingStation3				
3	Robot2	inputMagazine1	3 Magazine	inputMagazine1,0,2	Robot2,1,1	
1	Robot2	DA1_R				
3	Robot2	DA1	3 Magazine	Robot2,1,1	DA1,3,1	
1	Robot2	inputMagazine1_M				
3	Robot2	inputMagazine1	4 Magazine	inputMagazine1,0,1	Robot2,1,1	
1	Robot2	DA1_R				
3	Robot2	DA1	4 Magazine	Robot2,1,1	DA1,3,1	
1	Robot2	ChargingStation2				
2	Robot2	ChargingStation2				
1	Robot1	DA1_R				
3	Robot1	DA1	2 Magazine	DA1,4,1	Robot1,1,1	

Figure 6.3: Lot schedule (example case)

The schedule is as explained below -

1. **Task type** – There are 3 different task types namely, 1(Move to location), 2(Move to charging station) and 3(Transfer between from and to).
2. **Robot\_ID** – Identification number of the Robot which is executing a particular task at a particular moment in the schedule.
3. **Information** – The current location of Robot.
4. **Column 1 (or product ID)** – Identification number of the product that is being processed.
5. **\_1 (or the container type)** – Type of the product being processed or container type (example – cassette, magazine or lead frame box).
6. **\_2 (or the Origin)** – Applicable only for *task type 3*. Specifies the origin from where the product has to be transferred to another machine.



7. **3 (or the destination)** – Applicable only for *task type 3*. Specifies the destination to where the product has to be transferred.

Now that the schedule has been established, the next step is to see how this schedule is processed by the simulation environment. As explained earlier, the simulation environment is made up of a 3D model (that represents ASMP T’s actual physical FAS) as well as the embedded simulator logic, that controls how the 3D model behaves. The figure 6.4 shows the simulator logic, modelled on Flexsim’s process flow interface.

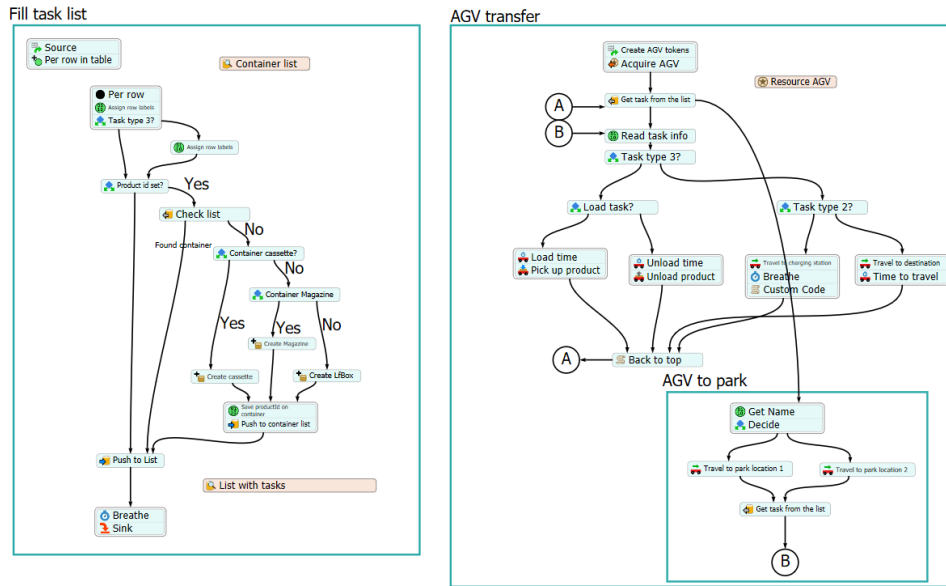


Figure 6.4: Simulator logic for processing the lot schedule

The simulator logic to process the lot schedule has been split into two different blocks, namely the creation of a task list (*Fill task list*) for the AGVs and the execution of those tasks (*AGV transfer*). The first block (i.e. *Fill task list*) deals with the conversion of the lot schedule file into a readable instructions that can be executed by simulator. These instructions are then translated into tasks to be assigned to the individual AGVs. The second block (i.e. *AGV transfer*) concerns the AGVs executing their assigned tasks, hence successfully executing a lot. The underlying logic behind the simulator logic has been explained via the following flow diagrams (refer figures 6.5 and 6.6).

As explained earlier, Figure 6.5 lists the steps undertaken for the translation of the list schedule into a list of task to be undertaken by AGVs. As can be seen in the figure below, the process starts with creation of tokens. Tokens are a means of exchanging information within Flexsim. When a token is assigned to a row in the lot schedule, all the information stored in that particular row is transferred to that token. Hence, the primary activity is the creation of tokens per row for the lot schedule file. The next step deals with referencing the different parts of the information carried by the token for further processing of the lot schedule. So at first, a row token is accessed and the labels *Task\_type*, *Robot\_ID*, *product\_ID*, *container* and *Information* are created. Then, the label *Task\_type* is accessed and it is checked whether the task type is 3 or not. Row tokens pertaining task types 1 and 2 are directly added a newly created container list, that will be used later as an input to the AGV transfer logic. In case of the instances of the label "Task\_type" that carry the value **3**, additional labels on "from" and "to" locations for the AGVs are created and assigned to these instances. These labels are only assigned to Task type 3, as this is the only task that refers to the *origin* (*from*) and *destination* (*to*) of a product. After this step, the tokens are pulled out,

as the file is read, and the label "container" is checked against each of the three product types, namely cassette, magazine and lead frame box and products are created here. Finally, the label **Product\_ID** is attached to the created products and these are added to the previously created container list. With the addition of task type 3, the list is completed and can be used for the AGV transfer task now. The flow ends with the entire list being split based on the different Robot\_IDs. This split ensures that each robot (or AGV) has its own list to execute. This list is named as *List with tasks* and will serve as the starting point for the next part of the simulator logic.

