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THE APPLICATION OF LOW COST INTELLIGENT AUTOMATION TO ASSEMBLY OPERATIONS USING A DISCRETE EVENT SIMULATION

by

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Executive Summary

This report proposes using a discrete event simulation approach to investigate the application and integration of Low Cost Intelligent Automation (LCIA) at a local automotive manufacturer located in Rosslyn, Pretoria. Low cost automation solutions are implemented in the form of Automated Guided Vehicles (AGVs) which are used as material handling mechanisms. Critical factors pertaining to the design and operation of these systems are the guide-path layout, the number of AGVs required and the vehicle dispatch rules. Literature on the subject matter showed that these design problems can be solved by using analytical models or simulation models. AGV systems are large and complex with various interrelating components that make up the complete system. Therefore, simulation modelling is chosen as the tool for this application as it is capable of handling these complex systems. The three main issues pertaining to the AGV system design are presented and analysed in this report. The conventional and tandem guide paths are analysed together with the workload-based Maximum Remaining Outgoing Queue Size (MROQS) dispatch rule and time-base Modified First Come First Serve (MFCFS) dispatch rule. These guide paths and dispatch rules are combined in four scenario models, each focussing on a specific combination of a guide path and dispatch rule. For each of the scenario models, the number of AGVs are varied and the changes in system performance are observed and documented. These scenario models are developed with discrete event simulation models, and are evaluated based on key performance indicators. The specific performance indicators comprised of the total throughput of the AGV system, the utilisation of AGVs and the buffer sizes at three stations. From the scenarios it is found that both the conventional and tandem guide path have similar results for both dispatch rules. Of the two guide paths, the conventional is more sensitive to the changes in dispatch rules. It is concluded that the best performing system is the tandem guide path with a MFCFS dispatch rule and a total of three AGVs in the system. It provided, on average a total output of 135 front and rear end bumpers. The AGVs in the loop are also fully utilised with a high utilisation of 85%. The proposes system also reduced the total walking distance by 37% and streamlines the material supply process to the station by eliminating unnecessary motions.

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List of Acronyms

LCIA	Low Cost Intelligent Automation
AGV	Automated Guided Vehicle
VPS	Value-added Production System
JIT	Just-in-Time
STTF	Shortest Travel Time First
STT/DF	Shortest Travel Time(distance) First
LTT/DF	Longest Travel Time(distance) First
NWF	Nearest Work station First
NVF	Nearest Vehicle First
NVFTP	Nearest Vehicle First Time Priority
MOQS	Maximum Outgoing Queue Size
MROQS	Maximum Remaining Outgoing Queue Size
FCFS	First Come First Served
MFCFS	Modified First Come First Serve
MODFCFS	Modified First Come First Serve
NV	Nearest Vehicle
FV	Furthest Vehicle
LIV	Longest Idle Vehicle

Chapter 1

Introduction

Since the start of the automotive industry in the early 1890s, it has become a vastly competitive market with a wide variety of different manufacturers emerging from numerous countries around the world. The automotive industry has pioneered the development of a transportation mechanism that offers mobility and accessibility at a reasonable price. The world-renowned automotive manufacturer, BMW, established in 1916, is one of the companies that has emerged as a competitor in the automotive industry and has quickly gained the reputation of being a manufacturer of premium quality products, with premium brands such as MINI and Rolls-Royce also forming part of their group. The BMW group strive to become the world's leading provider of premium products and services for individual mobility.

At the core of their manufacturing excellence lies the Value-added Production System (VPS). Its goal is to ensure continuous improvement and the addition of maximum value to all processes whilst eliminating all sources of waste in all production and support processes. Through the application of Lean manufacturing principles to their production processes, BMW has set themselves apart from their competitors due to their continuous improvement strategy. At BMW Plant Rosslyn, the principles of the VPS are embedded in all of their processes, and the benefits thereof can be seen by being awarded with the J.D. Power and Associates' Quality Award on four separate occasions. BMW Plant Rosslyn produces the 3 Series, four door model range in both right and left-hand drives for the local and global automotive markets. Motor vehicles are produced in three distinct, serial areas, namely the Body-in-White shop, the Paint shop and the Assembly plant.

The process starts in the Body-in-White shop where metal sheets are assembled to form the shell of the vehicle. The shell then proceeds to the Paint shop where the shell undergoes various treatments to apply the E-coat, primer and finally the base coat for the vehicle in either a metallic or solid base. The last stage of the process is where the painted shells are sent to the Assembly plant and where the "marriage" of the vehicle body, engine and drive chain takes place. Within the Assembly plant, the workers assemble more than one hundred specialised features and components to every car built. BMW plant Rosslyn produce an average of 75 000 3 series sedans annually, of which just short of 90% of all vehicles are manufactured for the international market. BMW refers to their plant workers as *associates* and for the remainder of this paper, will be referred to as such.

Within the Assembly plant, manual labour is extensively used in all processes, which has a tremendous impact on the productivity, efficiency and performance of the plant. To ensure high levels of productivity, BMW Plant Rosslyn aims to reduce all non value-adding activities that creates unwanted wastes in the assembly process. Being a manufacturer that relies on the principles of Lean manufacturing and eliminating all forms of wastes, a Just-in-Time (JIT) supply system has been key to their success in (jwj: in?) ensuring that parts are supplied just when it is needed, enabling uninterrupted production. In an effort to reduce wastes, BMW is looking to install Low Cost Intelligent Automation (LCIA) to the assembly line. This in the form of Automated Guided Vehicles (AGVs) which will be used to reduce the waste of overproduction, waste of motion and waste of inventory.

1.1 Problem statement

The front and rear end bumper assembly takes place on Line 09 which consists of six consecutive work stations. This area is categorised as a *diamond area*, meaning that the focus of this area is to achieve the highest standards in terms of Lean manufacturing principles. Currently workstations are being supplied with parts from one big supermarket which contains one and a half hours' worth of stock to supply the line. A supermarket—or as BMW refers it as a *suma*—is a central holding area where all the parts required for production are sourced from. In this project we will also refer to the holding area as a *suma*. One associate picks all the parts required for each station, places them in a trolley, and moves the parts to the respective station. A two-bin Kanban approach is followed for stocking parts on the line. Each station is equipped with trolleys which contains the required parts for production. As soon as one trolley is empty, a signal is sent for the collection of the empty trolley and a replacement with a full trolley. In this manner stations are continually stocked to ensure continuous production.

The process of moving parts to each station requires a lot of walking for the associates, resulting in excess motion. The two-bin approach is not implemented consistently at each workstation as there are more parts than required for a two-bin approach, resulting in a large number of parts stocked at each workstation. This congests the workstations which, in turn, results in an overstocked line that is not consistent with principles of Lean. Figure 1.1 depicts the current facility layout and the paths that the associate uses to move materials to each station.

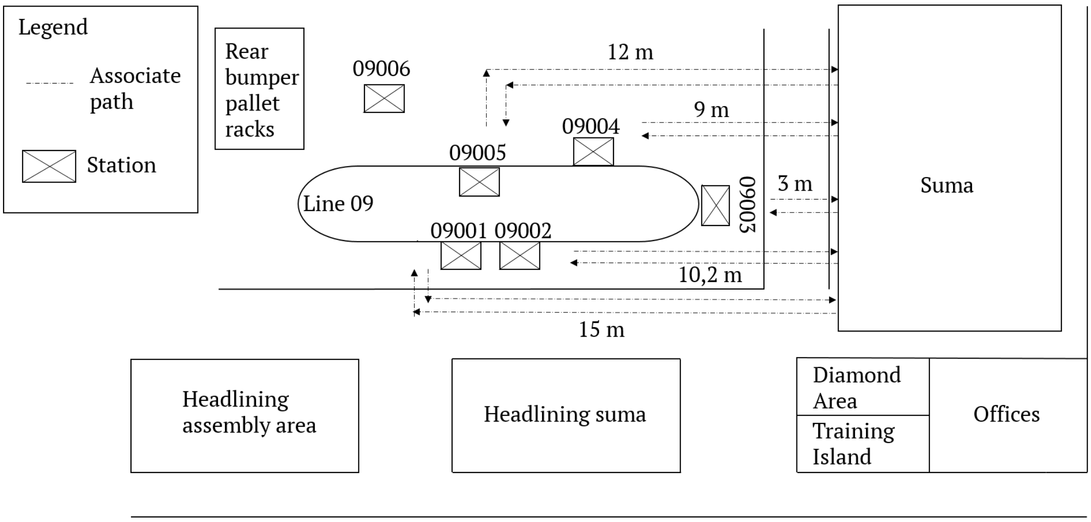


Figure 1.1: Current facility layout.

To reduce the amount of stock on the line and eliminate the waste of inventory, BMW is in the process of optimising the suma layout. With the current system where stock is kept on the line at work stations and in the big suma, there is inventory duplication. The same stock that it kept on the line is also held in the big suma, and as soon as the stock is replenished on the line, associates fill up the stock from the the big suma. The suma optimisation entails dividing the big suma into four smaller sumas, categorized as sumas A, B, C and D as depicted in Figure 1.2. Consequently, sumas will be moved closer to workstations and parts will be supplied to workstations directly from the respective smaller sumas. This would mean that the stock currently being held on the line will be moved into the smaller sumas, clearing the congestion at work stations. Subsequently it will also reduce the total amount of stock in the suma, as it can only accommodate a certain amount of stock. The AGVs will be used in this process, where the associate picks the parts in the suma and the AGV transports the part trolleys to the respective station. At present, only one AGV will be used to supply parts from suma A to workstation 09001. The newly designed facility layout is depicted in Figure 1.2, with the AGV and associate movement paths.

Line balancing has also been done to equally divide work packages between stations. This resulted in station 09003 being removed from the line, and the work previously done at this station has been divided into station 09001, 09002 and 09004. Also, due to space constraints, and the current location of the headlining suma, suma A has been moved to an open section in the facility next to the headlining suma. This section is a preliminary location for suma A that will be used for the remainder of this year.

As from next year, BMW will not be producing the 3 series sedans, but will start producing the X3 model range. For this new model, the manufacturing of headlinings for vehicles are going to be outsourced and consequently the headlining assembly area and headlining suma will be removed. This will make space for suma A to be moved closer to workstation 09001.

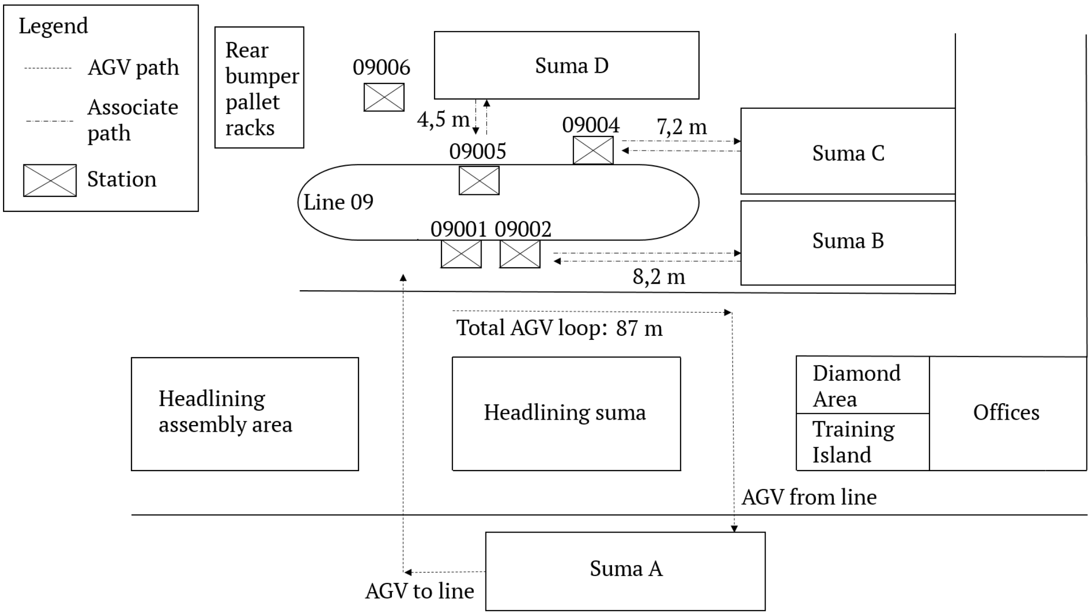


Figure 1.2: New facility layout.

There exist the need to investigate the integration of the newly designed sumas, the operations on the line and the impact that it will have on the performance of the system. Since there are various interrelating components in the process, each with their own variability, discrete event simulation can be applied to simulate the process of supplying materials to the line. This will incorporate the use of the AGVs from a JIT perspective.

The aim of this investigation is to :

i. Determine the performance of the new process.

ii. Study the effect of the AGV system on the materials handling process.

iii. Identify improvement initiatives of how the AGVs can be further applied and fully utilised in the process.

The goal with the installation of LCIA in this diamond area is to test its capabilities and applications with the aim of duplicating the principles used in installations at various workstations across the entire Assembly plant.

1.2 Research design

Le-Anh and De Koster (2006) pointed out that for AGV system design and control, decisions are made on strategic, tactical and operational levels. A decision on a strategic level is the guide-path design, as this decision has an impact on decisions on lower levels. The number of vehicles and the operational transport control are decisions made on a tactical level. Issues such as deadlock resolution and routing are done on an operational level. Because this is the first application of LCIA in the form of material handling AGVs at BMW Plant Rosslyn, a discrete event simulation is used to investigate the integration of the AGV system and assembly operations in a JIT manufacturing environment. It focusses on the design issues on strategic and tactical levels to aid BMW in their design process.

This simulation focusses on the three main decisions as encountered in literature such as the guide-path followed by the AGVs, the number of vehicles required to sustain the process and the dispatch rule used in the system. Similar to the approach used by Kesen and Baykoc (2007) these design decisions are design factors for the simulation model, and by altering these design factors their influence on system performance are evaluated at the hand of performance measures. The following measures are used:

1. The throughput of the AGV system in terms of the amount of deliveries and pick-ups it makes for the whole duration of a shift.
2. The AGV utilization.
3. Size of inventory buffers at work stations.

Scenario models are developed where each scenario focusses on a particular combination of the three design factors. The specific combinations are selected by reviewing relevant literature to choose the most applicable combinations. The performance of each scenario is evaluated and compared to the base model.

The simulation model runs for an entire shift, including tea and lunch breaks. In total, the model runs for the entire length of the actual available production time. The output of the simulation provides a visual representation of the system and depict the behaviour of the different interrelated agents and components. Moreover, the simulation model provides quantitative results on system performance under different operating scenarios. The main deliverable of this simulation model is to provide BMW with decision support in implementing the optimal combination of guide-paths, number of vehicles and dispatch rule to ensure the most efficient end effective AGV system.

1.3 Research methodology

To ensure the successful completion of the research project a structured approach is followed. The eight steps depicted in the methodology in Figure 1.3 are broken up into four main phases.

In phase one the current assembly and material supply processes are analysed. The key measures that are required to evaluate system performance is identified and data is gathered by conducting time studies of processing times, takt times, picking times etc. Critical to the data analysis in this phase is to determine the distributions of data that will be used as input for the simulation model to be constructed in the next phase.

In phase two the base model of the current system is developed to obtain a model that represents the real system as close as possible. To ensure the model is a good representation of reality, model validation will be conducted by comparing model outputs against system outputs.

In phase three alternate scenarios are developed and each scenario's simulation is run a predetermined number of times. The outputs of each of the three scenario models are documented to be compared against the base model.

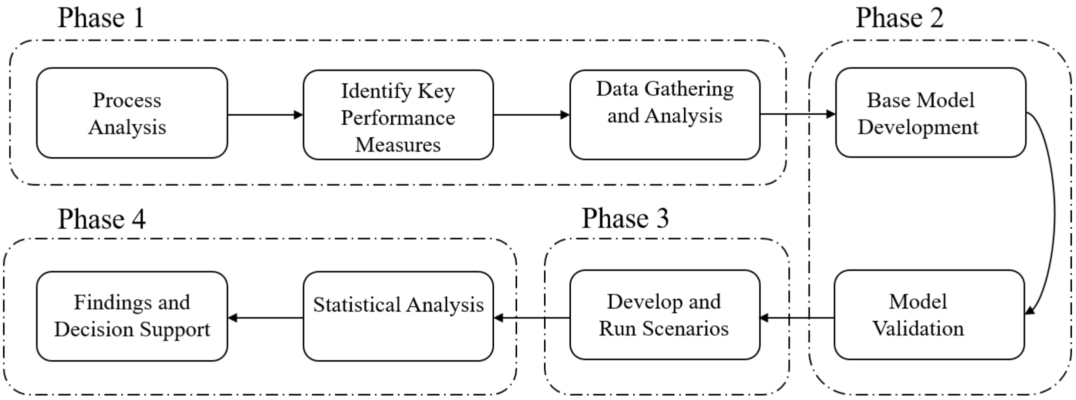


Figure 1.3: Simulation methodology.

And finally, in phase four the outputs obtained by the scenario models are statistically analysed and compared against the base model using the performance measures to determine the most effective process, producing the most consistent end efficient outputs. From the statistical analysis, findings are presented in a suitable manner to provide decision support on the design of the AGV system.

1.4 Document structure

In Chapter 2, literature with regards to AGV system design and control is presented and discussed with reference to applications in the manufacturing industry. The most appropriate system design tools are presented and the reason why simulation modelling has been chosen as the preferred method is also discussed. In this literature review special focus is placed on three main design factors for AGV system design. These are the AGV guide path, the dispatch rule and the number of vehicles used in the system. From these design factors three types of guide paths and two types of dispatch rules are identified that would be most applicable to this application. Chapter 3 discusses the simulation model environment and the development of the base case model. Two scenario model layouts are developed and two dispatch rules are integrated into the model layouts. These two guide paths and two dispatch rules are used to develop four conceptual scenarios to be compared against the current base model. Chapter 4 presents data analysis on the input data for the simulation, model validation and outputs obtained from all four scenario models. These models are compared against key performance indicators to determine the best performing system. In Chapter 5 three possible solutions to the design problem are discussed and compared based on the findings in Chapter 4. The final solution is presented and compared against the performance of the base model. And finally, Chapter 6 concludes the findings of this paper and discusses recommendations on future work.

Chapter 2

Literature Review

Low Cost Intelligent Automation (LCIA) are systems for effective manual production. It integrates the manual processes within production operations with smart control systems and tools to provide high quality, flexible and productive methods of assembly. LCIA is used in the manufacturing industry as a Lean manufacturing tool primarily to reduce production waste, increase productivity, increase manufacturing flexibility and provide high quality products. LCIA has a wide range of applications, such as mechanical processing and mechanisms for materials handling but are primarily used in assembly processes where manual labour is extensively used. The focus of this literature review is to present literature on the application of LCIA as a material handling mechanism in manufacturing environments, more specifically in the form of Automated Guided Vehicles (AGVs). This review also looks at the analysis and design of AGV systems through the use of simulation based approaches.

2.1 Design of AGV systems

AGVs are unmanned vehicles used as transportation systems for the movement of materials, since its first introduction in 1955. The application of AGV systems has increased quite significantly and are frequently used in both outside and inside environments such as manufacturing plants, warehouses, distribution centres and transshipment areas. In manufacturing environments, AGVs transport the required materials to various points in the system to sustain the manufacturing process of a particular product (Vis, 2006). Two types of AGVs are found:

Free-ranging vehicles operate by means of laser/infra-red light equipment with the light being reflected on the walls to determine the vehicle's position. Grid patterns are used for calibration, which is created by transponders or chess board patterns that is optimally scanned.

Path-restricted vehicles are restricted to a fixed track layout and the vehicles are guided by either induction wires in the floor or magnetic tape on the floor which the vehicle follows (Mantel and Landeweerd, 1995).

Vis (2006) noted that the objectives of AGV systems are to: (1) maximise system throughput, (2) minimise the required time to complete jobs, (3) minimise AGV travel time, (4) distribute workload evenly between AGVs, (5) minimise the cost of moving materials and (6) minimise expected waiting time of loads.

The design of AGV systems involve taking a wide variety of decision variables into account, as it is important to look at the interrelated relationships between system components which could have a tremendous impact on the performance of the system. During the design process, the system objectives need to be taken into account to produce an efficient system.

2.1.1 Solution approaches for AGV system design

Kesen and Baykoc (2007) pointed out that two types of modelling approaches are frequently used to address the design issues.

Analytical modelling encompasses the application of analytical methods to management in decision making. This includes the development and use of quantitative mathematical models (Sanderson, 2006). To handle the complexity of real world systems, analytical models function under a set of assumptions to simplify the system and produce near optimal outputs. The most popular analytical models that were encountered in literature are binary integer models, linear programming models, enumeration algorithms, branch-and-bound algorithms, queueing models, network-flow models and simulated annealing heuristics.

Discrete event simulation involves the development of descriptive computer models of a system and executing those models to predict the operational performance of the system being modelled (Smith, 2003). More specifically, discrete event simulation is one of the most popular techniques used to understand and analyse the dynamics of manufacturing systems (Negahban and Smith, 2014). Simulation is useful and flexible, as it allows the user to evaluate different alternatives of system configurations and operating strategies to ultimately support decision making.

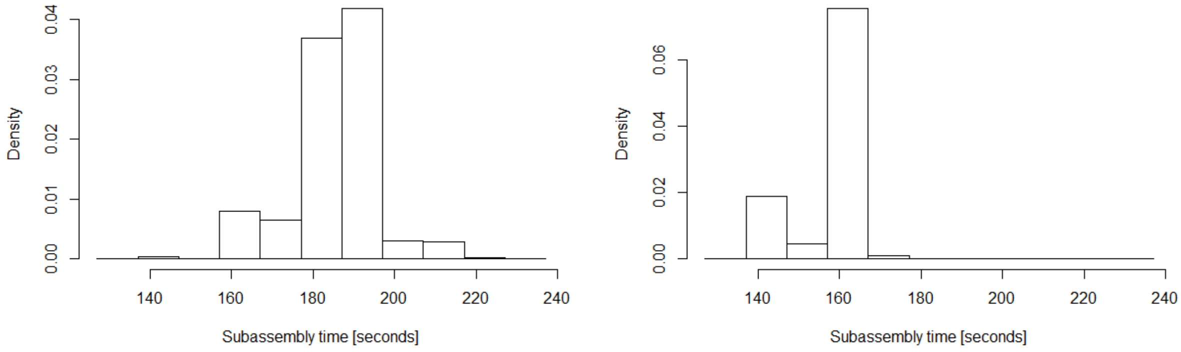
Each approach has certain advantages and disadvantages. Although analytical models have the ability to optimise the system, a large number of assumptions are required to successfully model the system through mathematical equations (Kesen and Baykoc, 2007). The more assumptions made, the more unreal the system becomes. Simulation models, however, do not give optimum results but it provides the ability to study the systems' long term behaviour given various sources of uncertainty. Developing simulation models may also be more time consuming than developing analytical models, but are much more convenient when having to model complex systems.