Moving on, figure 6.6 deals with the execution of the created list (also known as the *List with tasks*) in the first step. This begins with the creation of tokens for referencing values from the *list with tasks*. Once the required tokens are created, the AGVs are acquired and the task list is read for each individual AGV. There is a check that follows regarding the task type. If the task type is 3, a load or unload task is executed. If it is task type 2, the AGV is directed to travel to its assigned charging station. Else, it is a task type 1, in which case the AGV is directed to be at a certain location, based on the label "Information". This label references to a certain location in developed simulation model. Thus, when the task type 1 is accessed, the AGV is prompted to be at location being referred to. This cycle repeats itself after every row is read in every task list for the individual AGVs, until all the tasks are executed. Once the tasks lists are exhausted, there is a special task, *Task type 4* which is added to the list. This task is included in the list for every AGV so as to direct the AGV to an appropriate location to park and avoid any network congestion. This way the AGVs that are done with their tasks are stowed away in a parking location and do not block the other AGVs that might come in their way. To make the simulator as flexible as possible, there is an option to push tasks at the end of the list. This means that if there are any new tasks that are required to be executed, whilst the AGV is parked away, then their existing task list can just be updated and fed to the simulator logic. Once executed, the AGVs will pull out of their parking spots and resume work as usual. This concludes the explanation on the working of the simulator logic.