The quality of the system design and control greatly affects the performance of the system, as noted by Kim and Jae (2003). AGV systems require thorough planning to account for the large variety of factors and decision variables. They also pointed out that the analysis approaches as traditionally followed to address design and control issues are not robust enough to handle the the level of complexity of these systems. Also, randomness and variability is inherently present, adding to the complexity of these systems. As the complexity increases, the potential ability of analytical models to present accurate results decreases. It is therefore that the use of simulation models have gained popularity as it is capable of handling more complex systems, especially if design issues are addressed simultaneously.

For the specific application at BMW Plant Rosslyn, variability exists in the assembly and material supply processes. The total completed front and rear end bumpers vary according to the assembly time at each station. Figure 2.1 depicts the distribution of assembly times for stations 09001, 09002, 09004 and 09005. Also, Table 2.1 depicts how the material supply varies according to the picking times at sumas.

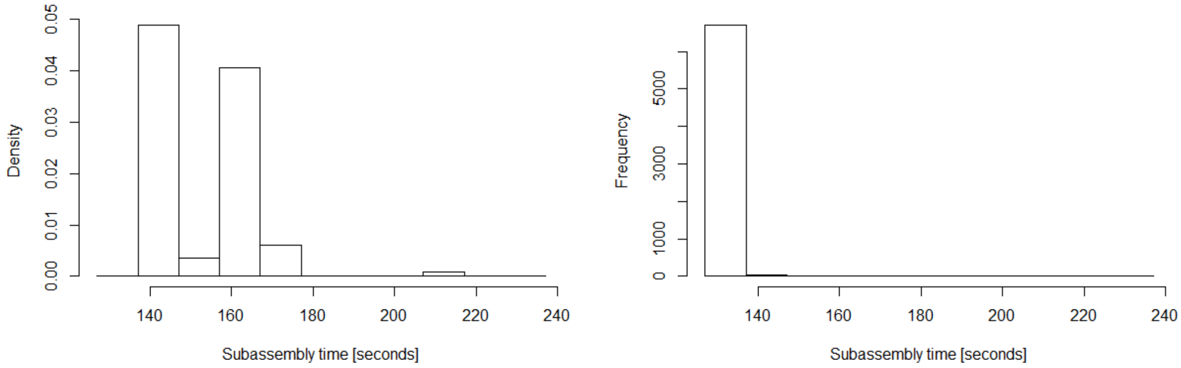
Table 2.1: Variability in the picking times at sumas

Suma	Average observed time	Minimum time	Maximum time
A	7.055	6.2	8.25
B	2.53	1.58	3.25
C	2.56	1.56	3.2
D	3.86	2.78	5.27



(a) Station 09001 assembly time distribution.

(b) Station 09002 assembly time distribution.



(c) Station 09004 assembly time distribution.

(d) Station 09005 assembly time distribution.

Figure 2.1: Histogram plots to show the variability of the assembly times at workstations 09001, 09002, 09004 and 09005.

This signifies the appropriateness for the use of simulation modelling as a solution approach to the AGV system design at BMW Plant Rosslyn. As the simulation model is able to incorporate these variabilities in the design.

The next section continues to examine simulation approaches to AGV system design problems, as encountered in literature.

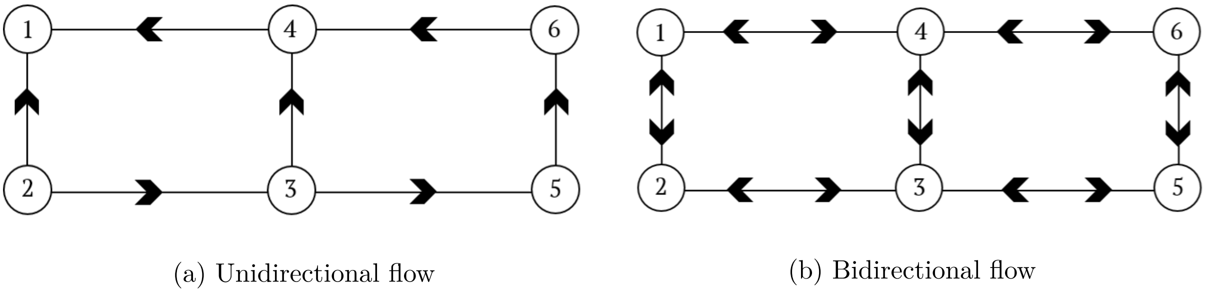
2.2 Simulation modelling applied to AGV system design

Three main design issues consistently occurring in literature are: (1) guide path design, (2) the number of AGVs required and (3) the operation and control of transportation (Mantel and Landeweerd, 1995). The design of these issues are thoroughly examined in the forthcoming sections.

2.2.1 Guide path design

Le-Anh and De Koster (2006) describe the guide path to be one of the most important factors, and is one of the first problems to be considered when designing an AGV system. The connections and guide-paths to be included in the solution is of importance as this information is used to develop a *from-to* flow chart describing the network flow of AGVs. Intersections, pick-up and delivery points are represented by nodes, and are connected by arcs representing the vehicle guide-paths that the AGVs can follow. The main objective of the guide path design is to minimize the total distance that vehicles travel in the system.

The direction in which AGVs can move on a specific path can be described as either unidirectional or bidirectional . With a unidirectional flow path, vehicles are restricted to travel in only one direction. Vehicles may, however, have to travel greater distances between two points, but they require fewer control and are more economical (Gaskins and Tanchoco, 1987). Bidirectional flow, on the other hand, allows a vehicle to travel in two directions along a path. The advantage of bidirectional flows is that they reduce travel time, but requires greater control as vehicle collisions are likely to occur. Figure 2.2 depicts the differences between unidirectional and bidirectional flow for a hypothetical layout.



(a) Unidirectional flow (b) Bidirectional flow

Figure 2.2: Unidirectional and bidirectional path flow.

Egbelu and Tanchoco (1986) presented comparisons and issues regarding bidirectional and unidirectional flows during guide path design. In their study they compared the application of unidirectional and bidirectional paths in two different multi-job processing facilities. The system throughput was used as the main criterion in the comparison. A second supporting criterion was the vehicle utilisation. By using simulation they conducted three different experiments for each facility to compare the differences in flows.

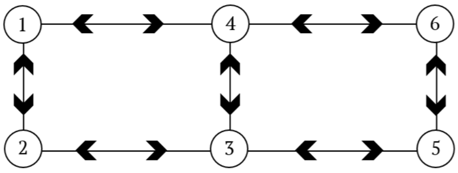
The first experiment investigated how an equal number of vehicles will influence the throughput of the system under the two types of flow modes. They found that for both the facilities, the throughput of the system increased with 30% – 99% when bidirectional flow was used instead of unidirectional flow. For example: for facility one, when six vehicles were used, the output in unit loads for bidirectional traffic flow was 2066 units, compared to the 1036 unit loads of the unidirectional flow. For both facilities the throughput generally increased as the number of vehicles increased.

The second experiment investigated the number of vehicles that would be required under each operating mode to meet a certain target output over a fixed period of time. They found that for both the facilities, the unidirectional mode required almost twice as much vehicles to reach the same throughput as bidirectional flow. They noted that although bidirectional systems require more advanced control systems, the investment costs saved in acquiring fewer vehicles with can cover the costs. To achieve an output target of 2066 unit loads, in their example, the bidirectional flow system required six vehicles compared to the thirteen vehicles that the unidirectional flow pattern required.

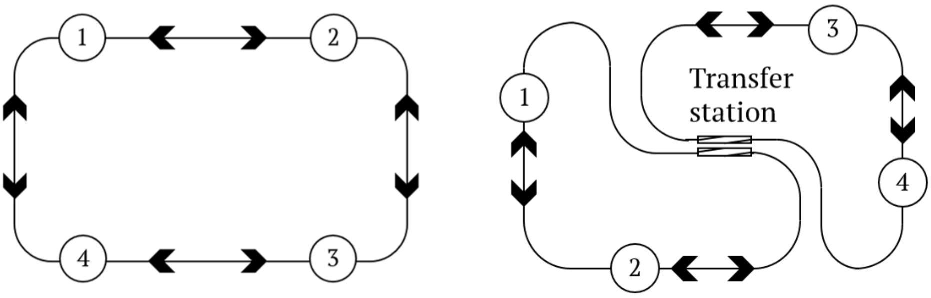
The third and final experiment investigated the amount of time it took to achieve a predetermined output target, when using the same number of vehicles for both facilities. The results confirmed that bidirectional flow required half the amount of time to achieve the predetermined output target. For example: for facility one to achieve an output target of 2066 unit loads, using six vehicles for both flow systems, the bidirectional systems took 80 hours compared to the 158 hours of the unidirectional system.

They conclude that bidirectional traffic flow can increase productivity and throughput while saving in investment cost by using fewer vehicles. They recommend that both flow strategies should be evaluated when designing guide path systems.

The three most frequently researched guide path systems are conventional systems, single loop systems and tandem systems (Le-Anh and De Koster, 2006). In order to evaluate and compare the performance of these different systems, Beamon (1998) describes the (1) travel time of vehicles, (2) utilization of vehicles, (3) length of queues and (4) material handling costs as important performance criteria. The most popular criterion for designing a guide path is the total distance a vehicle has to travel on a specific layout while adhering to the specific flow of the system (Gaskins and Tanchoco, 1987). Figure 2.3 depicts the three types of guide path systems.



(a) Conventional guide path



(b) Single loop guide path

(c) Tandem guide path

Figure 2.3: Guide path systems.

Conventional guide path systems are systems where there are various pick-up and delivery points in between departments on a given layout, and the AGVs have the choice to travel along various alternate routes. Whether free-ranging or path restricted, they are not restricted to only one path or loop. AGVs are assigned to a task depending on the demand at stations. Conventional systems are more complex networks compared to single and tandem systems due to the magnitude of pick-up and delivery points, intersections and possible flows. These systems can accommodate both unidirectional and bidirectional flow. Unidirectional conventional systems are popular systems that are used in distribution centres and warehouses (Le-Anh and De Koster, 2006). Bidirectional conventional systems are less popular in material handling systems, because the control of such a system becomes very complicated as the number of nodes, paths and vehicles increase.

Single loop guide path systems consist of only one loop in which vehicles travel, and does not consist of shortcuts or alternative routes. Because vehicles travel in a closed loop, there are no intersections where vehicle collisions occur as with conventional systems (Le-Anh and De Koster, 2006). Vehicles travel in a unidirectional mode. Bidirectional travel is possible, but is susceptible to interference and vehicle collisions.

Sinriech and Tanchoco (1993) pointed out that the throughput of single loop systems are lower compared to conventional systems. To achieve the same throughput of conventional systems, single loop systems therefore will require more vehicles.

Tandem guide path systems were first introduced by Bozer and Srinivasan (1991). A tandem system consists of multiple zones or loops, and can also be seen as multiple integrated single loop systems performing as one complete system. One vehicle operates in each loop, and the concept of transfer-stations are introduced integrate the various loops. It might be possible that a job is transported by more than one vehicle to reach its final destination. Only one vehicle is used per zone, therefore the possibility of vehicle blocking or collisions are reduced.

Ross and Mosier (1996) did a comparative study in which they evaluated and compared the performance of conventional and tandem systems under various configurations. They concluded that tandem systems perform equally efficient than conventional systems. In comparison to conventional systems, tandem systems are easier to control, easier to expand and has no congestion problems. Tandem systems do, however, require costly additional transfer buffers which increases the material handling time and subsequently reduces the system throughput. Table 2.2 gives an overall comparison of the guide path systems as discussed above (Le-Anh and De Koster, 2006).

The performance of AGV systems in flexible manufacturing systems were studied by Farling et al. (2001), where they compared the performance of three AGV guide path configurations under various experimental conditions. Using simulation models, they modelled three guide path configurations: conventional system, tandem system and tandem/loop system. They used the First Come First Served (FCFS) control rule, and the number of AGVs used were dependent on the specific configuration and number of stations in the system. For operational control and vehicle dispatching they used the Shortest Travel Time(distance) First (STT/DF) rule. They considered four experimental factors: (1) system configuration, (2) size of system, (3) loading time of vehicles and (4) failure rates of machines. The three system configurations were compared using three performance metrics: (1) mean flow time per job to move through the system, (2) mean tardiness and (3) mean proportion tardy. Jobs are referred to as tardy when they are completed after their assigned completion date.

They conclude that all factors considered in the experiments had a notable impact on the three configurations and performance. If the primary concern is timely completion of jobs, they recommend that conventional/traditional configurations be used in small systems with three or fewer workstations. For medium-sized systems of between four and nine workstations, the three

Table 2.2: A comparison of guide path systems (Source: adapted from Le-Anh and De Koster (2006))

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
Number of vehicles per zone	Multiple	Multiple	Single
Operating with a bidirectional system	Difficult	Difficult	Simple
Traffic control	Difficult	Easy	Easy
Vehicle scheduling/dispatching	Complex	Simple	Simple
Congestion (probability)	High	Low	None
Intermediate buffers required (to transfer loads between loops or transfer points)	No	No	Yes

configurations' performance were similar. For large systems of ten workstations or more, the tandem loop configuration is the best solution.

For the application at BMW, timely completion of assemblies at workstations are of conern, as this line is integrated with another line and should therfore adhere to the takt time of the whole system. Any halt on this line could cause a halt for all preceeding assembly lines. According to Farling et al. (2001) an applicable guide path for Line 09 would be a conventional system as this is a small system. There are, at most, three workstations that can possibly be served with the AGVs in either unidirectional or bidirectional flow. Although they did not include single loop systems in their study, it could also serve as a viable solution. Factors affecting the type of guide path is the size of the system as noted by Farling et al. (2001), but also the layout of the facility in the system. Therefore the two most appropriate guide paths are examined in the AGV system design.

2.2.2 Number of vehicles

The number of AGVs used in the system has a direct influence on the performance of the system and the costs associated with the type and number of vehicles should also be considered (Le-Anh and De Koster, 2006). For conventional and single loop systems, the number of AGVs have to be estimated. With tandem systems the amount of vehicles required equals the amount of loops used.

The three factors affecting the required vehicle fleet size, as pointed out by Egbelu (1987), are (1) the layout of the guide-path, (2) the location of stations and (3) the rules used to dispatch vehicles. Vis (2006) also pointed out that the following are critical factors for determining the optimal number of AGVs required: (1) number of units requiring transportation, (2) the time distribution of units requiring transportation, (3) vehicle capacity, (4) vehicle speed, (5) system costs, (6) system layout, (7) traffic intensity and (8) the number and location of pick-up and delivery points. The type of vehicles that are used in a fleet can be further distinguished as either single-load or multi-load capacity vehicles.

Bilge and Tanchoco (1997) compared the system performance when using multi-load capacity vehicles over single-load capacity vehicles. They conducted the study in a job shop environment where jobs are transported in unit loads. One unit load contains a certain number of parts, and all required parts must be present before the unit load can be transported to the next workstation. By reducing the unit load size (having advantages of better machine utilisation, less work in process and flow time) the requirement for transportation between workstations increased significantly. Instead of increasing the number of AGVs in the system they introduced the possibility of using vehicles with multi-load carrying capacity.

A job shop facility was used and was simulated with 11 departments. Each experiment consisted of 40 hours of simulation time. The main performance criterion used for the comparison of vehicles was hourly system output rate, which is the number of jobs processed per hour.

They concluded that, when using multi-load vehicles, the system performance is less sensitive to changes in guide path layout and the system can handle a high volume inflow of jobs without the AGV system becoming the bottleneck. Therefore increasing the throughput of the system when the demand for transportation is high.

Similarly, van der Meer and de Koster (1999) concluded, with simulation models, that the system performance increased when using multi-load capacity vehicles, especially when multiple loads are picked up at a central location.

The estimation of number of vehicles required varies considerably from application to application. Literature reviewed presented the use of analytical models as an estimation. Results obtained from using analytical models may differ from the actual requirement, mainly due to assumptions made in developing the analytical models (Le-Anh and De Koster, 2006). More so, the number vehicles that are required are also influenced by a variety of factors such as traffic management, dispatching rules, path layout and other factors. Egbelu (1987) point out that for estimating the number of vehicles required, simulation is more reliable, but more time consuming method and should be used above analytical models when it is certain that AGVs will be used in the process.

For the system at BMW, it is possible that mutli-load vehicles can be implemented if more than one workstation is served by the AGVs. Ultimately, the type and required number of vehicles would have to be determined by the simulation model.

2.2.3 Dispatch rules

Vehicles are controlled in the system by using dispatching rules according to the demand at certain workstations. According to Le-Anh and De Koster (2006), a dispatching system is similar to a scheduling system with no planning horizon. Dispatch decisions are made when (a) a vehicles makes a drop-off, (b) a vehicle returns to its parking location or (c) at the arrival of a new load. Vehicles are dispatched through a variety of dispatch rules. More specifically through single-attribute, multi-attribute and hierarchical dispatching rules.

Single-attribute dispatching rules dispatches vehicles according to a single parameter. Parameters can be based on distance, workload at stations or job waiting time (Le-Anh and De Koster, 2006).

Distance-based dispatching rules dispatches vehicles according to the distance or time vehicles have to travel (Le-Anh and De Koster, 2006). This includes the STT/DF, Nearest Work station First (NWF) and Nearest Vehicle First (NVF) rules. Egbelu and Tanchoco (1984) pointed out that the Shortest Travel Time First (STTF) rule dispatches vehicles to the closest load, where the closest load is determined by travel time or distance.

Workload-based dispatching rules dispatches vehicles according to queue sizes at workstations. Egbelu and Tanchoco (1984) introduced the Maximum Outgoing Queue Size (MOQS) and the Maximum Remaining Outgoing Queue Size (MROQS) rule. With the MOQS rule, a vehicle is sent to a workstation with the largest number of loads in its outgoing queue. With the MROQS rule, a vehicle is sent to a workstation with the smallest space left in its outgoing queue.

Time-based dispatching rules dispatches vehicles according to the time jobs wait at stations. Most reviewed time-based rules are the FCFS rule and two modified variances of the FCFS rule such as Modified First Come First Serve (MFCFS) and Modified First Come First Serve (MODFCFS) rules (Egbelu and Tanchoco, 1984). The MODFCFS rule is different from the MFCFS rule, as it aims to minimise the time vehicles have to travel with empty loads (Le-Anh and De Koster, 2006).

Multi-attribute dispatching rules combine several single-attribute dispatching rules to form a more comprehensive dispatching approach. Multi-attribute dispatcing rules uses various parameters to dispatch vehicles and generally perform better than single-attribute rules (Le-Anh and De Koster, 2006). The advantage of incorporating a variety of parameters is that it leads to a more efficient system and ensures the maximum utilisation of vehicles. With multi-attribute rules, the complexity of the system increases significantly as the size of the vehicle fleet and number of workstations increase.

Hierarchical dispatch rules are used in manufacturing industries where the value of a part in the production process has an effect on the dispatching decision. At the first level, jobs are sorted based on the priority of the demand for material at workstations. At the secondary level, a vehicle is sent to the workstation with the highest priority (Le-Anh and De Koster, 2006).

Egbelu and Tanchoco (1984) did a study on dispatching rules for AGVs in a job shop environment. They presented different work centre and vehicle initiated dispatching rules and compared them using a simulation model.

This shop consisted of 13 departments and a conventional, unidirectional guide path with a total of six AGVs. The throughput in unit loads were used as the main performance criterion to compare different combinations of the dispatching rules. A total of 30 simulation trials were run, two trials per combination. The rules included in their experiment are summarised in Table 2.3 (Egbelu and Tanchoco, 1984).

Table 2.3: Summary of dispatch rules used in simulation study

Work centre initiated dispatch rules	Vehicle initiated dispatch rules
Nearest Vehicle (NV)	MOQS
Furthest Vehicle (FV)	STT/DF
Longest Idle Vehicle (LIV)	Longest Travel Time(distance) First (LTT/DF)
	MROQS
	MFCFS

When they initially compared the different combinations of the dispatch rules, the results of the simulation model showed that the first nine rule combinations produced a stoppage in the production and material flow in the shop. This was due to machining centres' queue capacity reaching its maximum. They eliminated the initial queue capacity constraints, to asses the actual buffer space required under the unlimited queue capacity conditions. The model outputs are summarised in Table 2.4, outputs are given as the throughput of the system in unit loads (Egbelu and Tanchoco, 1984).

They concluded that, for the work centre initiated task assignment rules there were no real significant performance differences. On the other hand, vehicle initiated task assignment rules showed quite significant differences in output. With the MFCFS vehicle initiated rule outperforming all the other rules in their specific study.

De Koster and van der Meer (2004) tested different dispatching rules in three real world environments. The environments were a distribution centre, a production plant and a container transshipment terminal. Simulation models were built for each of the three cases, all operating under the same set of assumptions. The average minimum load waiting time was the main

Table 2.4: Shop throughput in unit loads for different task assignment rule combinations (Source: adapted from Egbelu and Tanchoco (1984))

		Vehicle-initiated				
		MOQS	STT/DF	LTT/DF	MROQS	MFCFS
Work centre-initiated	NV	348	669	431	346	764
	FV	334	664	434	350	758
	LIV	348	669	431	346	764

performance criterion. Other criteria were maximum waiting time of loads, utilisation of vehicles and the maximum number of loads in critical queues.

The most reviewed dispatching rules in literature, applicable for industry applications were selected for this study. The dispatch rules were NWF, NVF, MODFCFS, Nearest Vehicle First Time Priority (NVFTP) and other case specific dispatching rules used in each respective company and environment.

They concluded that distance-based rules (NWF, NVF) generally perform better under circumstances where the size of queues are not critical. However, when the sizes of queues at workstations are critical, time-based (MODFCFS) and workload-based rules obtained better performance than the other rules. The distance based rules minimised the total time vehicles travel empty and performed better than all the other rules in this study. Finally they noted that looking at the different outputs gained from the experiments, the NVF and NWF rules have a highest probability of producing good results in industry applications (De Koster and van der Meer, 2004).

For the system under study at BMW, the queue sizes of parts waiting to be processed in the assembly at workstations are of concern. This is to ensure Lean principles are adhered to in this diamond area and that parts are supplied in the right quantities at the right time, with minimal inventory at workstations. Therefore as De Koster and van der Meer (2004) concluded, workload-based and time-based, single-attribute dispatching rules will be the most applicable rules to be used for this application. The reason that distance-based rules are excluded form this evaluation is that this is a small system compared to other industrial systems and the distances between workstations are not big enough to realise the performance benefits of distance-based rules.

The two specific rules that will be evaluated include the MROQS workload-based and MFCFS time-based rules. The MROQS is chosen, as the remaining number of parts in the queue is an important factor to determine when the next part trolley should be dispatched to the station to ensure continuous production. The MFCFS rule is chosen as this rule outperformed the other rules in the study conducted by Egbelu and Tanchoco (1984).

2.2.4 Modelling in a Just-in-Time (JIT) environment

There are a broad spectrum of studies on AGVs in the literature, but very few deal with the integration of AGV systems into JIT production environments.

Baykoc and Erol (1998) describes a JIT production environment as one which employs a pull approach and materials only flow as it is pulled from the succeeding stage. The goal of JIT systems is to produce only the products that are needed, in the right quantity and at the right time. Ideally a JIT system would aim to achieve one piece flow with inventory of one unit at each stage, however, this is not possible due to the stochastic nature of demand and processing times. JIT processes are controlled by Kanban cards, which contains information of the material being pulled through the system and serves as a signalling tool for the production of the next unit or to reorder material when a certain inventory level has been reached.

Kesen and Baykoc (2007) simulated an AGV system based on a JIT philosophy in a job shop environment and the effect of four factor settings on system performance were analysed. The performance measures used in their study were (1) mean time in system of jobs, (2) mean queue length, (3) mean output rate and (4) mean inter departure time of jobs. The four factors that were considered for this experiment were (1) number of vehicles, (2) vehicle dispatching rule, (3) number of kanbans and (4) the arrival rate of demand. They used experimental design to conduct the experiment plan. The factor settings were evaluated at two levels for each factor as shown in Table 2.5, were Expo(μ) refers to the arrival rate of demand being exponentially distributed with a mean of μ minutes. A maximum priority dispatch rule was used for the AGV system.

Table 2.5: Experiment factors and levels (Source: adapted from Kesen and Baykoc (2007))

Factors	Level I	Level II
Number of vehicles	3	2
Vehicle dispatching rule	Shortest distance to the station	Longest distance to the station
Number of kanbans	1	2
Arrival rate of demand	Expo(10)	Expo(15)

They conclude that the number of vehicles, number of kanban and arrival rate of demand affects the length of time in the system for each job. In their specific study they found that the number of vehicles used in the system has a direct impact on all performance measures, while the vehicle dispatching rule did not affect any performance measures.

2.3 Conclusion

This review specifically looked at AGVs as a material handling mechanism in a manufacturing environment. Through literature it was found that three main AGV system design issues frequently occur, such as the guide path design, estimating the required number of vehicles and the dispatch rules used to control the system.

It was found that for the type of guide path, conventional and single loop systems will be applicable for this study as these two systems obtained the best results in a small system such as the one under observation. Although a tandem system is used in larger systems, it could also serve as a viable solution. Multi-load vehicles is a possibility if more than one station is served with AGVs, but the number and type of vehicles should be determined by the simulation. For operational control it was found that the time-based MFCFS and workload-based MROQS dispatch rules would be most applicable.

To address these design issues, discrete event simulation would be the most suitable tool to model the complexity of the AGV system and therefore these design issues will be evaluated with simulation models in the next chapter.

Chapter 3

Simulation Model

This section describes the simulation model for the integration of an Automated Guided Vehicle (AGV) system at BMW Plant Rosslyn. The simulation model is built with AnyLogic 7.3 software package as it supports simulation methodologies such as system dynamics, discrete event and agent based modeling. AnyLogic is flexible and highly capable software that is accessible and comprises of an extensive process modeling library.

3.1 Model environment

The simulation is built in a manufacturing environment, specifically for a production line in an automotive vehicle assembly plant. BMW Plant Rosslyn has three distinct assembly plants in their facility, and this simulation focusses on Line 09, in Plant Three. The conceptual floor layout of Line 09 is depicted in Figure 3.1.

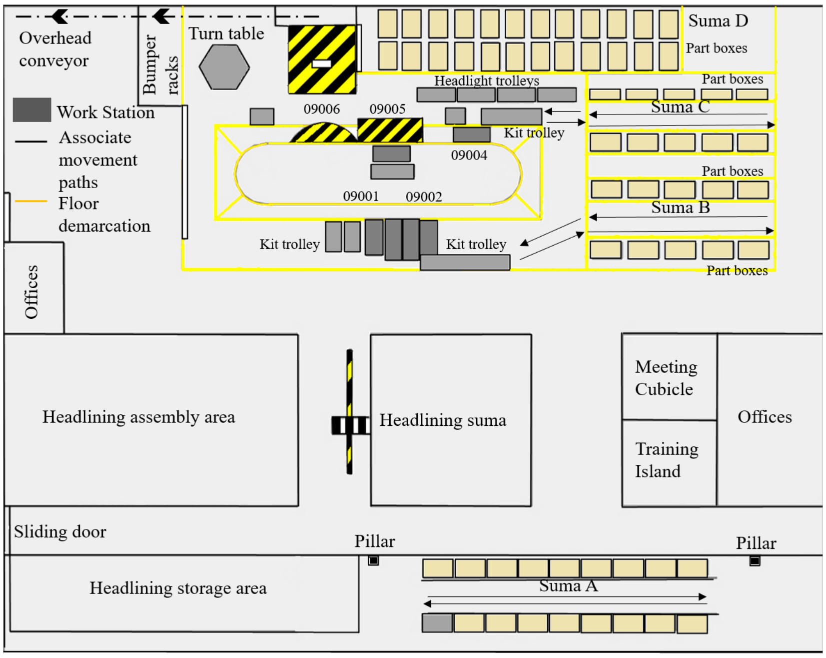


Figure 3.1: Line 09 floor layout.

This assembly line comprises of five stations and denoted on Figure 3.1 as station 09001, 09002, 09004, 09005 and 09006. With the new suma optimisation, station 09003 was removed from the process, and its work load is divided between the remaining workstations. BMW decided to keep the labels of the remaining workstations as is. There are four sumas, denoted as suma A, B, C and D. These sumas hold all the required parts for the assembly operations and associates supply new parts to the line by using part trolleys. Each suma is designated to hold stock for a specific workstation while workstations 09005 and 09006 do not have allocated sumas because at this stage in the assembly process most parts have been fitted onto the sub assembly and associates use automated machines to secure the bumper into position. In Figure 3.1 the position of the respective sumas are demarcated with yellow lines. These lines depict the division of the sumas, but does not hinder any movement over these lines. The purpose of these lines is to visually indicate where sumas are located and where they start and end. At suma B, there are two rows allocated for part boxes as indicated in Figure 3.1. The area where the associate moves in the suma to pick parts is indicated in the space where the description " Suma B " is positioned. This is the area where the associate moves with the part trolley and his associated movements in the suma are shown on the figure. Between suma B and C, there is a small open space which divides the two sumas. Suma C also has two rows allocated for part boxes as indicated on the figure. The associate moves in the open space between the rows of part boxes. This is where he walks with the AGV and part trolley through the suma. This area is depicted on the figure where the description " Suma C " is positioned. At suma D the yellow demarcation is placed around the whole suma to the left of the description " Suma D " in Figure 3.1. In suma D, there are small gaps and aisles which the associate uses. The yellow demarcation lines are also used as a way to sort the production floor. The yellow lines around the production line indicate the safety distance between the production line and the yellow line boundary. The area within the yellow boundary should be kept clean to ensure nothing disrupts the movement of the line. Table 3.1 gives a description of the allocation of sumas to workstations.

Table 3.1: Allocation of sumas

Suma	Workstation
A	09001
B	09002
C	09004
D	09004

Suma A holds all the stock required for the crash system pre-assembly at station 09001. In this suma, the associate picks all the required parts for a total of four vehicles. The trolley can accommodate a total of four car kits. Suma B holds all the stock related to the lock support pre-assembly at station 09002. The associate supplies parts from the suma to the line using a trolley that can accommodate three car kits. Sumas C and D together hold the parts required for the assembly at station 09004. Suma C holds the parts required for the headlight alignment and horn assembly and suma D holds all the different types of headlights. The reason why these two sumas are divided into two instead of being one suma, is for the reason that in suma C, the parts are picked and placed in car kits. These car kits are then supplied to the station with a part trolley. In suma D, the current process makes use of headlight trolleys as indicated in Figure 3.1. The associate picks the headlights from the suma, and places it into the headlight trolleys. The headlight trolley and suma needs to be as close as possible to the station to reduce the movements of associates walking with the headlights. Therefore, these two sumas are divided into two, to ensure the headlights are located as close as possible to the station and headlight trolleys. The associates supply a total of three car kits from suma C to a kit trolley on the line, and the headlights are supplied from headlight trolleys located next to suma D.

With parts being stored in the sumas, part trolleys are designed in such a way that they can accommodate car kits. A car kit is a lightweight box with compartments of different sizes, and associates insert the parts in each of these compartments. For each type of car kit, a compartment is allocated to a specific part as a fail safe mechanism, also referred to as poka-yoke in Lean terms. It is to ensure that associates picking parts insert the right component in the right quantities. The advantage of using a car kit is that it is easier for the associate picking parts to insert the components and, as a fail safe mechanism, it is easy to see which part is missing from the kit. Moreover, it allows for more efficient assembly as the associate conducting the assembly operations can focus on the assembly without having to search for the correct parts.

The main process in the simulation is the assembly of the front end bumpers. The assembly is broken up into five work packages. BMW refers to a work package as any function that is performed by an associate on the line. Each work package is built up out of small intermediate process steps, which contributes to the assembly of the whole vehicle. A high-level process flow of the five work packages is depicted in Figure 3.2.

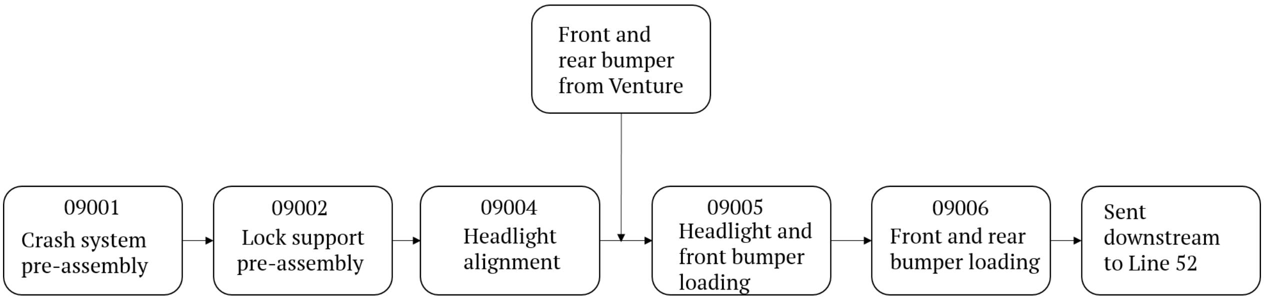


Figure 3.2: Process flow of assembly operations.

The manufacturing of the physical front and rear end bumper is outsourced to an external company, Venture, who continually ensures that the line is supplied with the bumpers. These bumpers are stored on in bumper pallet rack next to station 09006. From the bumper pallet rack, associates place the bumpers on a hexagonal turn table to assist the associates at station 09006 to pick the bumpers more efficiently. At station 09006 the completed bumpers are loaded onto a jig and are sent to Line 52 in the next assembly plant with an overhead conveyor as shown in Figure 3.1. BMW manufactures the crash system which is the skeleton of the front bumper with air guides, headlights and horns. The bumpers which Venture manufacture, is the cover that is placed over the crash system.

The cycle time or takt of this line should be equal to the cycle time of the whole assembly plant, especially the following line the bumpers are sent to, which is Line 52. There is a buffer of completed front and rear end assemblies between the two lines to account for any eventualities. The takt time is referred to as the heartbeat of the customer, and it determines the speed at which BMW should produce vehicles to satisfy the demand of the customer. Essentially, a vehicle must come out the end of an area at the speed of the takt time.

A secondary process in the simulation, essential to the functioning of the system, is the material supply to the line. It is at this process were special attention is given to the integration of the AGVs into their current material handling methodology and is discussed in the following section.

3.2 Base model

The base model represents the current state of the system and will be used as a reference model to compare against the conceptual solutions. The layout of the base model is given in Figure 3.3, indicating the AGV path.

For the current state, a single loop, unidirectional guide path system is used with one AGV in the loop. The process starts at the pick-up and delivery point at suma A where the associate walks with the AGV through the suma. As the AGV stop at certain points in the suma, the associate fills the trolley with parts. After the trolley has been filled the associate dispatches the AGV to station 09001. There is one pick-up and delivery point as the AGV travels along

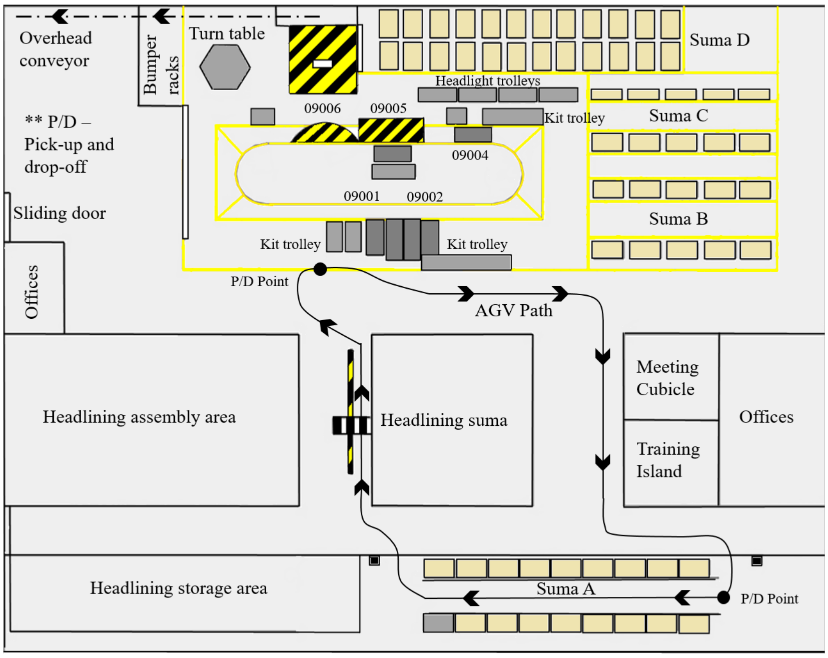


Figure 3.3: Base model layout.

the fixed guide path from suma A to station 09001. The trolley is unloaded, an empty trolley is attached and the AGV returns to the suma where the associate repeats the picking process for the trolley. For the remaining stations 09002, 09004, 09005 and 09006, the associates follow a very similar approach, but instead of using an AGV the associates push the part trolley to the station and collects the empty trolleys.

Each work station has one associate allocated to that station, except for station 09006 who has two associates allocated. For the material supply process from the sumas, there is a total of three associates. One associate is allocated to suma A, one associated to suma B and D, and a third relief associate is allocated to suma D, who also assists the associate at suma B and C with picking.

Currently AGVs are dispatched to station 09001 according to no specific rule as encountered in literature, but once a trolley is available and station 09001 has only one buffer trolley left, a fully loaded trolley is dispatched. A *from-to* flow chart of the AGV process and network flow is depicted in Figure 3.4. Table 3.2 gives a summary of the base model characteristics.

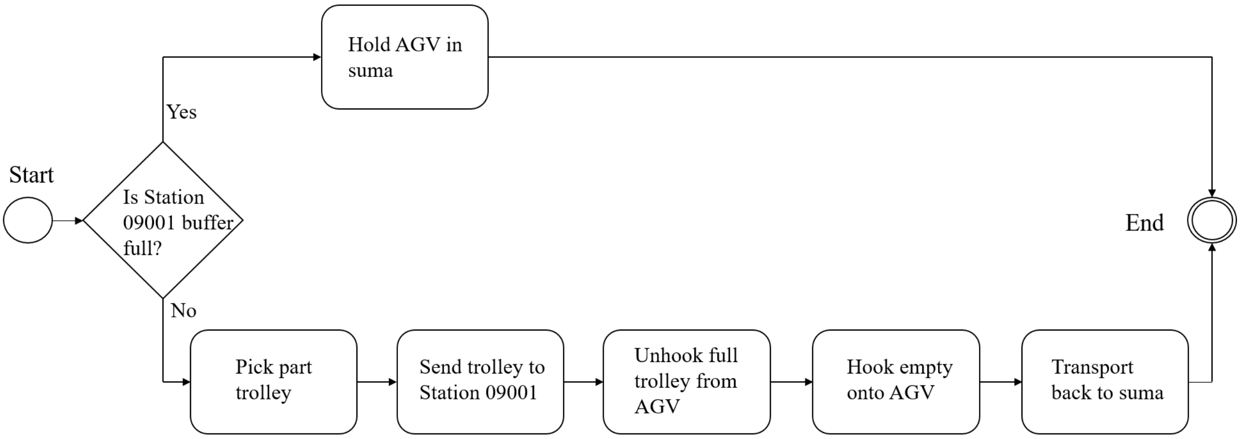


Figure 3.4: Base model from-to flow chart

Table 3.2: Base case system characteristics

AGV system design characteristics		
Type of guide path system	Number of vehicles	Dispatch rule
Single-loop, unidirectional	1	None

Buffers are required at each station to ensure continual production whilst the suma associates pick new parts. The buffer for each station is depicted on Figure 3.3 with the respective part trolleys. These trolleys are moveable but are placed at the locations indicated on the layout. For station 09001, a buffer of two trolleys are used and each trolley holds parts to assemble four vehicles. At station 09002, a special type of part trolley is used, whereby the physical trolley remains in its indicated position, and a buffer of three car kits are placed in the trolley. At station 09004 a similar trolley is used which also contains a buffer of three car kits. Also at station 09004, four headlight trolleys are also used as shown on the layout. Each headlight trolley can accommodate six headlight pairs, three pairs on one level and three pairs on a lower level.

At BMW Plant Rosslyn vehicles are manufactured on a 24-hour basis, and workload is distributed between three, eight-hour shifts. Table 3.3 indicates the time slots of the three different shifts, lunch and tea break times.

Table 3.3: Time slots for production shifts, lunch and tea breaks

Shift	Production	Lunch	Tea
A	22:00 - 06:00	01:30 - 02:00	04:30 - 4:45
B	06:00 - 14:00	12:30 - 13:00	09:15 - 09:30
C	14:00 - 22:00	18:30 - 19:00	20:30 - 20:45

For the base model and the scenario models the simulation model runs for an equivalent time of one shift. The total time for one shift is 480 minutes. When the 30 minute lunch and fifteen minute tea break times are deducted, the remaining available production time is 435 minutes. The simulation model runs for a total of 435 minutes, uninterruptedly. The reason why the model is not expanded to run for an entire production cycle of 24 hours, is that in each of the three shifts the process remains exactly the same and it would be redundant to repeat all three shifts and run such a long simulation when the data gathered from one shift is more than sufficient to assist decision making.

3.3 Scenario model development

The focus of the simulation study is to determine which combination of design factors to use that will produce the most efficient AGV system. The three design factors are (1) guide path design, (2) number of vehicles and (3) dispatch rule. From the literature it was concluded that the most applicable guide path for this application would be conventional or single loop systems. This was based on the size of the system and that this system is regarded as a small system. During solution development it was found that although Farling et al. (2001) concluded that single loop guide paths work best for small systems, it was discovered that it ws not the most practical solution for this specific application mainly because the layout of the stations and the sumas. Farling et al. (2001) noted that tandem systems work best for large systems. After investigation for this specific application, it was found that the tandem loop could be a viable solution and was incorporated into the scenario models.

For the dispatch rule, the Maximum Remaining Outgoing Queue Size (MROQS) or Modified First Come First Serve (MFCFS) would be the most applicable and the optimal number of vehicles will be determined by the simulation. The conceptual scenarios are developed in such a way that multiple design factors are incorporated in each scenario. Ultimately the most effective design factors want to be determined, therefore four conceptual scenario experiments are developed. Table 3.4 gives the combination of design factors for each experiment. For each experiment a single AGV will be used as a starting point, and consequently the optimal number of vehicles will be determined by increasing the number of vehicles in the simulation and evaluating against system performance.

Table 3.4: Conceptual scenario experiments

		Dispatch rule	
		MROQS	MFCFS
Guide path system	Conventional	1	2
	Tandem loop	3	4

Scenario 1 focusses on a conventional guide path system with AGVs being dispatched with the MROQS rule.

Scenario 2 focusses on a conventional guide path system, but with AGVs being dispatched with the MFCFS rule.

Scenario 3 focusses on a tandem loop guide path system with AGVs being dispatched with the MROQS rule.

Scenario 4 focusses on a tandem loop guide path system, but with AGVs being dispatched with the MFCFS rule.

The purpose of the scenario simulations is to determine the interference point in terms of guide paths, number of vehicles and dispatch rule that produce the best results. The performance of the base model and scenario models will be evaluated by three performance measures: (1) the throughput of the AGV system, (2) AGV utilization and (3) size of inventory buffers at work stations. Also, all of the models operate under the following set of assumptions:

1. Materials are supplied from a Just-in-Time (JIT) perspective.
2. The speed of the AGVs remain constant at 25 meters per minute with no acceleration.
3. All AGVs in the fleet have identical properties.
4. Throughout the whole simulation, sumas are fully stocked with no shortages.
5. The speed at which associates walk are fixed at 1.4 meters per second.
6. The simulation uses the whole distribution of values for processing times at each station, instead of taking note of the time taken to complete all the various options and alternations.
7. All associates are present and available in at their work stations and sumas.

3.4 Scenario model layout development

The first and most important design component of the AGV system is the layout of the guide path. The associate working in sumas B and C walks with the part trolley to the station where the car kits are unloaded in each respective kit trolley. The relief associate picking headlights in suma D has to walk in and through the congested suma, pick a headlight and place it in the respective compartment in the headlight trolley. As previously mentioned, there are four headlight trolleys of which each contains six headlight pairs. A headlight pair consists of a right and left headlight for each bumper assembly. This is a total of twelve headlights stored on each headlight trolley. Furthermore, there are four headlight trolleys located close to station 09004. This amounts to a total of 48 headlights being stored in the trolleys. The use of these headlight trolleys creates inefficiencies as it results in an overstocked area, they are bulky and altogether take up a lot of space. By using the headlight trolleys, it also creates unnecessary double handling of the headlights which creates the risk of an associate dropping and damaging the headlight. Furthermore, the whole of suma D is fully stocked with part boxes containing headlights in addition to the headlights contained in the headlight trolleys. The result thereof is over stocking of headlights that congests the area and reduces the amount of available floor space. Figure 3.5 depicts the part boxes in suma D containing headlights and the four headlight trolleys.

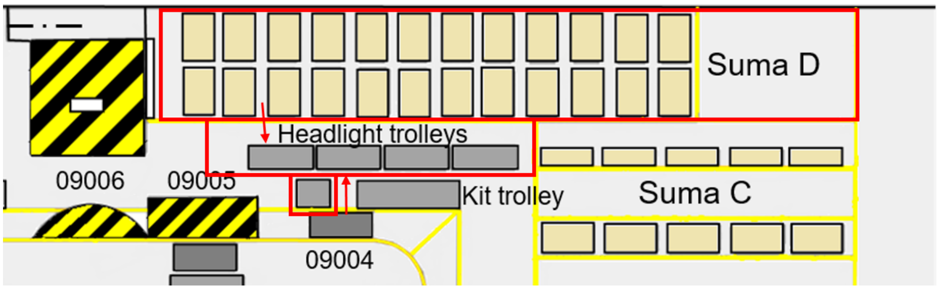


Figure 3.5: Current layout of suma D.

The current process flow for the suma and station 09004 is depicted in Figure 3.6. After the relief associate picks headlights and fills headlight trolleys, the associate assembling at station 09004 has to walk to the trolleys through the small gap indicated on Figure 3.5, pick up a headlight and put it on a table next to the kit trolley. After the associate places it on the table, he adds a component to the headlight and takes to the line and adds it to the front end assembly.