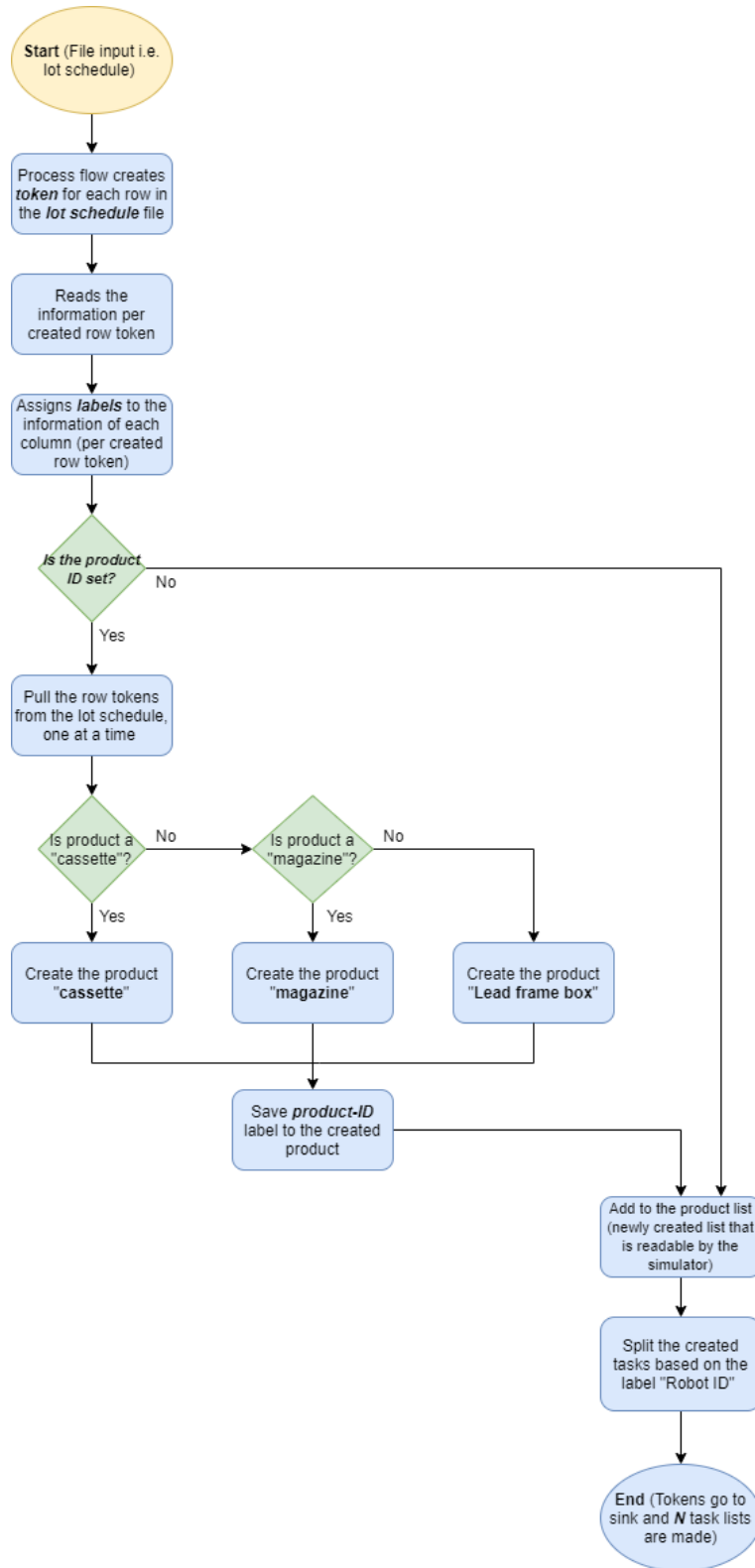


Figure 6.5: Creation of a task list for the AGVs from the lot schedule

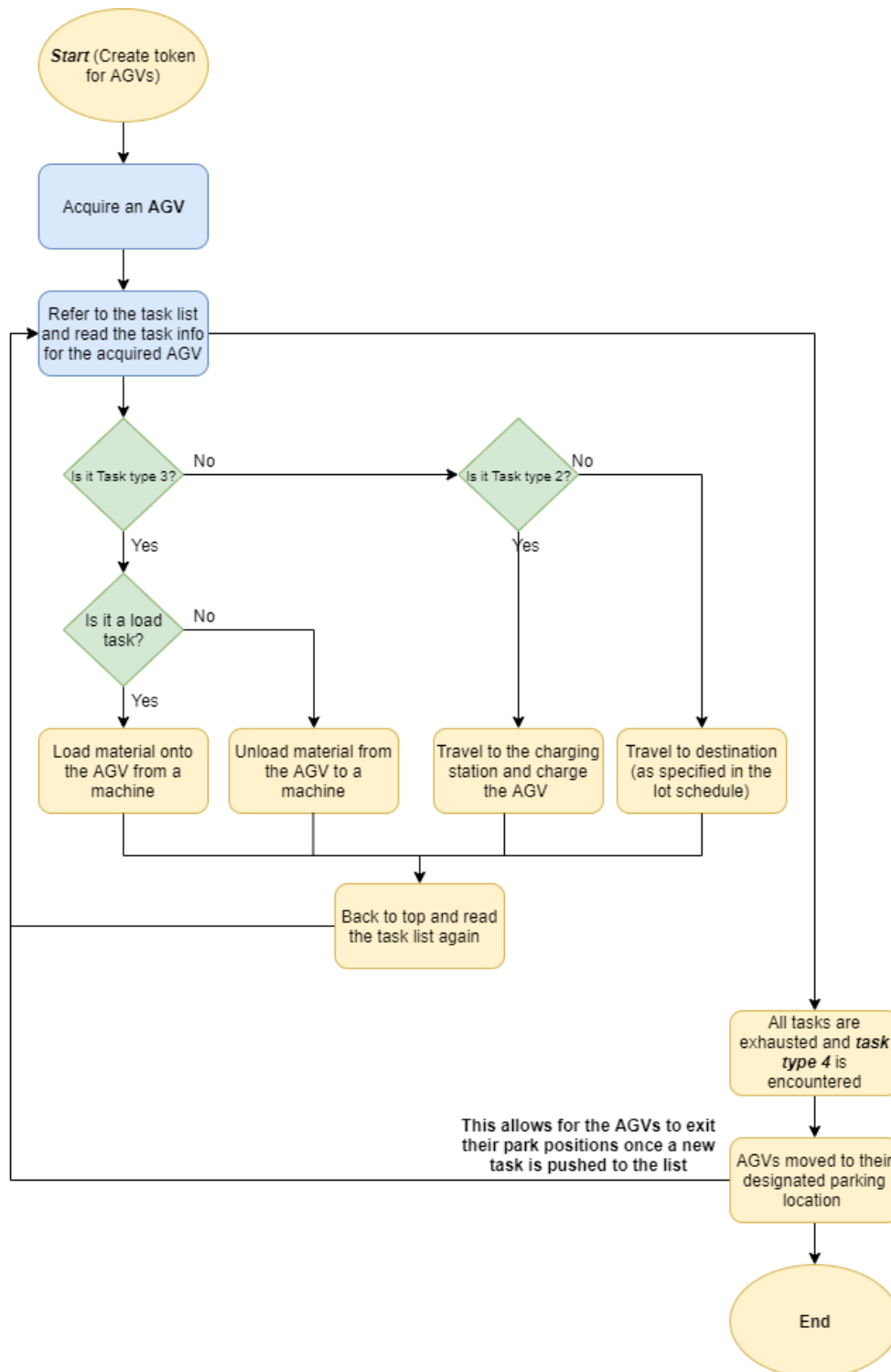


Figure 6.6: Execution of AGV tasks

### 6.3 Running the simulation model

Now that an understanding of the underlying simulator has been established, the next step concerns the execution of the simulation models developed as a result. The simulation model execution begins with the initialisation of the system. This concerns two important factors, namely -

1. **Simulation run time** - The simulation run time is duration for which the model has to be executed and the resulting data has to be recorded. In the case of all the models that have to be developed on the simulation environment, the simulation run is defined as the time that takes to exhaust all the task as per the lot schedule that is given as an input to the simulator.
2. **Warm-up time** - There are two different kinds of system behaviours when it comes to a simulation run, namely **terminating and non-terminating**. A non-terminating (or steady state) simulation is the one where the steady state behaviour of a system is under consideration. In order to analyse the system during this steady state, there is an initialisation bias that has to be taken into consideration. This bias ensures that the simulation starts recording the data only once the steady state behaviour of the system is achieved. This bias is also known as the *warm up period* of the simulation [50]. In the case of this research, the start and end states of the system are known (start with all unprocessed products in the system input and ends with processed items in the system output), hence it is an example of a terminating system behaviour. Terminating systems are specific about their boundary conditions and hence do not require any initialisation bias to be specified for their simulation runs. Thus, such a period does not have to be specified for the model developed in the case of this research.

The procedure for executing a simulation model designed on the developed simulation environment for this research can be summarised as follows -

1. Set the system parameters for the components of the simulation model.
2. Set the simulation run length, speed as well as the warm up period (if applicable).
3. Run the simulation by clicking the "START" button and wait until the simulation run is finished.
4. Check the dashboard for results. All the system performance indicators are reported here.
5. Reset the simulation.
6. For testing new layouts and/or schedules, construct a new model.
7. Start again with Step 1.
8. Analyse the results and conclude.

The analysis includes testing of different lot schedules that vary in the number of machines and products involved, as well as an increased complexity of control in terms of the material handling system. The other analysis that is conducted is based on the different guide path design layouts (as reviewed in the literature study done for this research). Multiple layouts are developed and tested for the same system configuration to initiate analysis into their effect on the system performance. More on this is expanded upon in the following chapter.

### 6.4 Summary

This chapter starts with initiating a brief discussion on the simulation tool Flexsim. This is followed by an explanation on the underlying simulator logic and how a lot schedule is broken down for its processing on Flexsim. Then, the execution of the simulation model and the key parameters involved are discussed. This concludes the design and development phase of the project. Following chapters explore the validation and experimentation phase of this research.

## Chapter 7

# Validation and verification

This chapter discusses the validation and verification of the developed simulation environment. First, model verification and the related roadblocks to its realisation are discussed. Then, the simulation environment is used to construct an appropriate 3D model, according to one of the lot schedules being tested. Then, a varied number of guide path layouts for the same case are presented. The related dashboard consisting of the model in hand is also shown here. The following section presents a comparative study on the traditional vs tandem layout for the same case as presented before. The chapter concludes with a general summary of the findings of the validation, experimentation and verification phase.

### 7.1 Model verification

Model verification is essential to ensure that the conceptual model is accurately reflected in its computerised representation. Model verification techniques can be broadly classified into two categories namely, *Subjective tests and objective tests* [51]. Subjective testing concerns consulting people who are knowledgeable about the system whereas objective testing requires data on the real world system, which then leads to a comparison with the data generated from the simulation model. Since a real world system does not exist in the case of this research, subjective testing can not be executed. This leaves us with the option of objective testing, wherein a number of statistical tests are available to relate the performance of the simulation model to the real world system. In order to perform statistical analysis on the simulation results, it is essential to do several replications runs of the models to extract varying results on key performance metrics like *average waiting time in the queue, average queue length, average utilization rate etc.* These results can be used in direct formulas to analyse the overall performance of the simulator from statistical results like *mean, SD, half width, CI etc.* These statistics can only be obtained in case there is randomness in the processing times of the machines or the inter-arrival times of the products. However, all of the products are available at the same time in the input material tower (so there is no randomness in the inter-arrival times of the products) as well as the process times of the machines are all deterministic (as explained in Chapter 4). Thus, the simulation runs will always produce the same results, no matter how many runs are executed, given the absence of randomness in the entire line. Thus, owing to the above stated reasons, simulation verification has not been pursued for this research.

### 7.2 Model validation

Validation is essential to determine whether a model's output behaviour has the accuracy required for the model's intended purpose over domain of its intended applicability. To obtain a high degree of confidence in a simulation model and its results, the comparison of the model's and the actual system's output behaviour under a different set of experimental conditions is usually required. In

the case that the model is not observable (as is the case in this research), it is not possible to obtain high degree of confidence in the model. Robert [4] presents a classification on validation techniques for both an observable and non-observable system. They have been summarised as seen in table 7.1 -

Table 7.1: Validation approach classification (Robert [4])

	Observable system	Non-observable system
<b>Subjective Approach</b>	1) Comparison Using Graphical Displays 2) Explore Model Behavior	1) Explore Model Behavior 2) Comparison to Other Models
<b>Objective Approach</b>	1) Comparison Using Statistical Tests and Procedures	2) Comparison to Other Models Using Statistical Tests

As can be seen in the summary, the validation approach can be broadly classified into a subjective and an objective approach. A further classification can be done based on the whether the system is observable or not. As in the case of this research, where actual physical setups for the FAS manufactured by ASMPT does not exist, the *non-observable system* approaches can be applied. *Exploring model behaviour* concerns examining its output behaviours and whether their reported magnitude is reasonable or not. The second step concerns with comparison to other models developed on the simulation environment. This has been explored in Section 7.2. Another one of the approaches deals with statistical testing of the developed models. This has been touched upon in Section 7.1 in more detail.

### 7.3 Model experimentation

As discussed in Chapter 2, an extra emphasis been laid upon the guide path layouts. The designed simulation environment provides a platform for development and implementation of multiple layouts for the same test case. The composition of the test case FAS is as described below -

1. **Input product** - Magazine, Cassette and Lead-frame box.
2. **Machines** - DA 1 and 2, Oven, Plasma and WB (1 to 10).
3. **Output** - Magazines and Cassettes.
4. **Other components** - System input towers, System output towers, Charging stations (1,2 and 3) and Parking stations (1,2 and 3).



Figure 7.1: Guide path layout (Option 1)



Figure 7.2: Guide path layout (Option 2)



Figure 7.3: Guide path layout (Option 3)

Based on the listed system configuration, a number of layouts have been designed on the simulation environment, as shown in Figures 7.1, 7.2 and 7.3. The guide path layout designs have been inspired by the traditional guide path layout configuration. All the components of the FAS are placed around a singular loop in which the AGVs operate. Each machine has an area in front of them, which an AGV can temporarily occupy, while a load/unload operation is executed by it. This area ensures that an AGV does not block another AGV while performing any of its tasks at a machine. The three guide path layouts are a slight modification of one another. The second layout is suggested to be as one of the possible layouts of the actual physical FAS (by one of the domain experts), the first layout is a generic single loop configuration and the third layout is adapted from the first option, with a minor adjustment of the inclusion of exit lanes in front of each machine. These exit lanes have been included to allow AGVs to exit after completing their operations on one of the machines, instead of having to go around the entire loop. The developed simulation environment has been used to test all of these above mentioned layouts and compare their performance on certain key system metrics.

Before the key performance statistics can be reported, it is essential to validate if the simulation environment is modeling the FAS accurately enough or not. Due to the absence of an actual physical FAS setup, any data on the performance of the real system is not made available. This leads us to the only possible source of validation, the lot schedule. The lot schedule (as seen in figure 6.3, specifies the flow of the product, as it is processed through the FAS. For validation purpose, a product flow tracker is built into the simulation environment. This product flow tracker refers to each individual product ID and shows their flow in real time, as the simulation is being executed. Thus, this product flow tracker can be used as a validation tool for the models developed on the simulation environment. Figure 7.4 shows the results post a simulation run. This statistic is tallied with the schedule to see if the lot is executed correctly. As can be seen in Figure 7.5, the flow of product with an ID "2" as per the schedule can be cross-checked with the results reported by the product flow tracker. It can be seen that product 2 has an identical flow in the simulation run as compared to its schedule. Hence, this validates that the simulation has executed the lot



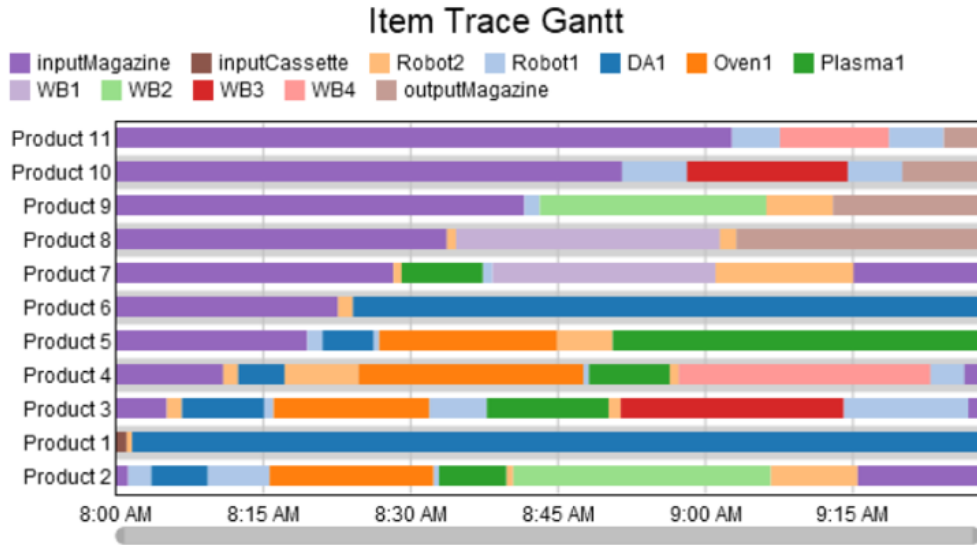


Figure 7.4: Product flow tracker

Task_Type	Robot_ID	Information	Column1	_1	_2	3
3	Robot1	inputMagazine1	2 Magazine	inputMagazine1,0,1	Robot1,1,1	
3	Robot1	DA1	2 Magazine	Robot1,1,1	DA1,3,1	
3	Robot1	DA1	2 Magazine	DA1,4,1	Robot1,1,1	
3	Robot1	Oven1	2 Magazine	Robot1,1,1	Oven1,1,1	
3	Robot1	Oven1	2 Magazine	Oven1,4,1	Robot1,2,1	
3	Robot1	Plasma1	2 Magazine	Robot1,2,1	Plasma1,1,1	
3	Robot2	Plasma1	2 Magazine	Plasma1,2,1	Robot2,1,1	
3	Robot2	WB2	2 Magazine	Robot2,1,1	WB2,1,1	
3	Robot2	WB2	2 Magazine	WB2,3,1	Robot2,3,1	
3	Robot2	inputMagazine1	2 Magazine	Robot2,3,1	inputMagazine1,0,1	