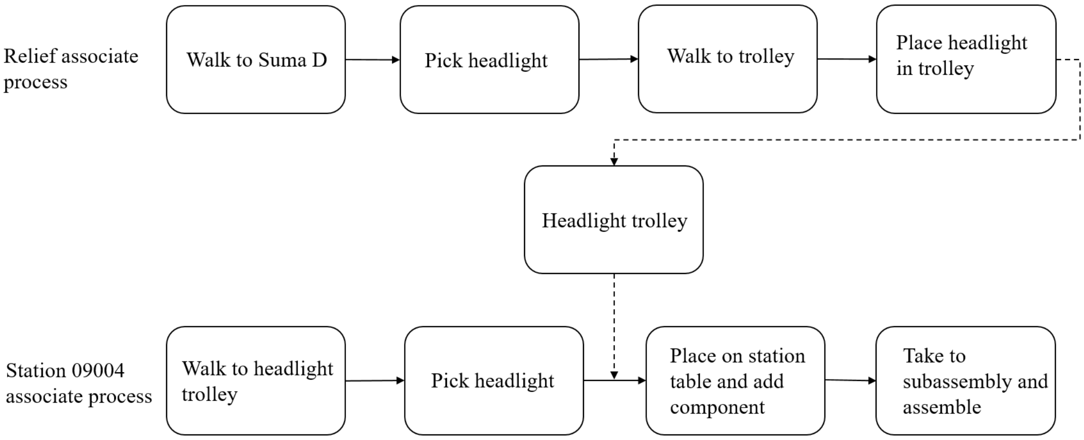


Figure 3.6: Current process flow at station 09004 and suma D.

A proposed solution to this problem is to:

i. Decrease the excess headlights in suma D.

ii. Combine suma D and suma C to form one suma to supply to station 09004 from one central point.

iii. Remove the headlight trolleys from the process.

iv. Adjust the size of the car kit used at station 09004 to accommodate for two headlights.

As a result, the associate picking the parts for the car kits for station 09004 also picks the headlights and places it in the same car kit. This eliminates the double handling of the headlights between the suma and the station. As soon as the fully picked car kit reaches the station, the associate responsible for assembly can pick from the kit, instead of walking to the headlight trolley to and fro. All the components required for the assembly is then contained in one complete kit, as opposed to the current process where the parts are contained in two different points. This also removes the intermediate table at the station, leaving only the kit trolley from where the associate picks his parts.

The proposed solutions are incorporated into the process and layout for the scenario models as it simplifies the process and frees up space where AGVs can possibly travel. Subsequently, these solutions are used in the development of the conventional and tandem AGV loops. The layout of the combined suma C and D is depicted in Figure 3.7.

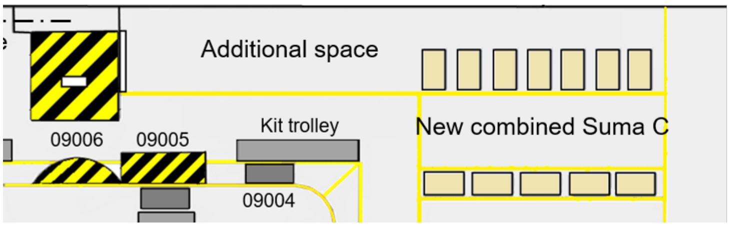


Figure 3.7: Layout of combined suma.

3.4.1 Conventional loop

A conventional loop is a one that connects all of the stations and AGVs in one complete system. This means that all of the stations are accessible for an AGV by using different paths between the stations. Whilst travelling on a given path, the AGV is directed to the station requiring a pick-up of parts or where parts should be unloaded. Also important to such a loop is a central holding area from which the AGVs are dispatched to the respective stations.

Stations 09001, 09002 and 09004 all require parts from their respective sumas, and therefore could be integrated into one AGV system by using a conventional loop. This conventional loop spans from suma A, to suma C connecting the stations with their sumas.

The main objective for the design of the guide path is to minimise the total distance that AGVs travel in the network. To determine the location of a central AGV holding area for the AGVs the problem is developed using the single-facility, rectilinear minisum location problem (Tompkins, 2010). The main purpose of the singe-facility model is to minimise the total travelling distance the AGVs would have to travel between stations and the central AGV area.

The central AGV holding area is seen as a single facility, and the pick-up and drop-off points at the stations and sumas are seen as the facilities which the single facility must service. The rectilinear model is chosen over the euclidean model as the AGVs do not travel in straight lines between stations. Because this is a relatively simple model that is quite simplified, it is used as an input to decide on the best location to place the central AGV holding area.

For the single-facility, rectilinear problem we let (Tompkins, 2010):

$X(x, y) \triangleq$ Location of new facility
$P_i(a_i, b_i) \triangleq$ Location of existing facility i, $i = 1, 2, ...m$
$w_i \triangleq$ Weight associated with travel between new facility and existing facility i
$d(X, P_i) \triangleq$ Distance between new facility and existing facility i

The objective is to:

$$\min f(X) = \sum_{i=1}^{m} w_i d(X, P_i) \tag{3.1}$$

The rectilinear model measures the distances by the sum of the absolute differences between coordinates, that is

$$d(X, P_i) = |x - a_i| + |y - b_i| \tag{3.2}$$

Therefore we formulate the single facility minisum location problem as:

$$\min f(x, y) = \sum_{i=1}^{m} w_i |x - a_i| + \sum_{i=1}^{m} w_i |y - b_i| \tag{3.3}$$

Because Equation 3.3 is separable in x and y, the optimal values for x and y can be obtained independently.

$$\min f(x) = \sum_{i=1}^{m} w_i |x - a_i| \tag{3.4}$$

$$\min f(y) = \sum_{i=1}^{m} w_i |y - b_i| \tag{3.5}$$

Equations 3.4 and 3.5 are piecewise linear functions and optimal values for x and y will be coordinates of existing facilities. If we use the piecewise structure of Equations 3.4 and 3.5 we can determine x^*, which is the optimal x-coordinate, by summation of the weights for each facility. The optimal x-coordinate will be such that no more than half of the weights will be to the right of x^* and no more than half the weights will be to the left of x^*. The same conditions hold for y^*, the optimal y-coordinate. No more than half the weights will be above y^*, and no more than half of the weights will be below y^*. This method and conditions are referred to as the median conditions of an optimum solution to the single-facility, rectilinear minisum location problem (Tompkins, 2010).

Solving for the conventional loop with a total of six pick-up and drop-off points which is seen as the ‘existing facilities’, our AGV area as the ’new facility’, we determine the coordinates of the locations on the layout. The locations of these six points can be seen in Figure 3.8. Table 3.5 indicates the coordinates of our locations in meters from the reference point.

Table 3.5: Location and weights of locations

Location i	Coordinate a_i	Coordinate b_i	Weight w_i
1	35	3	35.5
2	21	22	35.5
3	28	22	47.3
4	41	26	47.3
5	41	31	47.3
6	30	34	47.3

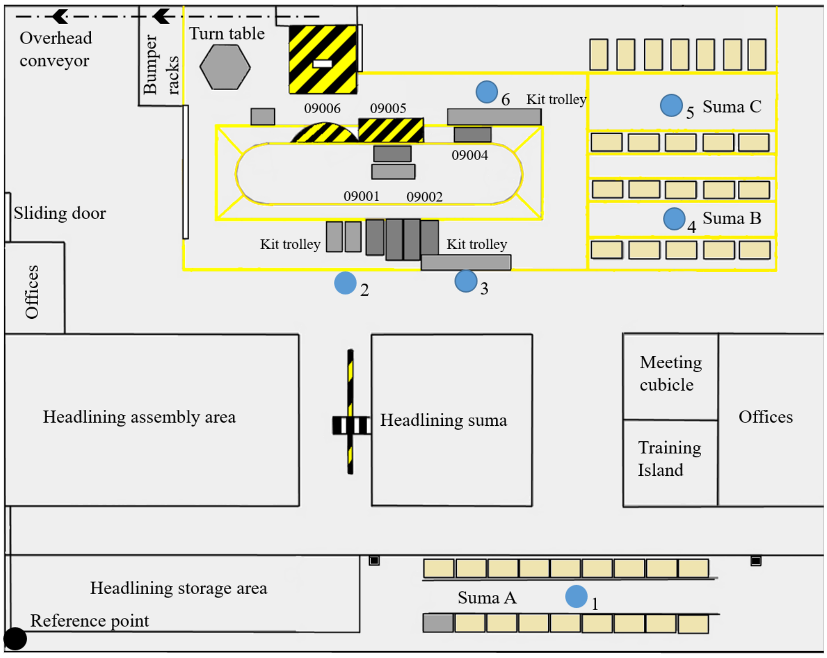


Figure 3.8: Facility layout and pick-up and drop-off points.

Weights are assigned to each location based on the total demand for pick-up and drop-off's at that point. The weights are derived from the high level demand for front end bumpers per shift, which is 142. Essentially, this becomes the demand for parts at each work station as associates would require the correct amount of parts to assemble for that demand. The part trolleys that are used to deliver parts to stations contains a certain amount of car kits. Therefore the weights associated with the demand for a work station can be calculated by using total demand at the station and the amount of car kits that the station receives per drop. This will then approximately determine how many times the station would require delivery of parts. The weight for station $i \in \boldsymbol{I} = \{1 \dots 6\}$ is denoted by w_i and is calculated as:

$$w_i = \frac{\text{Demand at station } i}{\text{Amount of car kits per unloading}}$$

At station 09001, the part trolley can deliver four car kits per delivery to station 09001. Therefore the weight associated with that station is:

$$w_i = \frac{142}{4} = 35,5$$

This means that parts would approximately have to be delivered to station 09001, 35 times during the shift. At station 09002 and station 09004, a part trolley can deliver a total of 3 car kits. Therefore the weight associated with those stations are:

$$w_i = \frac{142}{3} = 47,3$$

Because each station is supplied by a specific suma, weights are assigned to each suma according to the weight of that station which it supplies to. Meaning that for the AGV to supply parts to station 09001, it would require roughly 35 trips. Similarly, the AGV would have to also make 35 trips to suma A to collect those parts. The same principle is applied to determine the weights for suma B and C. Table 3.5 shows the weights allocated to each location.

To determine x^*, we arrange the locations in order of increasing distance of x-coordinates in a table with their corresponding weights as indicated in Table 3.6. In the last column we sum the weights, and where the summation equals half or just over half the total sum, that

x-coordinate becomes the new optimal point. In Table 3.6 the sum of all the weights is 260,2. Thus half the total weights is 130,1. When looking at the summation in the last column it is evident that the midpoint is at location 6 with the sum being equal to half the sum of all weights. Thus, our x^* is equal to the x-coordinate of location 6 which is 30.

Table 3.6: Conventional loop optimal x-coordinate

Location i	Coordinate a_i	Weight w_i	$\sum_{b=1}^{i} w_b$
2	21	35.5	35.5
3	28	47.3	82.8
6	30	47.3	130.1
1	35	35.5	165.6
4	41	47.3	212.9
5	41	47.3	260.2

The same procedure is repeated to determine y^*. The locations are arranged in Table 3.7 in order of increase distance of y-coordinates. The sum of weights up until location 3 equals 118,3 which is smaller than half of the total summation. Therefore, we add another weight to the summation and obtain a summed weight of 165,6 at location 4. This is larger than half of the total summation, and because this method looks for the median, we select the y-coordinate of location 4 as it is the first point that is just larger than our midpoint of median point. Thus the optimal y-coordinate is equal to 26. For the conventional loop, the optimal location for our central AGV holding area is $X^* = (30{,}26)$.

Table 3.7: Conventional loop optimal y-coordinate

Location i	Coordinate b_i	Weight w_i	$\sum_{b=1}^{i} w_b$
1	3	35.5	35.5
2	22	35.5	71
3	22	47.3	118.3
4	26	47.3	165.6
5	31	47.3	212.9
6	34	47.3	260.2

The location of this optimal point, falls right next to the assembly line. This is not a practical solution because of space constraints in that area. Therefore using the optimal point obtained from the minisum problem as input, three alternative locations are considered. Alternative one is located in the current meeting cubicle as shown on Figure 3.8. This is an open area consisting of a table and chairs where the associates meet daily for shift start-up meetings and also has demarcations displaying all of their goals, attendance and improvement ideas. Alternative two is located in the training island. This area consists of parts, bumpers, kits and all required components to train new associates on the assembly operations on Line 09. This is also an open area, and can be relocated to another area. Alternative three is located in an open area in the bottom end of facility. Figure 3.9 depicts the optimal location, X^* and the three alternative locations A1, A2 and A3.

To determine the best location it is necessary to look at quantitative but also qualitative factors. The feasibility of locations are quantitatively determined using Equation 3.3. The total travel distances for the optimal location and alternative locations can be seen in Table 3.8.

It makes sense that the total distance increases as the point moves further away from the optimal point as shown in Table 3.8. Although alternative one is the next most optimal point, it would not be feasible to move the meeting area. The reason for this is that the meeting area

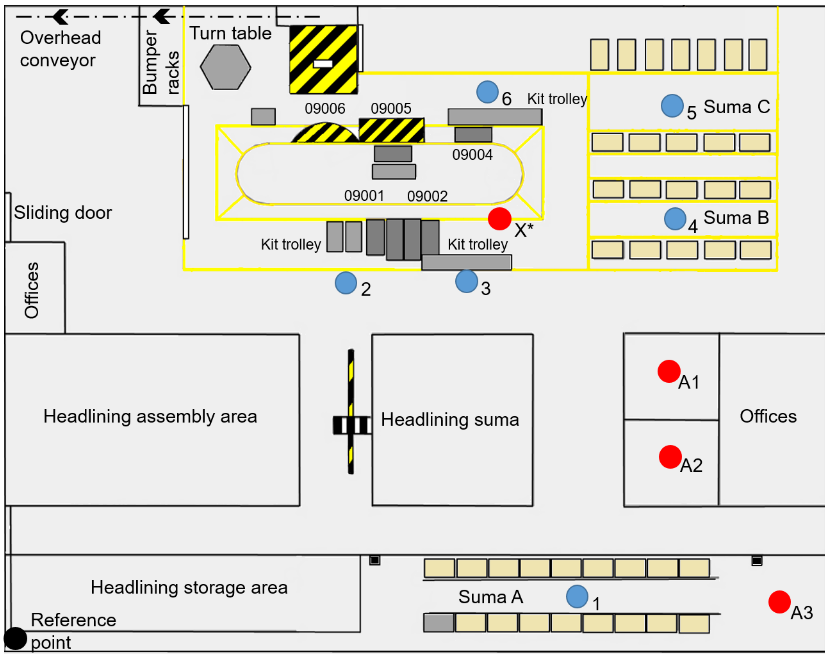


Figure 3.9: Optimal location and alternatives locations for AGV holding area. Current locations of pick-up and drop-off points are indicated with blue dots labeled as 1 to 6. The optimal location is indicated with a red dot and labeled as X^*. The alternative locations are also indicated with red dots, but labeled as A1, A2 and A3.

Table 3.8: Total traveling distances for optimal and alternative locations

Location i	Total distance (Meters)
X^*	3394.8
A1	4979.4
A2	5925.4
A3	8811.0

is frequently used by associates and management. Also, the furniture and demarcations in this area is fixed and BMW prefers to keep this area as is. Therefore, alternative two is chosen as the best location of the AGV area as the furniture and training materials can be moved to the open area at alternative three.

The purpose of the AGV area is to have a central holding and dispatching area. This area can also be used to hold AGVs in need of maintenance or battery replacements.

Incorporating the AGV area, the conventional loop is developed. The layout of the conventional loop used in Scenario models 1 and 2 can be seen in Figure 3.10.

The conventional guide path is a unidirectional path, and it consists of various intersection where paths cross. The characteristics of a conventional loop is such that it has intersections that pose the risk for vehicle collisions. The technology on modern AGV are such that it detects an obstacle approaching and waits for the obstacle to move before it proceeds. The risk of collisions are also reduced by having unidirectional paths. The reason for the paths being spread apart is to account for other vehicles also travelling on the main paths in the facility. Therefore to avoid AGVs colliding with such a vehicle, the paths are located off the main paths. There are certain points where the AGV path crosses the main path, but currently, by order of BMW management the AGVs have right of way.

As a station requires parts, an AGV is dispatched to that station from the central holding

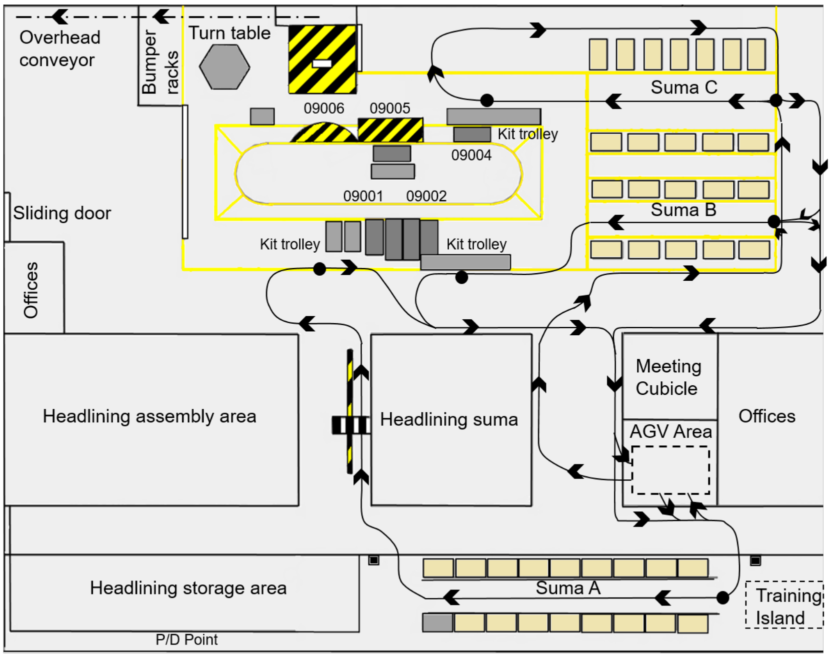


Figure 3.10: Conventional guide path layout.

area. The AGV travels to the respective suma of the station, where an associate attaches the trolley to that AGV and starts the picking process. After all the kits have been fully picked, the AGV and trolley is sent to the station where the the kits are unloaded in the kit trolley. After the full kits are unloaded the AGV returns to the suma where the associate detaches the trolley and releases the AGV to return to the central holding area or to other stations.

The delivery of parts at a station relies on a docking concept which BMW is currently looking to implement. The basis of this docking concept is that it eliminates the process where the associate at the station attaches and detaches a trolley as in the base case. In this concept the AGV stops at the station, and with mechanical movements the full kits move from the part trolley onto the kit trolley into position. After the full kits are unloaded, the remaining empty kits move from the kit trolley onto the part trolley which is then transported back to the suma. All scenario models are developed based on this docking concept. Ultimately, an assumption was made to determine the time it would take to unload kits and collect empty kits. Because such a docking concept has not yet been developed at Plant Rosslyn, video material on similar docking concepts at BMW plants in Germany were analysed. Based on the video material, it was assumed that the docking concept would take between 30 and 60 seconds. Subsequently, a uniform distribution with maximum 60 seconds and minimum 30 seconds is used for all the scenario models.

3.4.2 Tandem loop

A tandem loop guide path system is one which is traditionally made up of different single loops each having their own AGV servicing that loop. A tandem loop guide path system can have multiple loops in the same system but AGVs are assigned to specific loops and they stay within that loop. The development of the the tandem guide guide path for this area comprised of dividing the system into two AGV loops. The first loop is based on the original base case loop, where the AGV is dispatched from suma A to station 09001. After the parts have been unloaded at the station, the AGV travels back to suma A. The second loop integrates station 09002, station 09004, suma B and the newly designed suma C into one system being served by multiple AGVs.

Similarly with the conventional guide path, it is required that AGVs be held in a holding area where maintenance, charging or battery replacement can be done. Because there are two loops, and each loop uses utilises its own AGV and therefore this system requires two holding areas located in close proximity to each loop.

The optimal locations for these holding areas are determined with the single-facility, rectilinear minisum location problem (Tompkins, 2010). In each loop the central location is seen as the new holding area and the locations are the existing stations in the loop. This solution method is applied to loop one and loop two to determine the optimal or near optimal location for the holding areas for each loop. Figure 3.11 depicts the locations of the stations. The green points indicate the points to be integrated with loop one and the blue points indicate the points to be integrated with loop two.

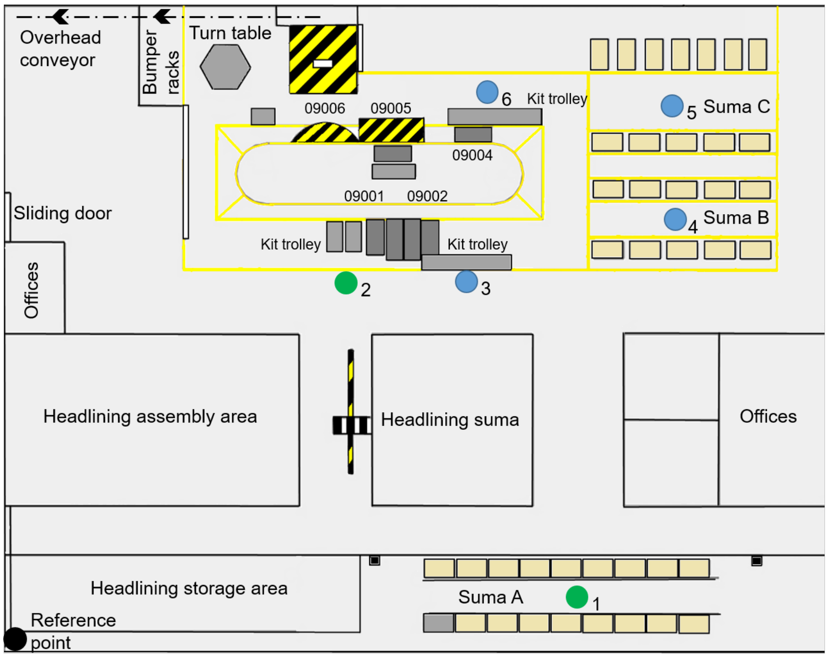


Figure 3.11: Location of pick-up and drop-off points.

Solving the single-facility, rectilinear minisum location problem for loop one by using the method as discussed in the previous section yields the results in Table 3.9. With the weights for each location remaining constant, the sum of weights indicate that the midpoint is located at the x-coordinate of location 2. The optimal x-coordinate is subsequently, $x^* = 21$.

Table 3.9: Tandem loop 1 optimal x-coordinate

Location i	Coordinate a_i	Weight w_i	$\sum_{b=1}^{i} w_b$
2	21	35.5	35.5
1	35	35.5	71

The optimal y-coordinate is determined in exactly the same manner as depicted in Table 3.10. From the table the sum of the weights at location one is equal the half of the total summation of weights. Therefore, the optimal y-coordinate is, $y^* = 3$. For loop one, the optimal location for the AGV holding area is, $X^* = (21{,}3)$.