Figure 7.5: Transfer activities for Product ID "2"

correctly. The flow is checked for all products and even for multiple lot schedules to affirm this belief. Hence, the simulation environment is validated to be working correctly. Post validation, the testing phase follows. Here, some of the different lot schedules as well as guide path layouts are implemented. ASMP currently deploys the practice of constructing all the case scenarios from scratch, based on the lot they have to test via a simulation run. The developed simulation environment for this research eliminates the need for continuous model development. 3D model can be constructed and executed by a simple input operation of the lot schedule file. The cases shown in Figures 7.3, 7.2 and 7.1 are developed and tested on the simulation environment and the following statistics are collected as a result.

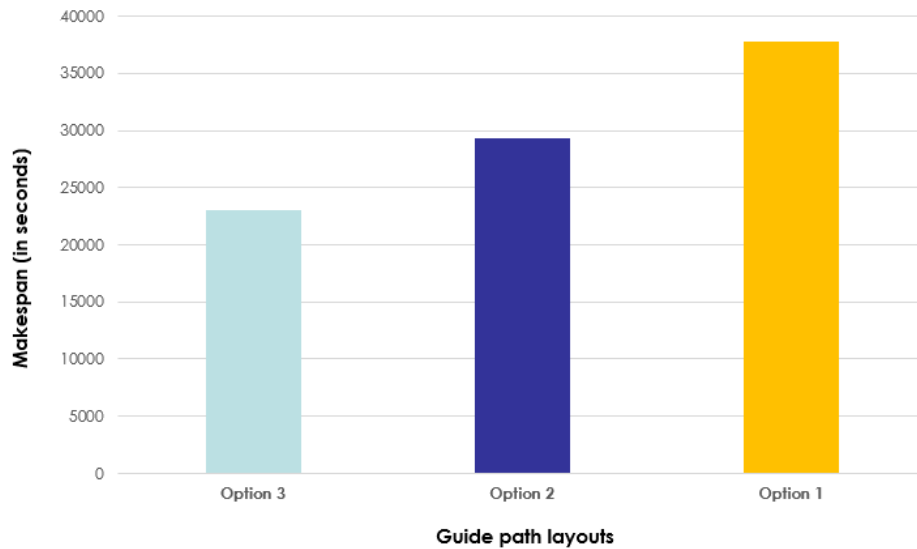


Figure 7.6: Makespan comparison between the three layout options

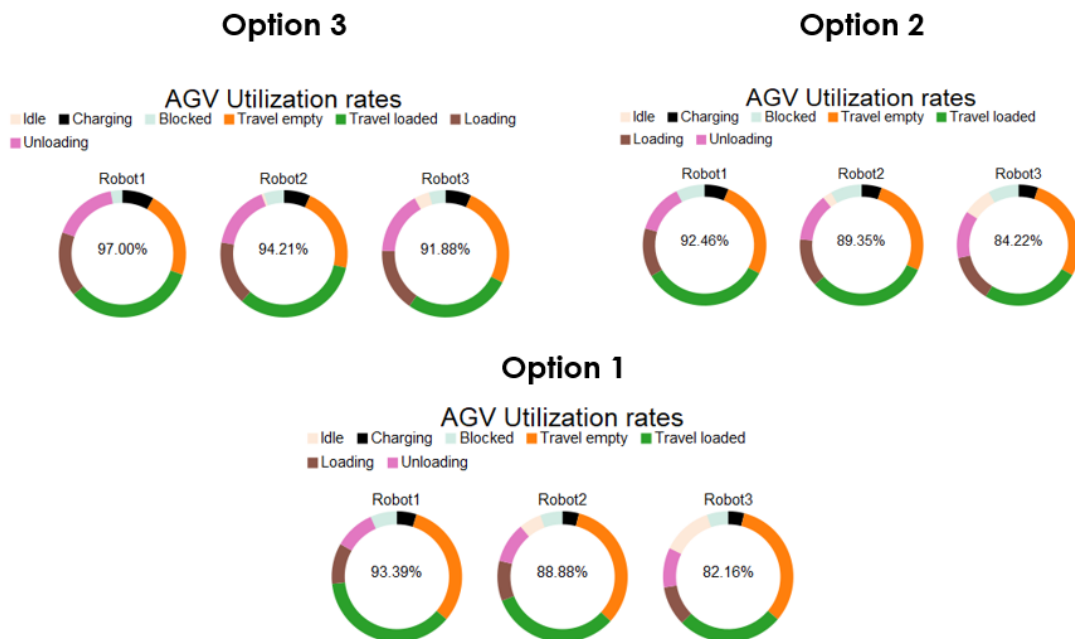


Figure 7.7: Utilization statistics for the AGVs (per layout)

As can be seen in Figure 7.6, the layout option 1 seems to have a significantly higher makespan compared to the other two options, owed to the longer travel path around loop for the AGVs. Here, makespan is defined as the time taken to execute a certain lot schedule by the FAS. Option 3 seems to have the shortest makespan and that can be related to the presence of exit lanes in front of every machine. Those lanes provide a shortened route to each AGV and thus, reduces the overall execution time for a lot. However, the statistics seen in Figure 7.7 seem to reflect a certain downside of the exit lanes. It can be seen that the utilization rates are higher for the

AGVs in option 3 as compared with option 1. A significantly higher amount of time is spent on empty travel by robots in the layout with the exit lanes as compared to the one without them, which can be related to the longer distances to be travelled in latter option. Also, with higher utilisation rates, the AGVs will also be expected to visit the charging stations more often, as they get exhausted faster given the shorter execution time. The same has been reflected in the utilization statistic, where it can be seen that as the guide path becomes longer, the AGVs utilise more of the charging stations than they would for a regular single loop layout (as seen in Option 1).

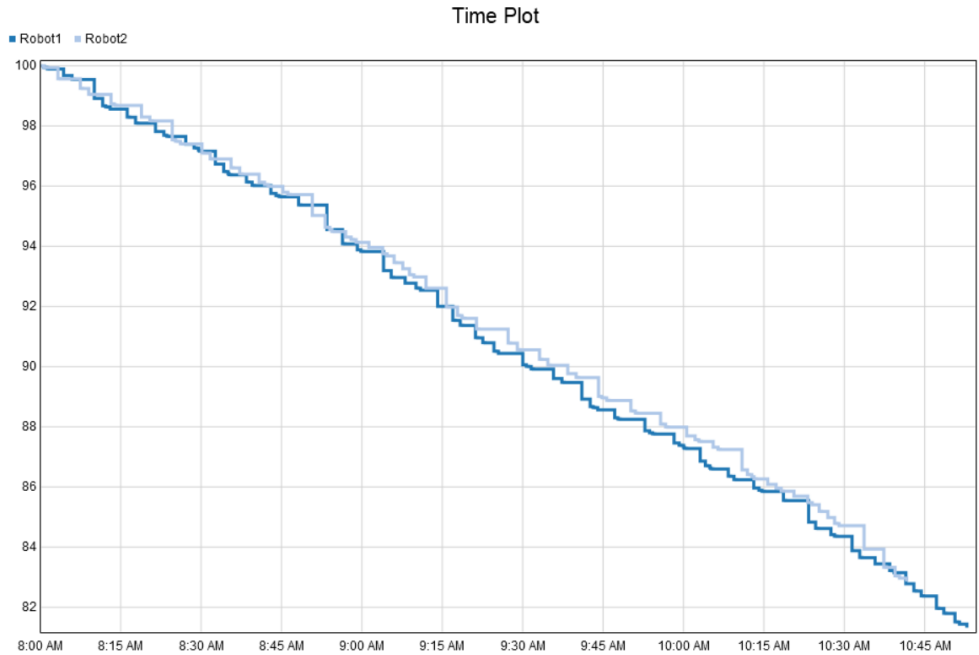


Figure 7.8: AGV battery consumption with time

Another conclusion that can be made is about the idle time of the AGVs, which clearly increases from option 3 to 1. This is again owed to the shorter travel guide path in option 3 as compared to the longer, single loop layout in option 1. Thus, these are some of the conclusions that can be drawn from the utilisation statistics drawn from the simulation model. These statistics can be looked at by a domain expert and iterations can be made to the model until desired model performance can be achieved. Another one of the key performance metrics obtained from the simulator is as seen in Figure 7.8, where the battery consumption of all the AGVs is plotted. Here, the y axis represents the battery level with time on the x axis. This statistic can be used to visualise the battery level of an AGV in real time. Along with this, a real time battery level display of each individual AGV is also built into the simulation environment. The above mentioned statistics are some of the key performance metrics that can be extracted out of the simulation model. There are several other metrics like *utilization pie charts for each individual machine*, *throughput per machine per part type*, *WIP in the system*, *Staytime per part type etc.* that can also be setup in the simulation environment.

### 7.3.1 Tandem configuration v/s Conventional configuration

As discussed in the literature review, Tandem configuration is one of the non-traditional AGV configurations that is being widely implemented as a preferred alternative over the traditional layouts (as the ones shown in the previous sub-section). A tandem configuration offers simplicity of control, ease of expansion and less vehicular congestion as some of its advantages over a traditional configuration. This subsection reflects upon the testing of a tandem configuration adapted layout for the test case established in the start of the chapter. The 3D model for the tandem configuration adapted layout is as shown in Figure 7.9.

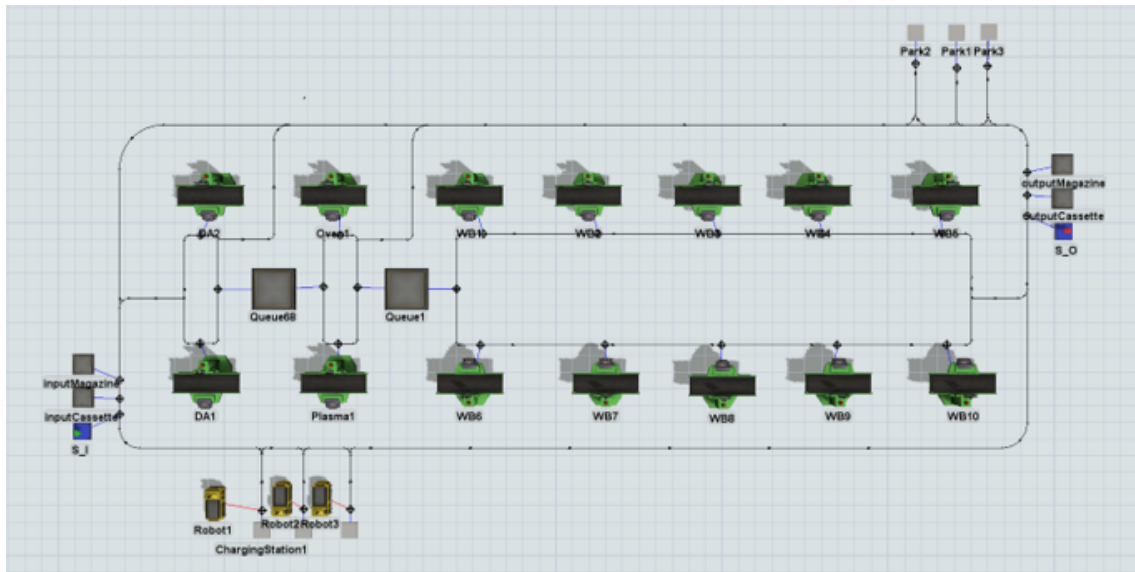


Figure 7.9: Tandem layout configuration (adjusted for the example case)

As can be seen in Figure 7.9, the layout has been split into 3 sub loops, which in turn are a part of a bigger single loop. This split is based on the machine types, where all the similar machine groups are kept in the same loop and a single AGV is assigned to that loop. Thus, the first loop is made up of DAs and AGV type 1 is assigned to it. The second loop is made up of plasma and an oven, while AGV type 2 operates in the loop. Finally, the third loop is made up of all the WBs and AGV type 3 operates in that loop. All three sub-loops are connected to the bigger loop via an exit and entry lanes. The AGVs can travel back and forth from the system input and output towers to their respective loops via this track (when needed). The charging and parking stations are also commissioned on this external loop. The external loop is a unidirectional (clockwise) loop. The three sub-loops are bidirectional (since a single AGV operates in a loop), with intermediate buffers between all three loops. These buffers are an essential part of any tandem configuration.