The feasibility of this location should is determined against quantitative and qualitative factors. Figure 3.12 gives an indication of the optimal location , X^* and alternative location, A1. The X^* point is located within the headlining storage area. Currently this area is fully occupied by headlining trolleys which are stored in the area. Alternative location one is an open

Table 3.10: Tandem loop 1 optimal y-coordinate

Location i	Coordinate b_i	Weight w_i	$\sum_{b=1}^{i} w_b$
1	3	35.5	35.5
2	22	35.5	71

area right next to the entrance of suma A, which is advantageous because the picking process starts at the beginning of suma A. If station 09001 requires parts, the AGV can be quickly dispatched to the suma. The determination of the optimal point did not take into consideration where the AGV starts, but merely looks for the midpoint between the two locations. Table 3.11 gives the total distance as calculated with Equation 3.3 for the optimal point and alternative one. Alternative one is chosen as the preferred location for the holding area as much more accessible for suma A.

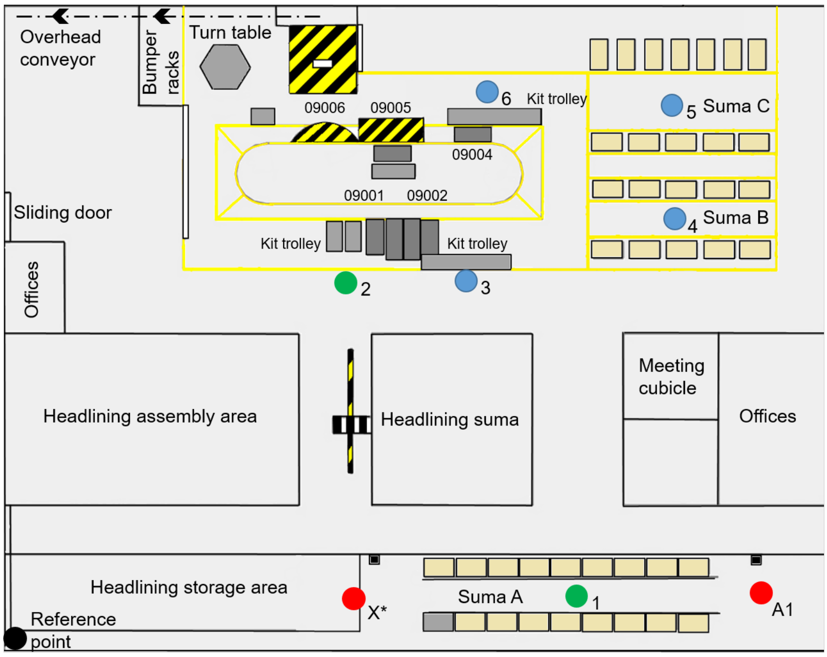


Figure 3.12: Optimal and alternative locations for loop 1 AGV area. The optimal point is indicated with a red dot, labeled as X^*. The alternative location is also indicated with a red dot, labeled as A1.

Table 3.11: Total distances for optimal and alternative location for tandem loop 1

Location i	Total distance (Meters)
X^*	1171,5
A1	1952,5

The optimal location for the holding area for loop two of the tandem guide path is evaluated by applying the same principle to location three, four, five and six. The objective is to find the holding area for the AGVs in this loop that will result in the smallest distance travelled. The optimum x-coordinate is determined using Table 3.12. To determine x^*, we look for the location where the sum of weight is equal or just bigger than half of the total summation. From

Table 3.12 the sum of weights up until location six is equal to half of the total summation, therefore $x^* = 30$.

Table 3.12: Tandem loop 2 optimal x-coordinate

Location i	Coordinate a_i	Weight w_i	$\sum_{b=1}^{i} w_b$
3	28	47.3	47.3
6	30	47.3	94.6
4	41	47.3	141.9
5	41	47.3	189.2

Similarly, using Table 3.13 we can determine the optimal y-coordinate of AGV holding area. From Table 3.13 the sum of weights up until location 4 is equal to half of the total summation of weights. Therefore, $y^* = 26$. The optimal location, for the hold area for loop two is, $X^* =$ (30,26).

Table 3.13: Tandem loop 2 optimal y-coordinate

Location i	Coordinate b_i	Weight w_i	$\sum_{b=1}^{i} w_b$
3	22	47.3	47.3
4	26	47.3	94.6
5	31	47.3	141.9
6	34	47.3	189.2

The actual location of the optimal point for loop 2 is located next to the assembly line close to station 09002. This might be the optimal point based on this model, but might not be the most practical and feasible location. Two other alternative locations, one and two were identified as possible locations. Figure 3.13 indicates the optimal location, X^*, and alternative locations A1 and A2. Alternative location one is located in an empty space in close proximity to suma C. This area opened up as a result of the proposed integration of suma C and D. Alternative location two is the same location where the current training island is located, but it can move moved to another area as indicated with the conventional loop design.

After applying Equation 3.3 to the optimal and alternative points, the total travel distance between the stations and point are summarised in Table 3.14. The optimal X^* for this loop is not feasible because of its close proximity to the assembly line. Alternative one is located in an open and accessible area and next had the second smallest total distance travelled. Whereas alternative two had the largest total distance travelled meaning the AGVs would have to travel greater distances to the respective sumas and stations. Alternative one is chosen as the location of the AGV holding area for loop 2.

Table 3.14: Total distances for optimal and alternative location for tandem loop 2

Location i	Total distance (Meters)
X^*	1939,3
A1	3925,9
A2	4588,1

By incorporating the two AGV holding areas, the tandem guide path for Scenario models 3 and 4 are depicted in Figure 3.14. The tandem layout consists of two unidirectional loops. Loop one is located at the bottom of Figure 3.14, it moves through suma A to station 09001. From

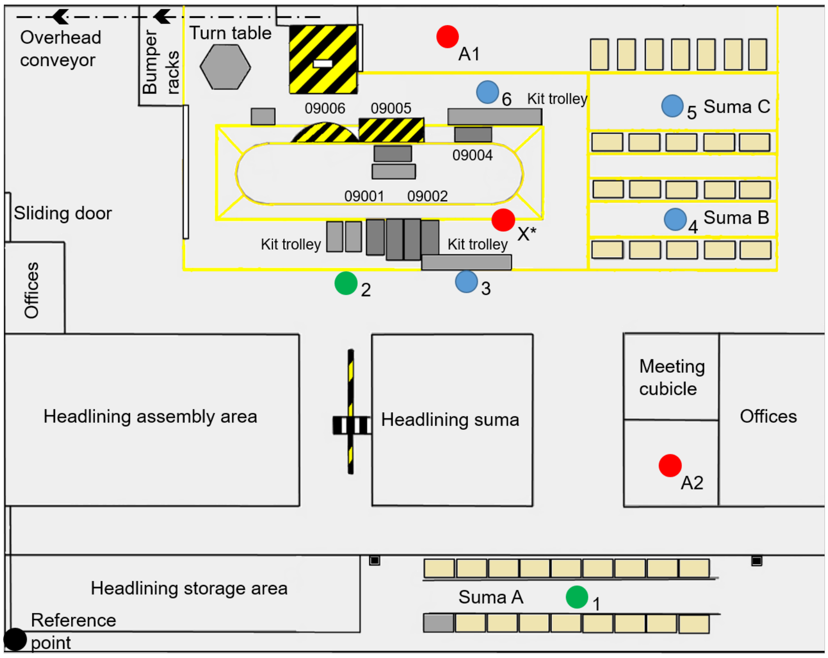


Figure 3.13: Optimal and alternative locations for loop 2 AGV area. The optimal location is indicated with a red dot, labeled as X^*. The alternative locations are also indicated with red dots and labeled as A1 and A2.

station 09001 the AGV travels back to suma A where the associate detaches the part trolley. If there are no requests for more parts at station 09001, the AGV is held in the AGV area next to the suma. The second loop is in the right corner of Figure 3.14, it allows the AGV to move through suma B to station 09002 and through suma C to station 09004. The guide paths are located next to the main paths where other vehicles travel. This is to minimise the risk of AGVs colliding with these vehicles. There is one interference point where the guide paths cross the main path, but as discussed in the design of the conventional loop the AGVs have right of way on these paths.

The tandem guide path also incorporates the docking concept BMW is looking to incorporate in the process to ensure that associates working on the line can continue with production without having to attach or detach part trolley to the AGV.

Collisions between AGVs are a possibility, especially in the second loop. Because this is such a small application, there would not be a large amount of AGVs in the loop which will minimise the risk of collisions.

3.5 Scenario model dispatch rules development

Dispatch rules are used to govern the flow of AGVs on any given guide path or segment. It serves as a decision making rule to determine to which point in the facility AGVs should be dispatched. The development of the MROQS and MFCFS dispatch rules are discussed in the following section.

The from-to flow charts of the conventional and tandem guide path system are given in Figures 3.15 and 3.16 respectively. The from-to flow chart describes the process flow of how the AGVs move on a guide path system. In this system there are decision points where a condition determines the route the AGV should follow. It is at these decision points where the dispatch rules are incorporated into the simulation model and govern the flow of the AGVs. Decision points are graphically depicted by diamond shapes in the from-to flow charts.

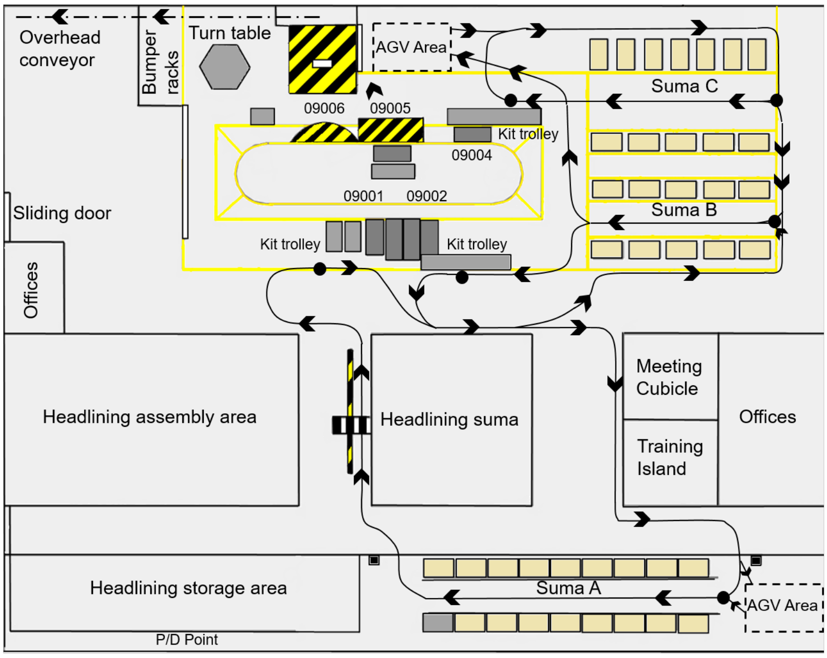


Figure 3.14: Tandem layout.

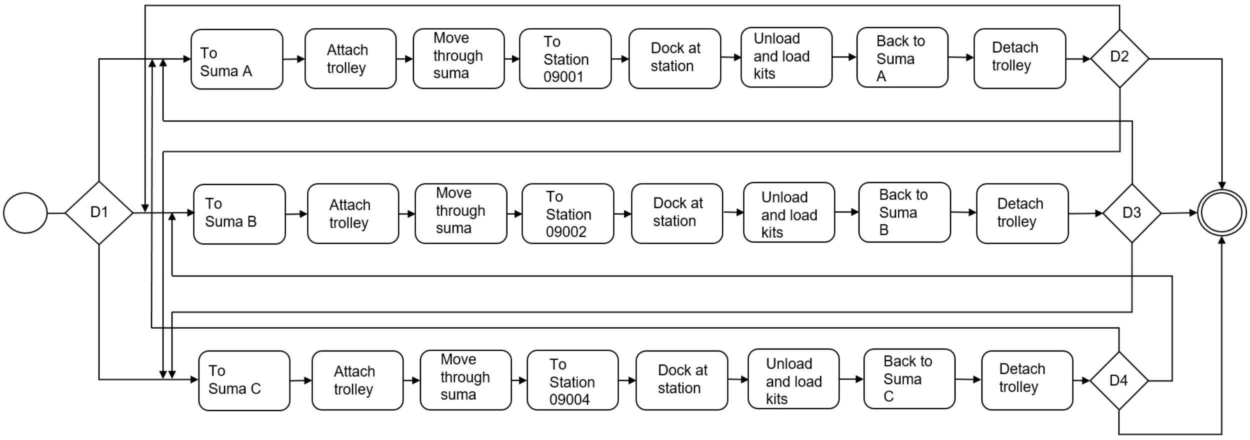
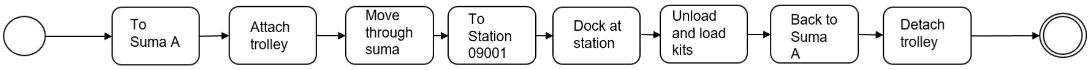
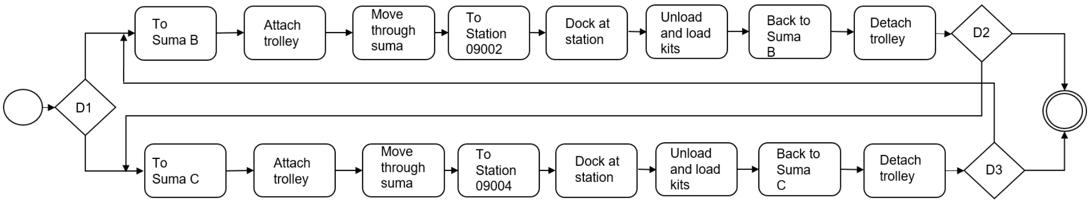


Figure 3.15: From-to flow chart for conventional guide path system.



(a) Tandem guide path loop 1



(b) Tandem guide path loop 2

Figure 3.16: From-to flow chart for tandem guide path system.

3.5.1 Maximum Remaining Outgoing Queue Size (MROQS)

The MROQS dispatch rule focusses on dispatching an AGV to the station who has the least amount buffer stock left in its outgoing queue. The output of each station at Line 09 is the subassembly the associate sends to the next station. It does, however, have an incoming queue buffer of car kits. It is essential to ensure that this buffer is continually maintained for continuous production. If an associate has no car kits left in its buffer queue, he stops the movement of the whole line behind him.

For the conventional guide path layout, the MROQS is incorporated in four decision points, D1, D2, D3 and D4 as indicated on Figure 3.15. The process starts at the central AGV holding area. As an AGV is requested, either simultaneously or by a single station, at D1 the model determines which of the stations requiring parts have the least amount of car kits in its buffer queue. The AGV is then sent to the appropriate station. In the event where there are multiple AGVs in the system and multiple stations request parts, this decision process is repeated at D1 if there are AGVs available in the holding area. The AGV is then dispatched to the next station with the least amount of car kits in its buffer queue. The pseudocode algoritm of the MROQS rule for the conventional guide path is given in Algoritm 1. The *S1Buffer*, *S2Buffer* and *S4Buffer* notation used in the algorithm signifies the size of the buffer queues at stations 09001, 09002 and 09002 respectively.

For the tandem loop the MROQS rule is incorporated in the same manner. Tandem guide path loop 1 services only one suma and one station as indicated in Figure 3.16a. The only rule governing the movement of AGVs in this single loop is the request for new parts. Because this is a single loop, one AGV is used in it, therefore the would not be a specific dispatch rule, other than the station requesting parts. Therefore, for both the MROQS and MFCFS dispatch rules discussed in this section, the pseudo code algorithm is the same for both dispatch rules. The pseudo code algorithm for loop 1 of the tandem system is given with Algorithm 2.

The MROQS dispatch rule is incorporated in loop 2, where there are two sumas and two AGVs as indicated in Figure 3.16b. The dispatch rule is applied at decision points D1, D2 and D3. In this system the process starts in the AGV holding area close to loop two and a decision regarding which station to send the AGV to is made at D1. Here the AGV can be sent to either suma B or suma C depending which one has the least amount of car kits in its buffer. The pseudo code algorithm for the MROQS rule applied to the tandem guide path is given in Algorithm 3.

3.5.2 Modified First Come First Serve (MFCFS)

The MFCFS dispatch rule focusses on dispatching an AGV to the station who requested the delivery of parts first. In the event of parts being requested by two stations the AGV is dispatched to the one who requested it first.

For the conventional guide path, the process for an AGV starts at the central holding area. If only one station requested parts, the AGV will be sent to that specific station. But in the event where multiple stations request parts, the MFCFS rule will send the AGV to the station who requested it first and consequently been waiting the longest for parts to arrive. The MFCFS dispatch rule is applied to decision points D1, D2, D3 and D4 as depicted in Figure 3.15. The pseudo code algorithm for the MFCFS rule applied to the conventional guide path is given with Algorithm 4. The notation *S1AGV*, *S2AGV* and *S4AGV* used in the algorithm signifies a binary variable in the code to determine if the particular station has been serviced by an AGV. This is for stations 09001, 09002 and 09004 respectively.

For the tandem guide path, the MFCFS rule is applied in loop 2 at decsion points D1, D2 and D3 as given in Figure 3.16b. A decision at D1 signifies the start of the process, and the AGV can be sent to either station 09002 or station 09004 from the AGV holding area located next to suma C. The pseudo code algorithm for the MFCFS rule applied to loop 2 of the tandem guide path is given with Algorithm 5.

Algorithm 1: MROQS dispatch rule for conventional guide path.

```
Data: Stations request delivery of parts with AGVs in holding area.
Result: Decision at D1.
if $S1Buffer < S2Buffer$ and $S1Buffer < S4Buffer$ then
    Send AGV to suma A;
if $S2Buffer < S1Buffer$ and $S2Buffer < S4Buffer$ then
    Send AGV to suma B;
else
    Send AGV to suma C;
Data: AGV delivered parts to station 09001
Result: Decision at D2
if $S2Buffer \leq 2$ and $S2Buffer < S4Buffer$ then
    Send AGV to suma B;
if $S4Buffer \leq 2$ and $S4Buffer < S2Buffer$ then
    Send AGV to suma C;
else
    Send AGV to holding area;
Data: AGV delivered parts to station 09002
Result: Decision at D3
if $S1Buffer = 0$ and $S1Buffer < S4Buffer$ then
    Send AGV to suma A;
if $S4Buffer \leq 2$ and $S4Buffer < S1Buffer$ then
    Send AGV to suma C;
else
    Send AGV to holding area;
Data: AGV delivered parts to station 09004
Result: Decision at D4
if $S1Buffer = 0$ and $S1Buffer < S2Buffer$ then
    Send AGV to suma A;
if $S2Buffer \leq 2$ and $S2Buffer < S1Buffer$ then
    Send AGV to suma B;
else
    Send AGV to holding area;
```

Algorithm 2: MROQS and MFCFS dispatch rules for tandem guide path, loop 1.

```
Data: Station 09001 request delivery of parts with AGVs in holding area.
Result: AGVs sent to suma A.
if $S1Buffer \leq 0$ then
    Send AGV to suma A;
else
    Keep AGV in holding area;
```

The conventional and tandem guide path systems developed, together with the MROQS and MFCFS dispatch rules, were integrated and built into the models to represent the four scenarios that are evaluated and compared against the base case results. The following chapter presents an analysis of the data gathered form the base model and scenario models.

Algorithm 3: MROQS dispatch rule for tandem guide path, loop 2.

```
Data: Stations request delivery of parts with AGVs in holding area.
Result: Decision at D1.
if $S2Buffer < S4Buffer$ then
    Send AGV to suma B;
else
    Send AGV to suma C;
Data: AGV delivered parts to station 09001
Result: Decision at D2
if $S4Buffer \leq 2$ then
    Send AGV to suma C;
else
    Send AGV to holding area;
Data: AGV delivered parts to station 09002
Result: Decision at D3
if $S2Buffer \leq 2$ then
    Send AGV to suma B;
else
    Send AGV to holding area;
```

Algorithm 4: MFCFS dispatch rule for conventional guide path.

```
Data: Stations request delivery of parts with AGVs in holding area.
Result: Decision at D1.
if $S1Buffer = 0$ and $S1AGV < 1$ then
    Send AGV to suma A;
if $S2Buffer \leq 2$ and $S2AGV < 1$ then
    Send AGV to suma B;
if $S4Buffer \leq 2$ and $S4AGV < 1$ then
    Send AGV to suma C;
Data: AGV delivered parts to station 09001
Result: Decision at D2
if $S2Buffer \leq 2$ and $S2AGV < 1$ then
    Send AGV to suma B;
if $S4Buffer \leq 2$ and $S4AGV < 1$ then
    Send AGV to suma C;
else
    Send AGV to holding area;
Data: AGV delivered parts to station 09002
Result: Decision at D3
if $S1Buffer = 0$ and $S1AGV < 1$ then
    Send AGV to suma A;
if $S4Buffer \leq 2$ and $S4AGV < 1$ then
    Send AGV to suma C;
else
    Send AGV to holding area;
Data: AGV delivered parts to station 09004
Result: Decision at D4
if $S1Buffer = 0$ and $S1AGV < 1$ then
    Send AGV to suma A;
if $S2Buffer \leq 2$ and $S2AGV < 1$ then
    Send AGV to suma B;
else
    Send AGV to holding area;
```

Algorithm 5: MFCFS dispatch rule for tandem guide path, loop 2.

```
Data: Stations request delivery of parts with AGVs in holding area.
Result: Decision at D1.
if $S2Buffer \leq 2$ and $S2AGV < 1$ then
    Send AGV to suma B;
if $S4Buffer \leq 2$ and $S4AGV < 1$ then
    Send AGV to suma C;
Data: AGV delivered parts to station 09001
Result: Decision at D2
if $S4Buffer \leq 2$ and $S4AGV < 1$ then
    Send AGV to suma C;
else
    Send AGV to holding area;
Data: AGV delivered parts to station 09002
Result: Decision at D3
if $S2Buffer \leq 2$ and $S2AGV < 1$ then
    Send AGV to suma B;
else
    Send AGV to holding area;
```

Chapter 4

Data Analysis

4.1 Assembly line and operations data

4.1.1 Work package data

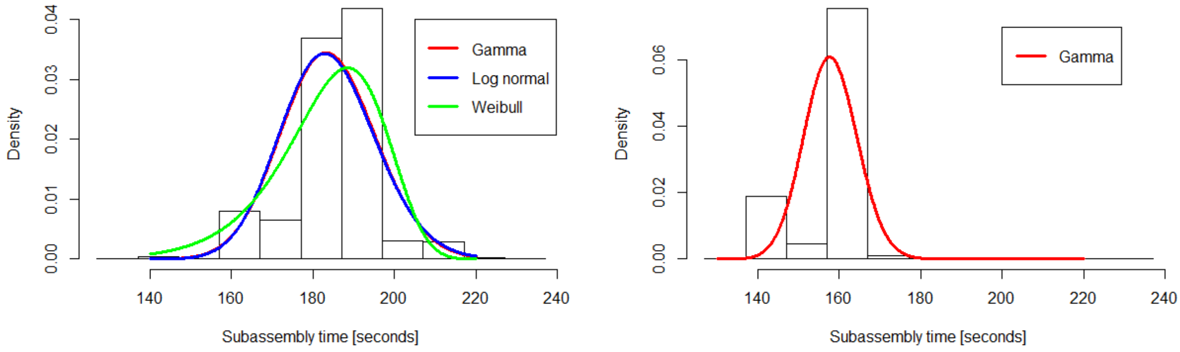
A work package is any function that an associate performs on the line. The total assembly operations required to completely assembly the front and rear end bumpers are divided between the the five stations. Each of the five work packages consist of a sequence of tasks to be completed before the subassembly can be sent to the next station. As associates fit components to each subassembly, the options of the components to be fitted varies according to the demand of the customer. An example of this would be where a customer added a sport package to his BMW 3-series sedan. Some of the air ducts in the front bumper would look different than the standard stock air duct. The associate would then have to fit the special air duct for that option on the front bumper. There are various options which customers can choose from therefore, impacting the total time an operator spends on an assembly. Data extracted from BMW's data system verified how the assembly time varies according to the options available for an assembly at each station. Figure 4.1 shows the histogram plots of the distribution of assembly times at stations 09001, 09002, 09004 and 09005. The distribution of assembly time at station 09006 was given by the data system as 180 seconds for all subassemblies completed at the station. A summary of the the descriptive statistics for the work package data at each station is given in Table 4.1.