Before the model can be executed on the simulator, the lot schedule file (that serves as the main input to the simulation model) is altered to suit the tandem configuration. AGVs were reallocated to the machine groups (as described above) and intermediate buffers were added to the lot schedule file. This modification is achieved via a MATLAB code, that takes in an original lot schedule file as an input and produces the modified file as an output, which can serve as a direct input to the tandem model. Once the lot schedule file is made ready, the tandem model can be executed.

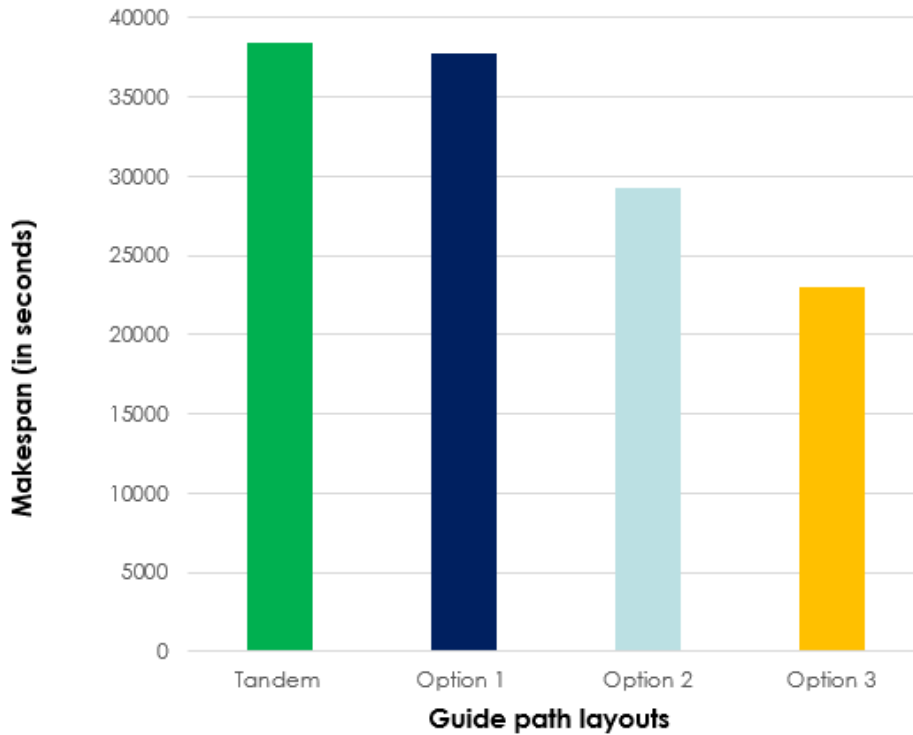


Figure 7.10: Tandem vs Traditional guide path layouts

Figures 7.10 and 7.11 highlight the performance metrics for a tandem configuration as compared with the traditional configurations discussed earlier. As can be seen in Figure 7.10, the tandem layout clearly has the highest makespan, which means that it takes the longest to process the same lot as the one tested on the traditional configuration. This can be owed to the fact that the AGVs work in a more restricted manner that doesn't allow for multi-tasking. This means that in a traditional configuration, where multiple AGVs can work on multiple machines allowed for a faster execution of the lot, in the case of a tandem layout that was not the case. Each loop has its own AGV and each AGV was responsible for a certain operation. This meant that an AGV down the line had to wait for the upstream tasks to finish before it can even start executing its own tasks.

A similar conclusion can be drawn from the utilisation rate statistic, where it can be seen (as per Figure 7.11) that the AGVs have a significantly low average utilisation rate as compared to the traditional layouts. This suggests that there is room for expansion in terms of the number of machines processing the lot as the AGVs are being under utilised. The under utilisation is also reflected in the high idle and low charging percentages in the state composition for each of the AGVs involved.

Thus, it can be concluded that for the test case in hand, the traditional configurations performs better than their tandem alternative. The higher makespan and significantly lower utilisation rates suggest that despite all the advantages of a tandem layout, the lot in hand is too small to make the best use out of the configuration. Although it does provide ease of control and lowered congestion for the MHS, which suggests that for an FAS consisting of a significantly higher number of machines and AGVs, a tandem configuration can prove to be a better choice for the guide path layout.

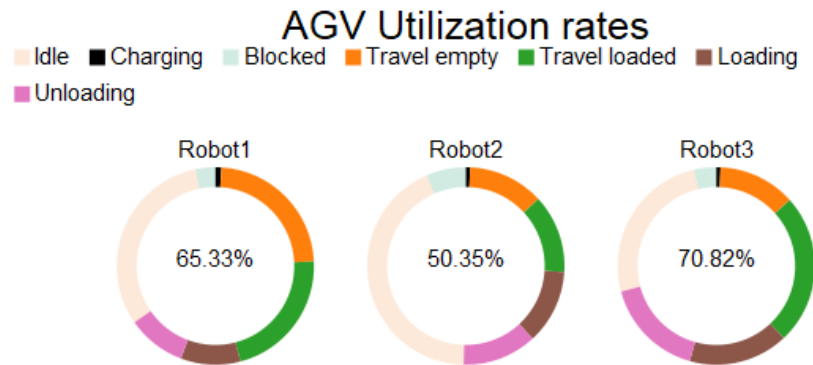


Figure 7.11: Utilisation rates for AGVs (Tandem)

## 7.4 Summary

This chapter expands upon the post development phase of this research. Model verification is the first step, where it is concluded that verification becomes difficult due to the absence of randomness in the input parameters. Subsequently model validation is discussed, where it is established that a direct comparison between the lot schedule and the product flow statistic generated by the simulation environment is the only way forward. Product wise comparison between the two implies that the developed simulation models are working correctly. A comparison between the different guide path layouts follows, which extends to both traditional as well as tandem configurations. The layouts are compared on a couple of key performance metrics, namely average utilisation rates of the AGVs and the makespan. It is concluded that traditional layouts perform better for the case in hand, but tandem layouts can prove to be more suitable for larger and more complex systems. This concludes the chapter and leads to the conclusions as well as the future scope of this research.



# Chapter 8

## Conclusions and future steps

In this chapter, the research is concluded, limitations of this research are highlighted and scope for the future research is discussed. Section 8.1 discusses general conclusions made from this thesis. The following subsection 8.2 discusses the future steps for this research.