Table 4.1: Summary statistics for work package data in seconds

Work package	Minimum	Maximum	Mean	Standard deviation
Station 09001	128.34	236.46	183.96	11.48
Station 09002	146.16	168.48	159.91	6.45
Station 09004	138.12	209.1	151.42	1.33
Station 09005	136.44	137.88	136.45	0.096

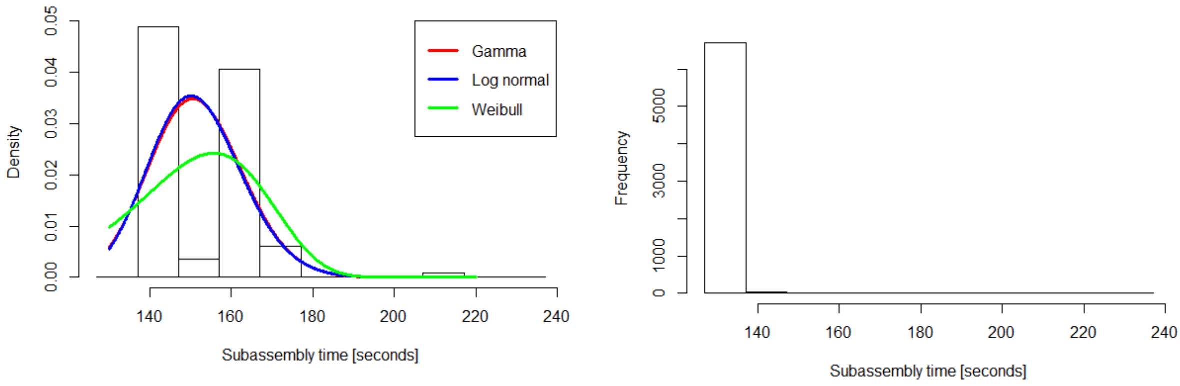
The probability distributions of the work package data were firstly obtained by using a skewness-kurtosis plot which served as an indication of possible probability distributions that best fit the distribution of the work package data. Secondly, the probability distributions were verified using histograms. The goodness of fit for possible probability distributions for station 09001, 09002 and 09004 were tested as indicated in Figure **??**. Station 09005 did not have a possible probability distribution as it only consisted of two values. The skewness-kurtosis plot for station 09005 indicated no distribution that can be approximated to fit the data. Therefore, no distribution was fitted to the histogram.

For each work package, the probability distributions are inserted as input to the simulation model to determine the accuracy of the probability functions. From the initial observation is



(a) Station 09001 assembly time distribution and fitted functions.

(b) Station 09002 assembly time distribution and fitted function.



(c) Station 09004 assembly time distribution and fitted functions.

(d) Station 09005 assembly time distribution.

Figure 4.1: Histogram plots for the distribution of assembly times for stations 09001, 09002, 09004 and 09005.

was found that the distribution of assembly times did not represent that of the observed data. This meant that the initial probability distributions is not as accurate fit to the data and custom distributions for all five work packages were used in Anylogic as input for the assembly times.

4.1.2 Suma picking process data

At BMW the picking times or the total time spent by an associate to pick one part is determined by a supermarket tool. This tool evaluates the total time an associate spends walking in the suma, picking parts, handling the containers which contains all the required parts and additional time per shift to incorporate variances in picking times. Together these four factors add up to give the picking time per suma. The results obtained from the analysis tool for suma A, B C and D are given in Table 4.2. These picking times are used for planning of processes at BMW and as such the picking times obtained from the supermarket analysis tool is used as input for the picking times in the simulation models. To verify the results of the analysis tool, time studies were conducted on the picking times of the sumas. As summary of the observed values and analysis tool value is given in Table 4.3. There are differences in the results form the time studies and the results from the analysis tool. This is because a small amount of samples were gathered from the time studies. Therefore as input in the simulation model the distribution of picking times were taken as uniformly distributed. For each suma, the distribution were varied between the maximum and minimum values to incorporate variability in the picking processes.

Table 4.2: Total picking times for sumas in minutes

Suma	Walking to suma	Suma picking	Container handling	Additional time	Total time
A	0.697	7.02	0.12	0.5	8.28
B	0.655	1.68	0.1	0.75	3.14
C	0.617	2.160	0.1	0.25	3.08
D	0.286	1.620	0.251	0.750	2.78

Table 4.3: Summary for suma picking times in minutes

Suma	Average observed time	Analysis tool time	Minimum	Maximum
A	7.055	8.25	6.2	8.25
B	2.53	3.14	1.58	3.25
C	2.56	3.08	1.56	3.2
D	3.86	2.78	2.78	5.27

4.2 Model validation

The main output from Line 09 is the total amount of front and rear end bumpers that are assembled and sent to Line 52. The simulation model is built on the assumption that this line runs continuously for the whole duration of a shift of 435 minutes at the speed of the takt time. The takt time is the speed at which the plant must produce a vehicle to satisfy the demand of the customer. The takt time is determined by the following equation:

$$\text{Takt time} = \frac{\text{Available production time}}{\text{Total demand}}$$

The high level demand of the plant is 142 vehicles per shift, and the total available production time per shift equals 435 minutes. Therefore dividing the total available production time with the demand yields a takt time of 3 minutes, or 180 seconds. This means that at each station, the associates have 180 seconds to complete the assembly for that specific station. Line 09 however does not run at a takt of 180 seconds as there is time lost when jigs move the subassemblies between stations. The transfer time between stations is on average 12 seconds, and as the subassemblies move from one station to the next the transfer time is added to the takt of the line. This means that the actual speed of Line 09 is the takt time plus the transfer time of the subassemblies. The actual takt time of Line 09 is therefore 192 seconds or 3,2 minutes. At a takt time of 192 seconds, the maximum output of the line can be calculated as:

$$\text{Maximum output} = \frac{\text{Available production time [minutes]}}{\text{Takt time [minutes]}}$$

Dividing the available production time with the takt time, yields a maximum output of 136 completed front and rear end bumpers that this line is capable of producing per shift, when producing at a continuous rate. A histogram depicting the distribution of outputs obtained from the base model and the maximum output of 136 front and rear end bumpers can be seen in Figure 4.2.

Figure 4.2 indicates that the total output of the model is very close to the maximum output if the line. The reason that the base simulation model is slightly less, is because the average assembly time at station 09001 is greater than the available assembly for each station of 180 seconds as can be seen in Figure 4.1a and Table 4.1. Because station 09001 assembles at a slower rate than the other stations the actual output will be slightly less than the theoretical output of

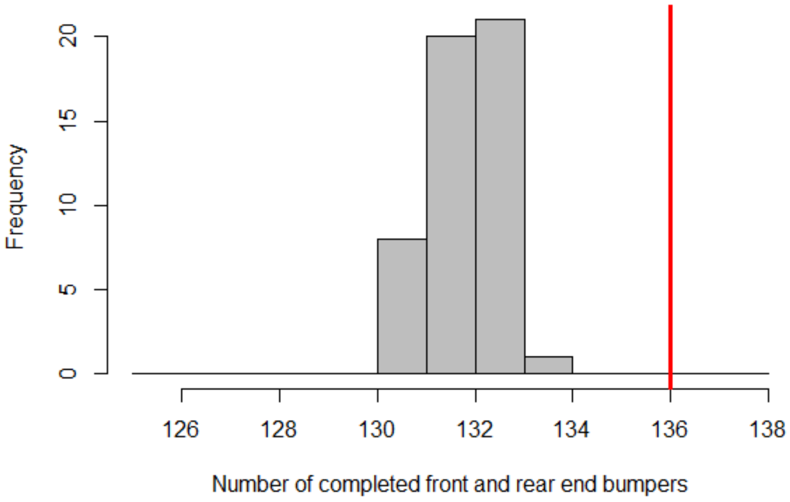


Figure 4.2: Distribution of number of front and rear end bumpers of base model.

136 front and rear end bumpers. We can therefore say that the simulation is producing results quite accurately in accordance to the actual line.

4.3 Simulation models output

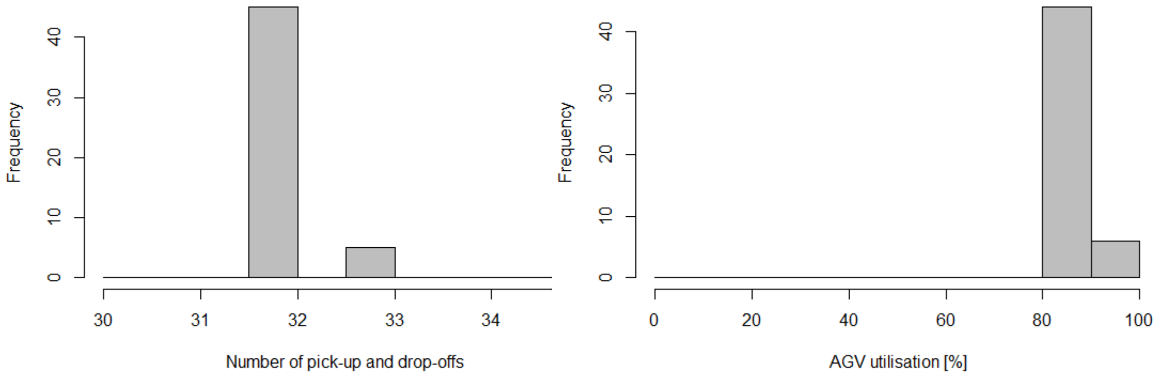
The output of the simulation models are evaluated using the key performance indicators as discussed in preceding sections. The results of the base model and scenario models are presented in this section. The base case and scenario models, with each scenario model being varied for a total of four Automated Guided Vehicles (AGVs), were run for 50 times each. These experiments were carried out using a random seed for each simulation run.

4.3.1 Base model

The distribution of the amount of completed front and rear end bumpers completed can be seen in Figure 4.2. This is used as a high level performance indicator, in addition to the three indicators which focussed on the AGV process. The first measure is the AGV throughput. This measures the total amount of pick-up and drop-offs the AGVs makes in the system and is depicted in Figure 4.3a in number of units. The second measure is the AGV utilisation, this measures the percentage of the total time the AGV was in use during the shift and is depicted in Figure 4.3b. The final measure is the size of buffer queues for stations 09001, 09002 and 09004. This measures the total size of the buffer queues as it varies throughout the simulation. The distributions of the buffer queues for stations 09001, 09002 and 09004 can be seen in Figure 4.4 . A summary of all performance measures is given in Table 4.4.

Table 4.4: Comparison of base case performance measures

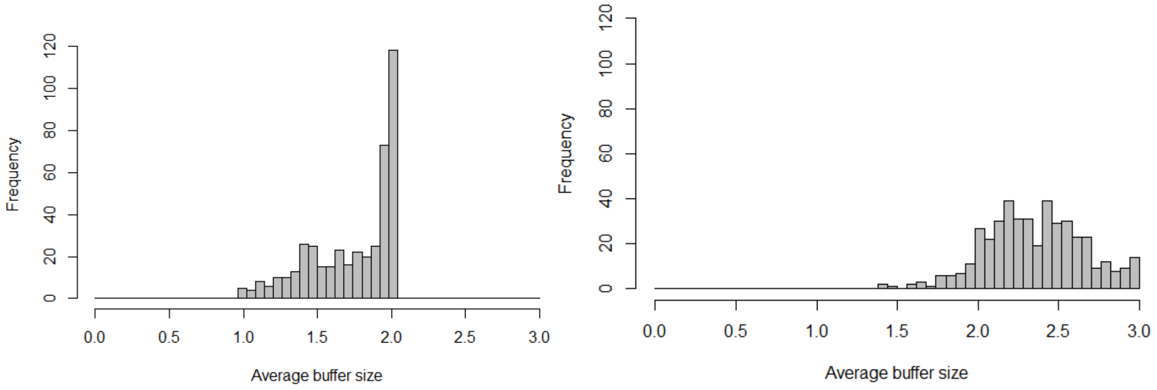
Total bumpers	Throughput	Utilisation	S09001 Buffer	S09002 Buffer	S09004 Buffer
132.3	32.1	89.55	1.74	2.35	2.55



(a) Throughput of AGV system.

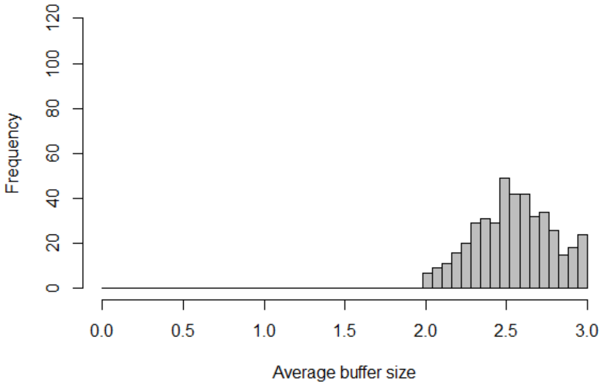
(b) Utilisation of AGV.

Figure 4.3: Distribution of AGV system throughput and utilisation.



(a) Station 09001 buffer size.

(b) Station 09002 buffer size.



(c) Station 09004 buffer size.

Figure 4.4: Distributions of buffer sizes for stations 09001, 09002 and 09004.

4.3.2 Scenario model 1

This scenario focussed on using the Maximum Remaining Outgoing Queue Size (MROQS) dispatch rule in a conventional guide path loop. The simulations were for run up to a maximum of four AGVs in the loop. The total output of front and rear end bumpers is given in Figure 4.5. From the figure it is evident that for this scenario the total throughput of the line was sensitive to a change in the number of AGVs. There is a large shift in the distribution from one AGV to two AGVs. As the amount of AGVs increased, the output stabilised close to the output that is desired when producing at a continuous rate. One thing to note in Figure 4.5 is that the output for three AGVs are not visible, as it corresponds exactly to that of four AGVs. On this figure it lies at the back of the yellow distribution.

Similarly, the throughput of the AGV system, as seen in Figure 4.6a, followed the same pattern as the throughput of the total system as one would expect. The output distribution of for three AGVs once again is almost identical to that of four AGVs and therefore, lies at the back of the yellow distribution.

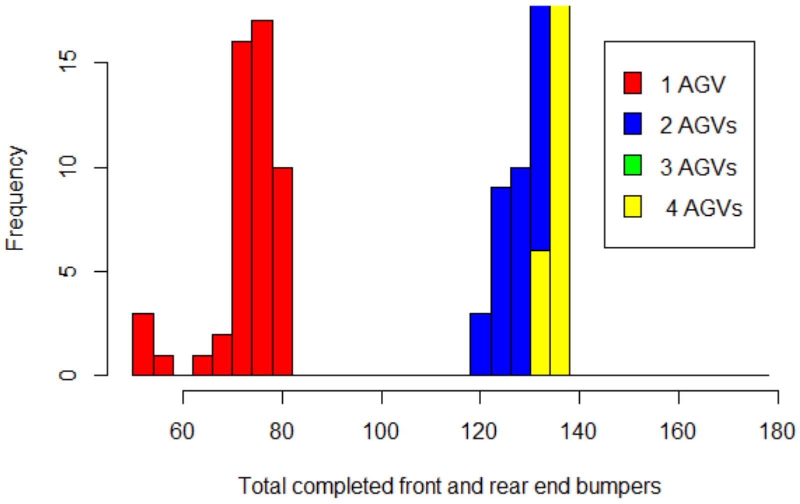
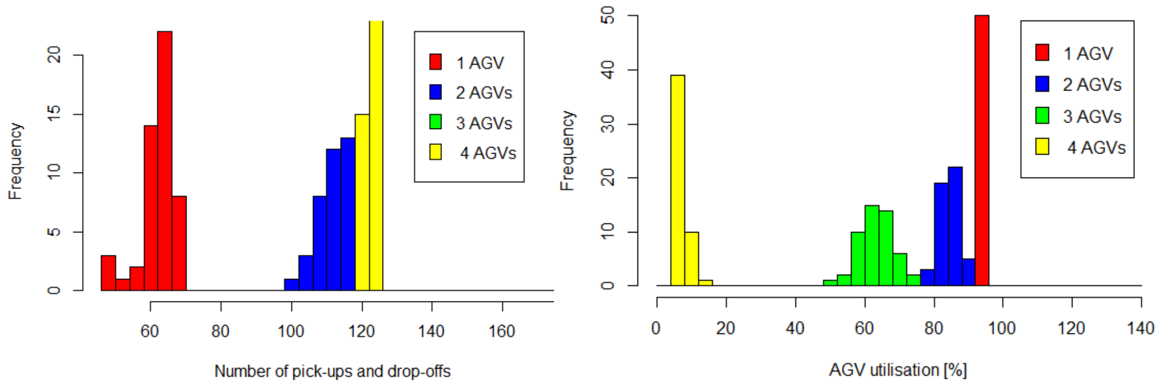


Figure 4.5: Distribution of number of front and rear end bumpers of scenario model 1.

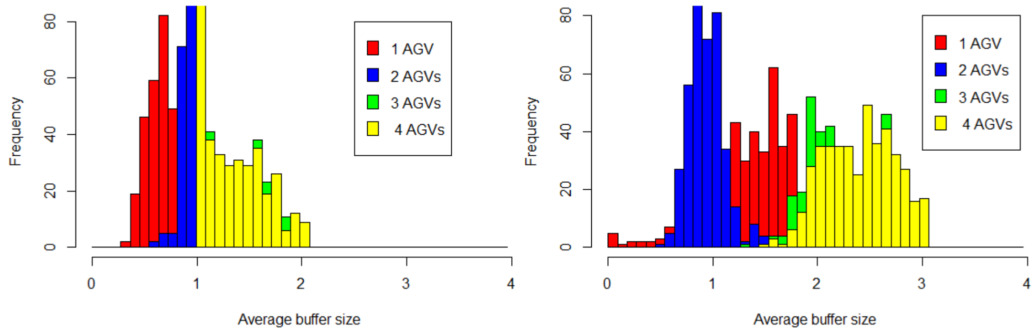
The utilisation of the AGVs decreased as the amount of AGV increased in the system as depicted in Figure 4.6b. It is evident on the figure that the utilisation decreased gradually, with a sudden decrease when four AGVs were used. A reason for this is that there are three stations that are connected in the system. When four AGVs are used, there are one more than the amount of stations in the system. This means that there are most of the time, one AGV waiting in the holding area. Over the total simulation run, the idle AGV decreases the utilisation.

The station buffers for station 09001, 0902 and 09004 are given in Firgrures 4.7a, 4.7b and 4.7c respectively. These results indicate how the average buffer sizes increased, as the number of AGVs increased. The reason for the increase in the sizes of station buffer is because the more AGVs there are in the system, the more frequently can buffers be refilled without stations having to wait for long periods. Table 4.5 gives a comparison of the results obtained from the model as the number of AGVs increased.

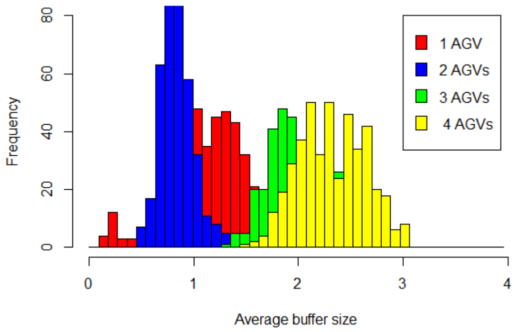


(a) Throughput of scenario 1 AGV system. (b) Utilisation of AGVs for scenario 1.

Figure 4.6: Distribution of AGV system throughput and utilisation for scenario 1.



(a) Station 09001 buffer size for scenario 1. (b) Station 09002 buffer size for scenario 1.



(c) Station 09004 buffer size for scenario 1.

Figure 4.7: Distributions for scenario 1 buffer sizes for stations 09001, 09002 and 09004.

4.3.3 Scenario model 2

This scenario focussed on incorporating the Modified First Come First Serve (MFCFS) dispatch rule in a conventional layout. The number of AGVs in the simulation was increased to a maximum of four AGVs in the loop. The total completed from and rear end bumpers are depicted in Figure 4.8. As seen in the figure, there is a large increase in the number of completed bumpers when the number of AGVs were increased from one to two. Thereafter, as the number

Table 4.5: Comparison of scenario 1 performance measures

Number of AGVs	Total bumpers	AGV Through-put	Utilisation [%]	S09001 Buffer	S09002 Buffer	S09004 Buffer
Base	132.3	32.1	89.55	1.74	2.35	2.55
1	67.46	57.6	93.75	0.77	1.39	1.19
2	129.8	113.8	84.12	1.01	1.00	0.911
3	135.36	122.56	63.16	1.28	2.32	2.09
4	135.3	122.64	7.44	1.30	2.41	2.32

of AGVs increased the total output gradually increased with the output converging very closely to the aimed output of 136 bumpers. Important to note is the similarity in output when three and four AGVs were used. The total output of the AGVs in terms of pick-up and dro-offs followed the same trend as Figure 4.8. The output of the AGV system can be seen in Figure 4.6a. Both of these figures show how sensitive scenario model was for a change in one AGV to two AGVs.