### 8.1 Conclusion

This thesis looks into the possibility of developing a solution for ASMPT in order to enable them to perform testing of their FAS, without actually having to develop a physical setup. This objective serves as the motivation for the research, where the goal is identified to be the creation of a simulation environment, that can facilitate the development and testing of the FAS produced by ASMPT, virtually. The research question used to fulfill this goal is stated as follows -

*To develop a simulation environment that facilitates the modelling and analysis of multiple factory automation setups.*

The research question is split up into the several sub research questions to help tackle the problem in hand, which are as follows -

1. *What are the system parameters that capture the components of an FAS?*
2. *How can the machines be modeled so that they effectively mimic the real world system?*
3. *How can the AGVs be modelled so that they effectively capture the behaviour of their real world copies and the rules they operate on?*
4. *How can the different system configurations be evaluated in order to select the most suited setup for the customer?*
5. *How can the simulation environment be delivered to the end users so that it can be used with minimal knowledge of the simulation tool?*
6. *How can the host software's operations be mimicked in the simulation environment so as to mirror the control logic as it is available through the actual host software?*

The first and second research questions are answered by a deep dive into the workings of the actual physical FAS. First, a typical FAS is shown and discussed. This leads to an explanation on the process flow through line and a discussion on all the main components of the FAS. Here the main parameters for the machines as well as all the other components of an FAS are discussed. These parameters are considered while modelling the machines on the simulation environment. Furthermore, the flow of material within a machine is also highlighted. The sources of variability in the system due to certain exceptions for the machine component are also discussed here.



The third research question has a multi-fold explanation to it, as it is captured over several chapters. The first step towards modelling the AGVs concerns a discussion into the simulation design methodology for the system, which is chosen to be a combination of discrete event modelling (for the system) and agent based modelling (for the MHS). Then, same as the rest of the components of the FAS, the system parameters for an AGV are discussed. Another important aspect of the MHS design is the guide path layout, which has been expanded upon in the systematic literature review. Traditional and tandem layouts are identified as the two broad categories that are relevant for this research. Later on, they are implemented on the developed simulation environment and compared via several key performance metrics.

The fourth research question is answered upon the realisation of the simulation environment and after a thorough understanding of the simulation platform, Flexsim is achieved. First, a number of different layouts for the same test case are developed. These are executed and the resulting statistics are compared to see which configuration performs better than the other.

The fifth research question is answered through the development of a simulation environment that requires minimum customisation from the user. The simulation environment facilitates ease of model development via a simple drag and drop operation. The system parameters for all components are pre-programmed into the simulation environment, so that the user does not have to enter them in repeatedly, every time a new model is developed. The underlying simulator logic allows easy processing and execution of the lot schedule file supplied as an input to a simulation model. Finally, the statistics dashboard is setup to provide the user with insights into the system performance.

The last and final research question deals with the modelling of the host software. As explained in Chapter 2, the host software acts as a control for the entire system, as it sets up the lot to be processed as well as provides with corrective measures in case of exceptions like machine/AGV breakdown, material shortage and changes in the lot schedule. This meant that a communication means in and out of Flexsim has to be realised so as to mimic dynamic changes in the simulation. Such a communication would capture the behaviour of the host software, as it would allow the user to communicate the changes in the schedule in case of an exception. Unfortunately, this research question couldn't be realised in the given time frame for this research. Hence, this leads to a future step in the research that delves into the area of dynamic scheduling.

## 8.2 Limitations

During the development phase of the simulation environment, a number of roadblocks and obstacles have been identified. They are as listed below -

1. *Lack of modelling details* - Due to lack of a number of model related details such as the physical layout, the floor plans, the AGV configurations and control strategies being used in the actual physical FAS, MTTF and MTBF data, a lot of assumptions had to be exercised. Due to such assumptions, the model developed on the simulation environment may or may not be an accurate representation of the real world FAS.
2. *Inability to verify the developed models* - As explained in the Chapter 7, due to the deterministic nature of the system parameters, there was a lack of variability in the process. This lack of variability leads to issues with exercising simulation verification in the case of this research. Since verification is an important step in the simulation modelling methodology, it has been identified as one of the limitations of this research.
3. *Dynamic scheduling* - Dynamic scheduling is associated with the last research question, that concerns mirroring the operations of the host software (as explained in Section 8.1). Given the limited time frame of this research, this question could not be pursued and thus forms another one of the limitations for this research. It forms an essential future step and has been expanded upon in Section 8.3.

As already mentioned in Section 1.1 of Chapter 1, ASMPT's inclination towards turning into a completely digital enterprise serves as one of the motivating factors for this research. At this stage, it can be concluded that the developed simulation environment is a step in the right direction towards serving the company goals going forward. Addressing the above mentioned limitations would make the simulation environment a more robust and efficient tool for simulation modelling and analysis of the company's FAS. As far as the implementation plans for this research are concerned, that is something the higher management still has to make a decision on. For the time being, future plans have been established towards improving the simulation environment, which has provided a solid base towards achieving ASMPT's Industry 4.0 objectives.

### 8.3 Future Steps

As explained earlier, the replication of the host software's behaviour forms one of the sub research questions that contributes to the main research goal. Incorporation of this aspect into the simulation environment allows the user to dynamically make changes to the simulation models and its inputs. This also allows for a better representation of the actual FAS as in reality such a system is highly prone to failures, breakdown or any other unforeseen circumstances. This can be achieved by establishing a means for communication between the simulation environment developed on Flexsim and an external system consisting of the host software. In case an exception occurs in the system, the simulator communicates that back to the host computer, which then assess the exception and supplies it back to the simulation model. For example, if there is a machine breakdown in the simulation model, the simulation environment can send a communication back to the host computer asking for a fix. The host computer can then redesign a new lot schedule, taking into consideration the exception and send it back to the simulation environment. The model being run on the simulation environment can then re route the AGVs accordingly. This is what the dynamic scheduler is envisioned to achieve and forms as one of the essential future steps towards achieving a more realistic modelling experience for the user. Another future step would be the modelling of the actual machines in terms of their external appearance. At present, the machine appearance is the stock components that are available within Flexsim. However, Flexsim does allow direct import of Solid edge files for modelling external appearance of essential components in a manufacturing scenario. Thus, this can also be included as one of the future steps to be exercised in order to make the simulation models more realistic. Moreover, modelling and testing of more guide path layout designs can also be incorporated in extension to this research.



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