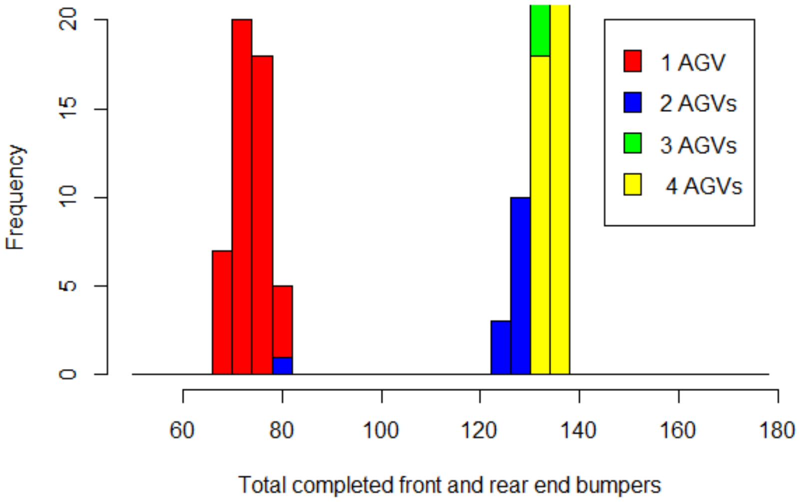
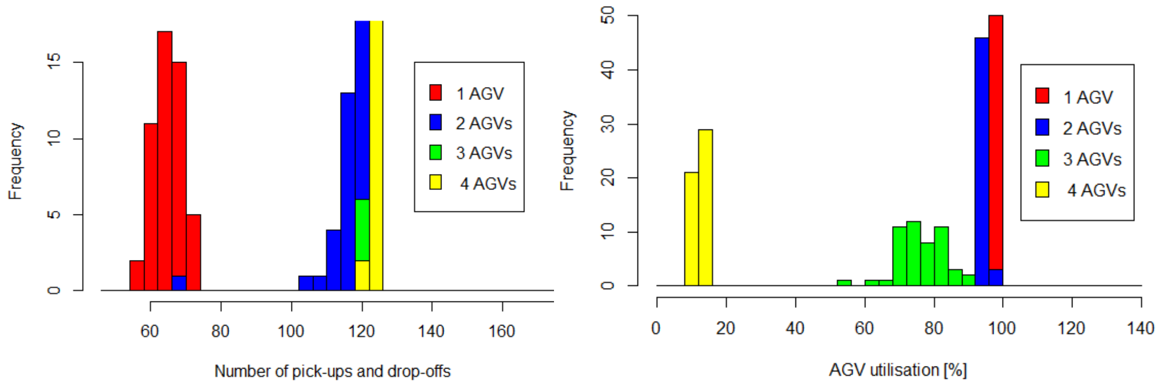


Figure 4.8: Distribution of number of front and rear end bumpers of scenario model 2.

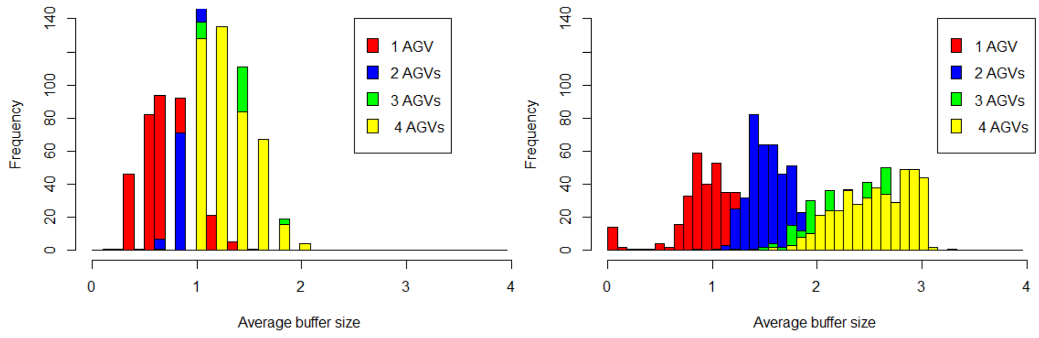
In Figure 4.9b it is evident that as the number of AGVs increased in the model, the utilisation of AGVs decreased. The biggest decrease is seen between three and four AGVs in the system. The reason being that there are three stations that are connected in this system. The fourth AGV will therefore be idle in the central holding area, as the other stations are being served by the remaining three AGVs. This decreases the total AGV utilisation over the whole simulation run.

When comparing the changes in the size of buffer queues, it is found that as the number of AGVs increased, the average buffer sizes increased. This is because there are more AGVs in the system to ensure that buffers are continually stocked. This can be seen in the distribution of average buffer queues for stations 09001, 09002 and 09004 in Figures 4.10a, 4.10b and 4.10c respectively. A summary comparison for all key performance factors are given in Table 4.6.

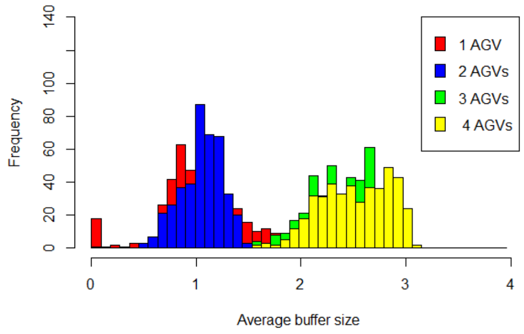


(a) Throughput of scenario 2 AGV system. (b) Utilisation of AGVs for scenario 2.

Figure 4.9: Distribution of AGV system throughput and utilisation for scenario 2.



(a) Station 09001 buffer size for scenario 2. (b) Station 09002 buffer size for scenario 2.



(c) Station 09004 buffer size for scenario 2.

Figure 4.10: Distributions for scenario 2 buffer sizes for stations 09001, 09002 and 09004.

4.3.4 Scenario model 3

In Scenario 3, a tandem guide path system was used together with the MROQS dispatch rule. The number of AGVs in loop one was kept constant with only one AGV. This is because there is only one station to service. From the base case model it was seen that the one AGV in the single loop is more than sufficient to handle the work load without putting pressure on the line. The first loop in this scenario corresponds to the single loop in the base model, therefore, the

Table 4.6: Comparison of scenario 2 performance measures

Number of AGVs	Total bumpers	AGV Through-put	Utilisation [%]	S09001 Buffer	S09002 Buffer	S09004 Buffer
Base	132.3	32.1	89.55	1.74	2.35	2.55
1	74.04	65.15	99.98	0.74	1.103	1.03
2	130.66	117.52	94.74	1.03	1.59	1.10
3	134.56	123.54	76.04	1.25	2.41	2.41
4	134.66	123.62	12.53	1.27	2.56	2.52

decision was made to use a single AGV in the scenario. The number of AGVs in loop two were increased to a maximum of three. This is because there are two stations to be serviced in this loop and the effect of the increase in AGVs were evaluated. In the analysis that follows, the effect of changing the number of AGVs in loop two are investigated.

The total output in terms of front and rear end bumpers are given in Figure 4.11. This depicts a shift in the distribution as the number of AGVs were increased in loop two from one AGV to, two AGVs. The legend in the figure indicates the number of AGVs used in loop 2. A key finding shown in the figure is that the shift in output from one AGV to two AGVs was much larger than the shift in output from two AGVs to three AGVs. Similarly, the output of the AGV system as depicted in Figure 4.12a, showed the same trend as the total system output. This is because the two performance indicators are closely linked. As the output of the whole system increases, the output of the AGV system also increases.

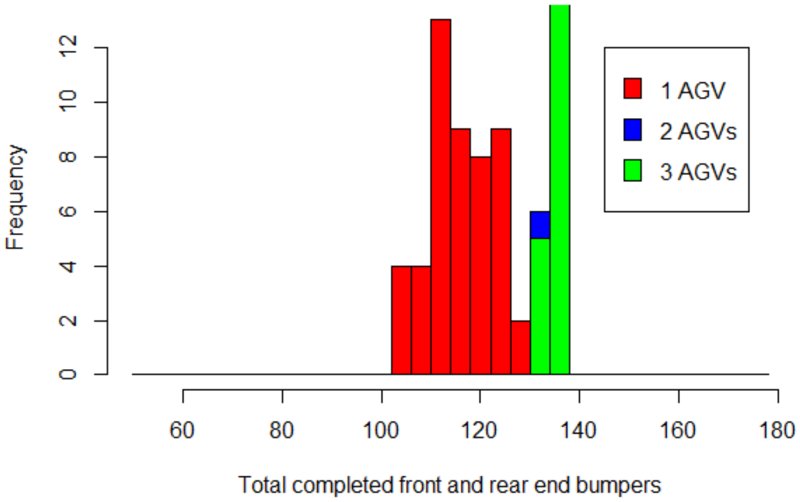
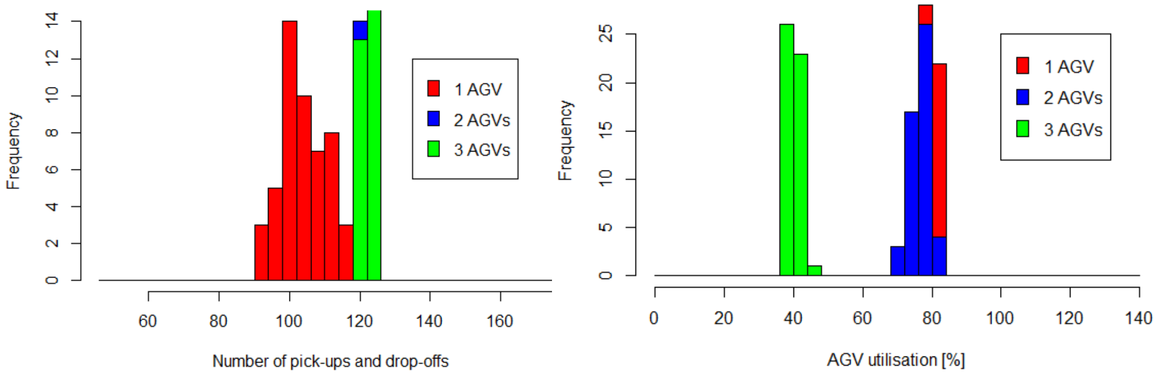


Figure 4.11: Distribution of number of front and rear end bumpers of scenario model 3.

The utilisation of the AGVs in the system is given in Figure 4.12b. As the number of AGVs increased, the utilisation decreased. As the number of AGVs increase, the the workload is distributed, and subsequently the utilisation decreases. The model was quite sensitive in the change from two AGVs to three AGVs. Figure 4.12b shows how the utilisation decreases rapidly when three AGVs were used. The reason for this is for this, is because the are two stations in loop two. In this specific process when there are three AGVs in the loop, the third is idle in the central holding area. This then decreases to overall utilisation of the vehicles.

The outputs for the buffer sizes for stations 09002, 09003 and 09004 are depicted in Figures 4.13a, 4.13b and 4.13c respectively. It is noted that for all three buffer queues, the distribution of outputs flattened out when the AGVs in the model was increased form one to, two. The outputs at station 09001 was not that sensitive to the increase in the number of AGVs in the system. This is because only one AGV is used in the loop servicing station 09001. The changes in the amount of vehicles in loop two did, however, affect the output. As seen, the dispersion of the distribution became larger as the amount of AGVs increased. The distributions for the outputs when two and three AGVs were used are closely linked. The buffer sizes at stations 09002 and 09004 were, however, more sensitive to the changes in the number of AGVs. This is because station 09002 and 09004 were directly affected. As there were more AGVs available to service the stations, the buffers could be maintained more regularly. In general, the size of the buffer queues increased as the number of AGVs increased. There are more available AGVs to service the stations and therefore their buffers are filled more frequently.



(a) Throughput of scenario 3 AGV system.

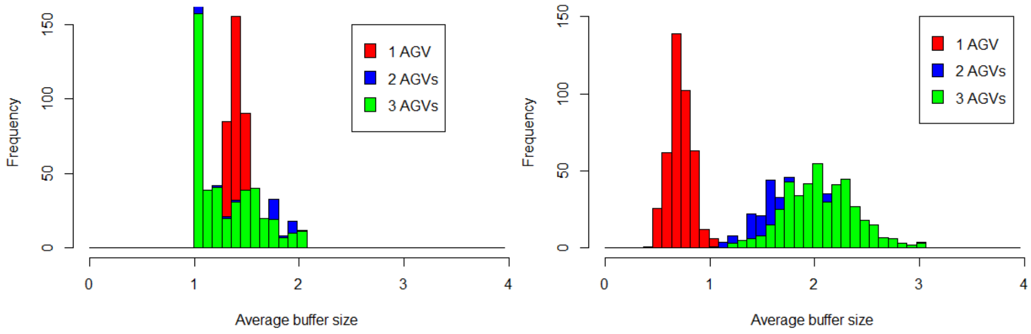
(b) Utilisation of AGVs for scenario 3.

Figure 4.12: Distribution of AGV system throughput and utilisation for scenario 3.

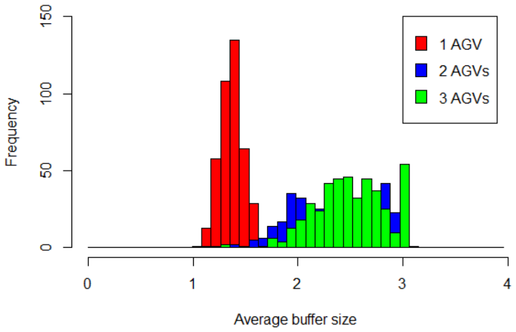
A comparison of all the performance measures for scenario 3 are given in Table 4.7. This table shows the shifts in the averages as the number of AGV are changed in the model. In the first column the number of AGVs in loop one and loop two are given in the brackets. The first element in the brackets signifies the amount of AGVs in loop one and the second element the amount of AGVs in the second loop.

Table 4.7: Comparison of scenario 3 performance measures

Number of AGVs	Total bumpers	AGV Through-put	Utilisation [%]	S09001 Buffer	S09002 Buffer	S09004 Buffer
Base	132.3	32.1	89.55	1.74	2.35	2.55
(1,1)	116.6	104.3	79.68	1.40	0.77	1.42
(1,2)	135.34	122.64	76.59	1.31	1.95	2.40
(1,3)	135.44	122.72	39.78	1.30	2.06	2.51



(a) Station 09001 buffer size for scenario 3. (b) Station 09002 buffer size for scenario 3.



(c) Station 09004 buffer size for scenario 3.

Figure 4.13: Distributions for scenario 3 buffer sizes for stations 09001, 09002 and 09004.

4.3.5 Scenario model 4

The last scenario also focussed on the tandem guide path system, but the vehicles were dispatched to stations using the MFCFS rules. Similarly in Scenario 3, the number of AGVs for loop one was held constant at one while loop two's number of AGVs were increased to a maximum of three. The total output of the system in terms of front and rear end bumpers are depicted in Figure 4.14. The output shows how the total bumpers increased as the number of AGVs increased in the system. The legend in the figure indicates the number of AGVs used in loop 2. When there are less vehicles in the system, some station might be delayed if they await the delivery of new parts. And it might be that the AGV is busy at another station. This delay has a knock-on effect on the proceeding stations. If this delay occurs frequently in the simulation, it will definitely affect the total output of the line. As seen in Figure 4.14 the shift in output did not vary as much when three instead of two AGVs were used. The largest shift in output occurred between one and two AGVs. The larger part of the output obtained using two AGV lies at the back of the green distribution. This is because the output obtained with two and three AGVs were much the same. Only from two AGVs upwards, the model obtained outputs close to the output of the line according to the takt time. Similarly, the same trend was followed in the AGV system output as depicted in Figure 4.15a.

The utilisation of the AGVs in the system are given in Figure 4.15b. The model was very sensitive to changing from two, to three AGVs. Once again the reason being that in loop two, there are two stations in the loop. If three AGVs are used, the total utilisation decreases as a result on one AGV being idle in the holding area. As the number of AGVs in the system increased from one to, two, there was a slight decrease in utilisation.

When looking at the buffer sizes of the stations in Figures 4.16c, 4.16b and 4.16c it can

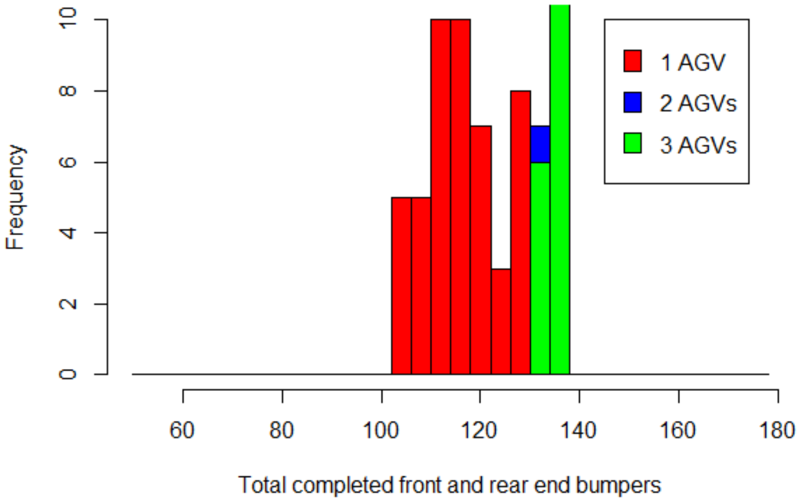
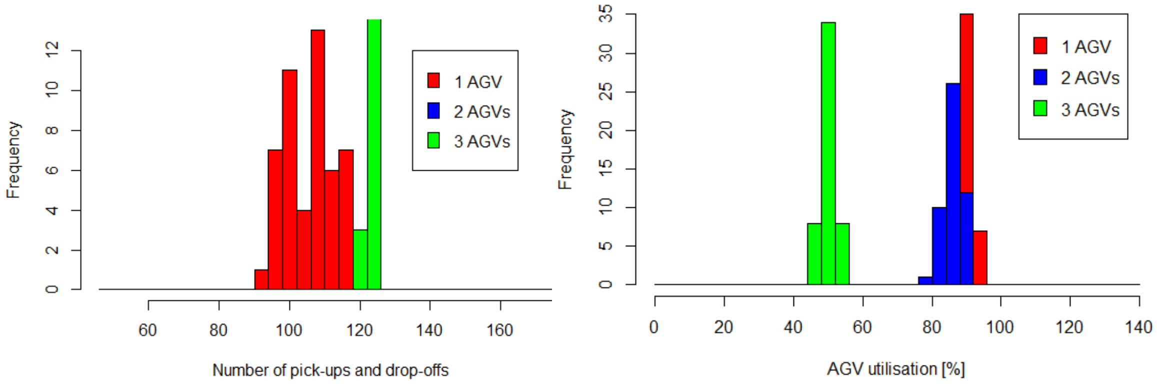


Figure 4.14: Distribution of number of front and rear end bumpers of scenario model 4.

be seen that as the number of AGVs increased the average buffer sizes also decreased. The buffer size at station 09001 was not that sensitive to an increase in the number of AGVs as there is only one AGV used in the loop. The effect of the changes in loop two did, however show in the results as the dispersion of the output flattened. This is because of the knock-on effect that delays or changes at stations have on the line. The buffer sizes at stations 09002 and 009004 proved to be more sensitive to the changes in the number of AGVs as these stations were influenced directly. The result thereof is that the dispersion of the output also flattened out, with the distribution using two and three AGVs being much the same.

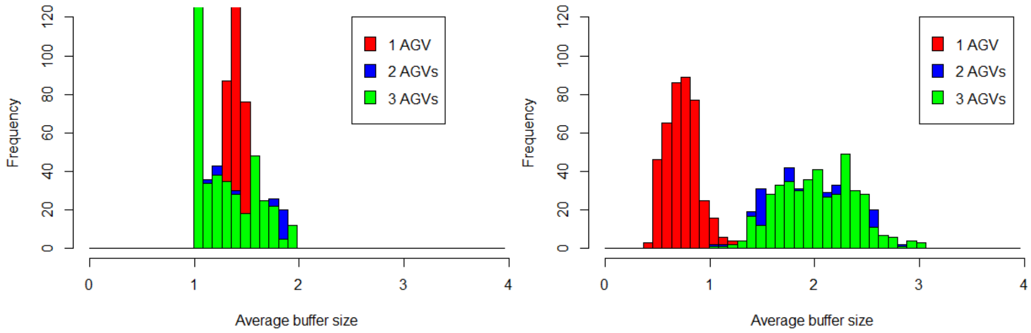
A comparison of the performance measures for scenario 4 are given in Table 4.8. The table depicts how the performance measures were influenced on average as the number of AGVs increased.



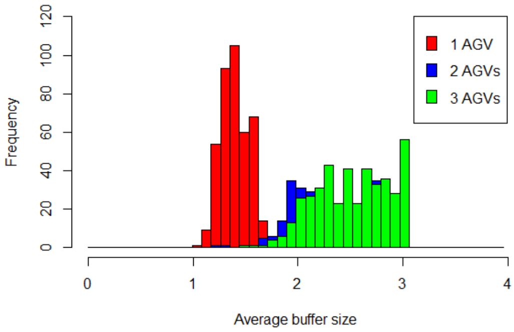
(a) Throughput of scenario 4 AGV system.

(b) Utilisation of AGVs for scenario 4.

Figure 4.15: Distribution of AGV system throughput and utilisation for scenario 4.



(a) Station 09001 buffer size for scenario 4. (b) Station 09002 buffer size for scenario 4.



(c) Station 09004 buffer size for scenario 4.

Figure 4.16: Distributions for scenario 4 buffer sizes for stations 09001, 09002 and 09004.

Table 4.8: Comparison of scenario 4 performance measures

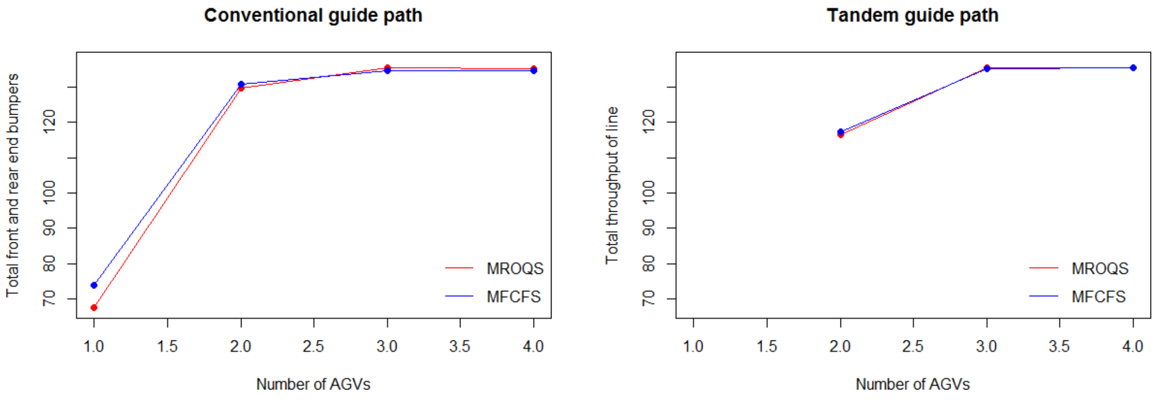
Number of AGVs	Total bumpers	AGV Throughput	Utilisation [%]	S09001 Buffer	S09002 Buffer	S09004 Buffer
Base	132.3	32.1	89.55	1.74	2.35	2.55
(1,1)	117.44	106.24	89.83	1.37	0.78	1.46
(1,2)	135.06	123.6	85.37	1.29	1.98	2.45
(1,3)	135.48	123.72	50.1	1.28	2.03	2.52

4.4 Output comparison

In the preceding section the outputs of each of the four scenario models were presented with reference to the key performance indicators used to evaluate the performance of the models. To further conduct the analysis of the outputs, it is necessary to do a broader and more descriptive comparison. It was noted in the previous section that the throughput of the AGV system was closely linked to the total output of the whole system in terms of completed front and rear end bumpers. Because these two indicators are closely linked and follow the same trend, the comparison presented in this section will only incorporate the total output of the system. The reason is the total system throughput is at a higher level and it is critical to know how the system throughput changes when comparing alternatives. From the analysis in the previous section we know, if the total system throughput increases, the AGV system throughput will also increase.

In each of the figures below, the performance of the conventional guide path is compared to the performance of the tandem guide path. In each figure the number of AGVs used in the system are given on the x-axis, and the applicable performance measure on the y-axis. Important to note that for the tandem guide path, the number of AGVs were only increased in the second loop. The AGVs were incremented to a maximum of three as described in the previous section. Also given are the dispatch rules used in each of those guide path systems.

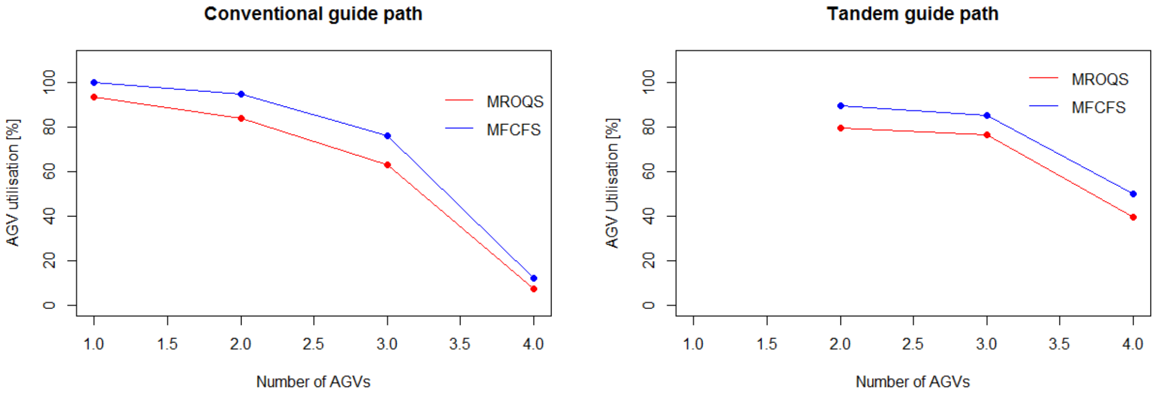
Figure 4.17 compares the difference in the total system output between the conventional and tandem guide paths. The blue line refers to the output obtained when using the MROQS dispatch rule and the red line refers to the output obtained from using the MFCFS dispatch rule. In both these guide paths the two dispatch rules had similar and closely linked performance.



(a) Conventional guide path total throughput. (b) Tandem guide path total throughput.

Figure 4.17: Comparison of total completed front and rear end bumpers for different guide paths and dispatch rules.

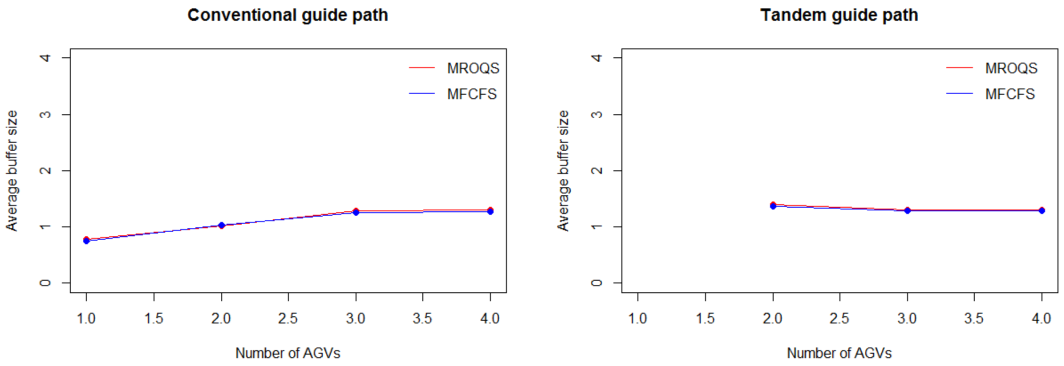
In Figure 4.18, the utilisation of the vehicles are compared for the different guide path systems. From the comparison is can be see that the type of dispatch rule used in the system had a definite impact on the average utilisation of the AGVs. On average, the MFCFS rule obtained a better utilisation in both guide paths.



(a) Conventional guide path utilisation. (b) Tandem guide path utilisation.

Figure 4.18: Comparison of utilisation different guide paths and different dispatch rules.

The average buffer size for station 09001 for both guide paths are given in Figure 4.19. For the conventional guide path the MROQS rule proved to obtain better performance as the number of AGVs increased, while the MFCFS rule remained relatively the same throughout. For the tandem guide path system, both dispatch rules remained relatively constant and had much the same performance. This is because in the simulation, the number of AGVs servicing station 09001 remained constant at one. The minor shifts and changes are accounted to the indirect influence that the changes in loop two had.

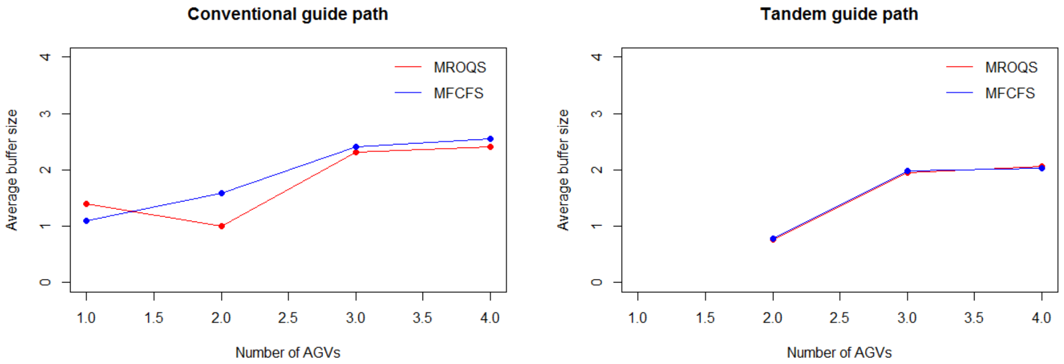


(a) Conventional guide path station 09001 buffer size.

(b) Tandem guide path station 09001 buffer size.

Figure 4.19: Comparison of station 09001 buffer size for different guide paths and dispatch rules.

Figures 4.20 and 4.21 give the average buffer sizes for stations 09002 and 09004 respectively. These compare the outputs for the conventional and tandem guide paths under the different dispatch rules. For the conventional guide path, in both stations 09002 and 09004, the MFCFS dispatch rule obtained better performance. Both stations had a similar trend as shown in Figure 4.20a and Figure 4.21a. For the tandem guide path, buffers sizes at the two stations once again followed the same upward trend. Also, for the tandem guide path it is seen that the buffer sizes for station 09002 and 09004 increased by much the same ratio under both dispatch rules.

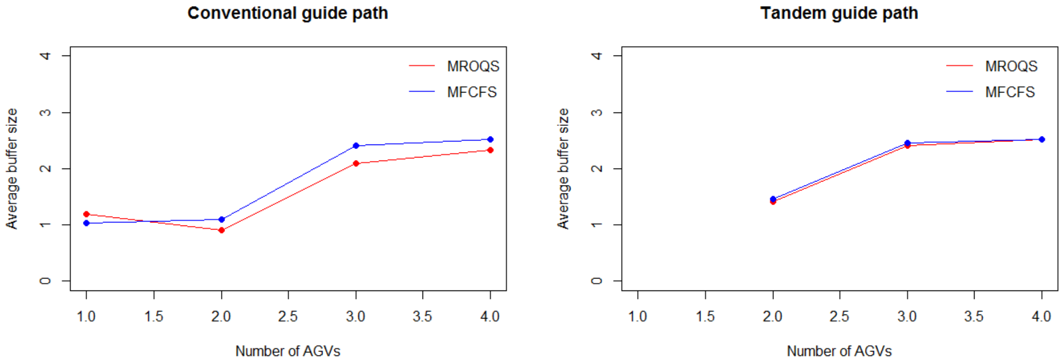


(a) Conventional guide path station 09002 buffer size.

(b) Tandem guide path station 09002 buffer size.

Figure 4.20: Comparison of station 09002 buffer size for different guide paths and dispatch rules.

After an observation of the comparative graphs for each performance metric, two conclusions are made. Firstly, the results of both guide path systems were similar with small differences for the different performance metrics. Secondly, the conventional guide path was more sensitive to the different dispatch rules. In most of the comparative graphs, the conventional guide path showed the bigger changes in performance under the different dispatch rules. The tandem guide path, on the other hand, was less sensitive to changes in the dispatch rule. This is advantageous,



(a) Conventional guide path station 09004 buffer size.

(b) Tandem guide path station 09004 buffer size.

Figure 4.21: Comparison of station 09004 buffer size for different guide paths.

because should there be a need to change the dispatch rule, there is confidence in knowing that the outputs would not differ that much.

This section discussed the data obtained from the base model and scenario models. These datasets were compared to one another to determine the differences in performance. In the next section solutions are discussed and the most efficient system is chosen.

Chapter 5

Solution Discussion

5.1 System solution

The purpose of the system analysis is to determine which configuration of system characteristics yields the best output for the system. In the analysis of the system under various configurations, these configurations need to be narrowed down to the most efficient configuration. To do this it is necessary to define a set of criteria that each configuration would have to achieve. The main performance metrics used in Chapter 3 and Chapter 4, were (1) The total system throughput, (2) Automated Guided Vehicle (AGV) system throughput, (3) AGV utilisation and (4) buffer sizes of stations. These metrics are used as criteria in evaluating the outputs from the scenario models. There were in total 14 configurations tested, each for a specific guide path, dispatch rule and number of AGVs in the system. In Table 5.1 the minimum acceptable criteria for each performance metric is given which are used to determine the best configuration.

Table 5.1: Minimum performance crietria

Perfomance metric	Acceptable criteria
Total system throughput [Number of units]	130 - 136
AGV utilisation [%]	> 80 %
Station 09001 buffer size [Number of units]	≥ 1
Station 09002 buffer size [Number of units]	≥ 2
Station 09004 buffer size [Number of units]	≥ 2

Based on the calculation of the takt time and the transfer time between the stations, the output that Line 09 is capable of achieving 136 units. Between Line 09 and Line 52 there is a buffer of that varies between two to four front and rear bumper assemblies. Therefore, the proposed solution should as least be able to produce the required amount of bumpers. If it produces less than required it would have a knock-on effect on Line 52 and the rest of the plant. Therefore this criterion is one of the most important factors.

The utilisation is second to the total output, a very important criterion. Because AGVs require such a large capital investment, as an asset, it should be fully utilised in the process. Therefore the utilisation should be at least 80%.

Station 09001 makes use of two part trolleys, each containing four car kits each. Therefore, there should be at least one part trolley at the station at all times. If there are only one, it signals the delivery of another until the station is stocked with two trolleys. If there is one full trolley at the station with four car kits, and the associate assembles each kit at the takt time of 180 seconds, it would take 12 minutes for the associate to replenish the parts in the trolley and require more parts. From the models is was found that it takes on average nine minutes for the AGV to deliver a full trolley to the station. This means that before the associate finishes his trolley, a second full trolley will arrive in time to fill the buffer. Therefore the buffer should at least be greater or equal to one.

Station 09002 makes use of a kit trolley which is able to contain four car kits. The associate picks from one kit, while there is a buffer of three kits in the trolley. Therefore on average, there should be at least two kits in the buffer throughout the shift. If the associate assembles each kit at the rate of the takt time of 180 seconds, it would take nine minutes for him to replenish his buffer. In the scenario models the average time it takes for an AGV to refill the buffer is six minutes. This means his buffer is refilled while he is busy with his last kit. Therefore the buffer should be at least greater or equal to two.

The same conditions hold for station 09004. This station also uses a kit trolley which is able to contain four car kits. One car kit is in use when an associate conducts his assembly operation, whilst there are three kits in the buffer. To ensure that the station is sufficiently stocked, the buffer size should be on average greater or equal to two kits. It would take the associate nine minutes to replenish his buffer. The simulation model showed that after a signal is sent for more parts, it takes the AGV four minutes to refill the buffer. Therefore a buffer of two kits would be more than sufficient to ensure continuous production.

5.1.1 Chosen system

Using the performance criteria in Table 5.1, all of the configurations were analysed and evaluated. For a configuration to be successful, it had to comply to the criteria. Or, if the specific value of the configuration was very close to the criteria it was also considered. After analysing the conventional and tandem guide paths with the Maximum Remaining Outgoing Queue Size (MROQS) and Modified First Come First Serve (MFCFS) dispatch rules for various number of AGVs in the system, three final configurations proved to be possible solutions. The three solutions, each with their type of guide path, dispatch rule and number of AGVs are given in Table 5.2.

Table 5.2: Possible system solutions

	Guide path	Dispatch rule	Number of AGVs
Solution 1	Conventional	MFCFS	3
Solution 2	Tandem	MROQS	3
Solution 3	Tandem	MFCFS	3

The first solution is the conventional guide path, employing the MFCFS dispatch rule with three AGVs in the loop. The second solution is a tandem guide path, employing the MROQS dispatch rule with a total of three AGVs in the system. One AGV in the first loop, and two AGVs in the second loop. The third and final solution is also a tandem guide path, employing the MFCFS dispatch rule with three AGVs in the system. One AGV in the first loop and two acpAGV in the second loop. For each of these possible solutions, values for the mean and standard deviation for each performance metric is given in Table 5.3.

From Table 5.3 it can be seen that all of the possible solutions have a total system output that is very close to the takt time output of 136 units. When comparing the utilisation of the possible solutions, solutions 1 and 2 are below 80%. The reason why they were evaluated is because their total system output is very good, and they show positive results for the other performance metrics. In both cases, 76% utilisation is still very good. Solution 3 on the other hand, had a very high utilisation of 85%.

When comparing the buffer sizes at the stations, it is evident that for the buffer size at station 09001, all of the solutions have the ability to maintain the size of the buffer to be greater than one. For the buffer size at station 09002, solution had the highest mean buffer size of 2.41. Although solutions 2 and 3 were not exactly equal or more than two, they are very

Table 5.3: System solutions comparison

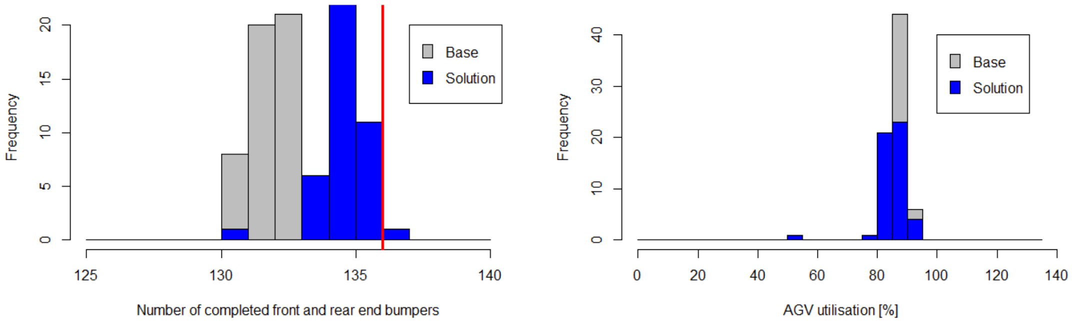
	Solution 1		Solution 2		Solution 3	
	μ	σ	μ	σ	μ	σ
Total throughput	134.5	0.812	135.34	0.717	135.1	0.867
Utilisation [%]	76.4	6.94	76.57	2.442	85.37	5.34
Station 09001 buffer	1,25	2.42	1.31	0.311	1.29	0.290
Station 09002 buffer	2.41	0.367	1.94	0.379	1.98	0.379
Station 09004 buffer	2.41	0.308	2.4	0.42	2.45	0.391

close with a small dispersion as seen with the standard deviations. The buffer size for station 09004 for all three solutions proved to be more than the minimum criteria of two car kits.

From Table 5.3, solution 3 has been chosen as the best system. The main reason being that this system is capable of producing front and rear end bumpers very close to the maximum output of the line. Therefore, the line would be able to easily produce for the demand of bumpers without shortages that could have a knock-on effect on preceding lines in the assembly process. Also, the utilisation of this system is also very high in comparison to the other models. Although the average buffer size for station 09002 is not greater than two, it is very close to two and still acceptable.

The output of the chosen solution was compared and validated to the output obtained from the base model using the performance metrics. Figure 5.1a depicts the total system output of the base model and the solution model. Also in the figure is the aimed output of 136 bumpers according to the takt time of this line. The aimed output is depicted with the red line. There is a shift in mean from 132 bumpers for the base case to 135 for the solution model. The distribution of the solution model also depicts that the model did obtain an output of 136 bumpers. The main reason for the solution model having a higher output is the new docking concept that is incorporated in the model. In the base case the associate at station 09001 had to leave his assembly station to detach the full trolley from the AGV, then attach the empty trolley. This in total amounted to lost time in the system. With station 09001 already having the longest assembly time, it added to the total time at the station.

The utilisation of AGVs in the solution model was slightly lower in comparison to the base model. This is depicted in Figure 5.1b. The mean utilisation of the base model is 89.55 % in comparison to the 85.37% utilisation of the solution model. Although the base model is higher, other advantages of the solution model outweighs the small decrease in utilisation.

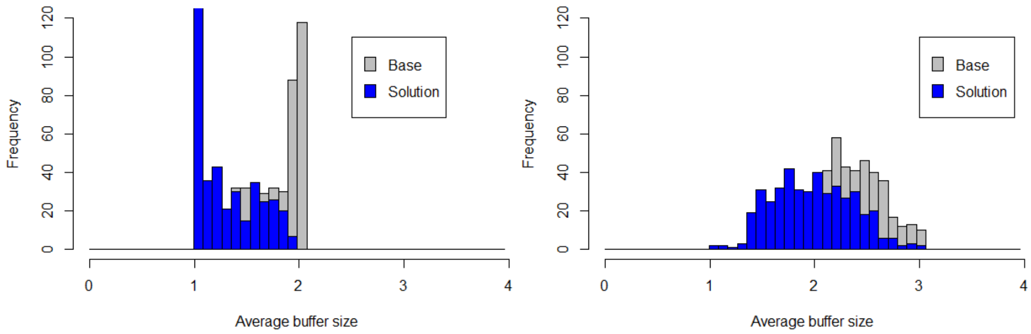


(a) Total line output.

(b) Utilisation of AGVs.

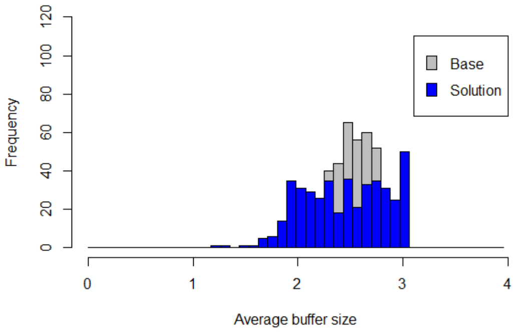
Figure 5.1: Comparison of base case model and solution model.

The comparison between the buffer size for station 09001 is depicted in Figure 5.2a. The mean size of the buffer for the base case is 1.74. Also, the distribution in the figure shows that a high frequency of times the buffer reached a full capacity of two trolleys. The mean station buffer for the solution model is 1.29 which is slightly lower than the base model. This is, however, a mean value and when looking at the dispersion of the data, the highest single frequency was at a buffer size of one. Although on average the buffer size was lower, the range of outputs still fell within the acceptable bounds.



(a) Station 09001 buffer size.

(b) Station 09002 buffer size.



(c) Station 09004 buffer size.

Figure 5.2: Comparison of base case model and solution model for stations 09001, 09002 and 09004 buffer sizes.

The distribution of buffer sizes for station 09002 are shown in Figure 5.2b. There is a decrease in the mean buffer size in the solution model. The mean buffer size for the base model is 2.35 kits in comparison to the 1.98 of the solution model. From all of the performance metrics, this is possibly the biggest decrease, but in essence it is not a major shift in mean. A positive factor is that there is no single instance where the average buffer queue was smaller than one. Meaning that although it might be smaller than the base model, it still ensured that the buffer had kits in its buffer queue so that it would not cause a halt in production at station 09002.

The last performance metric is the buffer size at station 09004. The base model had a slightly higher mean buffer size of 2.55 kits in comparison to the 2.45 kits of the solution model. The difference in the mean is negligible. There is ,however, a change in the dispersion of the output from the solution model. The base model has a more condensed distribution, whereas the solution model has a flatter dispersion. Ideally a more condensed dispersion is wanted, but the outputs were still within an acceptable range.

5.1.2 Performance confidence

For the outputs obtained from the solution model, it is important to determine a level of confidence for the values obtained. Therefore 95% confidence intervals are set up for the outputs for each of the performance criteria. Because the mean of the outputs are known, with an estimated sample standard deviation, the t-distribution is used with $n-1$ degrees of freedom. For n $\geq$ 30 , the t-distribution becomes approximately normal according to the central limit theorem. Therefore if the average of the population is approximately the average for the sample, $\overline{X} = \overline{x}$, the average of the sample with size n is normally distributed and with an unknown population variance, σ , the confidence interval for 100(1- α)% is given by:

$$\overline{x} - t_{\frac{\alpha}{2},n-1}\sqrt{\frac{s^2}{n}} \leq \mu \leq \overline{x} + t_{\frac{\alpha}{2},n-1}\sqrt{\frac{s^2}{n}}$$

With $\overline{x}$ the sample mean, $t_{\frac{\alpha}{2},n-1}$ the critical t-value, S^2 the sample variance and n the number of samples.

For our sample, $n = 50$ and to obtain a 95% confidence interval we let $\alpha =$ 0,05. The critical t-value as obtained from the t distribution table is:

$$t_{0.025,49} = 2,010$$

For the total completed front and rear end bumpers, $\overline{x} =$ 135,1 and $s = 0.867$. Substituting the values for $\overline{x}$ and s in the equation we get:

$$135,1 - (2,010)\sqrt{\frac{0,867^2}{50}} \leq \mu \leq 135,1 + (2,010)\sqrt{\frac{0,867^2}{50}}$$

$$134,85 \leq \mu \leq 135,35$$

This means that with 95% confidence, it can be concluded that the mean number of completed bumpers in a shift would fall within the interval (134,85 ; 135,35). Using the values in Table 5.3, the calculation is repeated for each of the performance metrics and the metric with its associated 95% confidence interval is given in Table 5.4.

Table 5.4: Confidence levels for solution outputs

Perfomance metric	95% confidence interval
Total system throughput [Number of units]	(134.85 ; 135.35)
AGV utilisation [%]	(83.85 ; 86.89)
Station 09001 buffer size [Number of units]	(1.21 ; 1.37)
Station 09002 buffer size [Number of units]	(1.87 ; 2.09)
Station 09004 buffer size [Number of units]	(2.34 ; 2.56)

The essence of the confidence intervals are, that with a confidence of 95%, we can predict that the average output values for a shift the performance metrics would fall in the confidence intervals in Table 5.4.

5.2 Implication on system

The integration of the proposed AGV system into the assembly operations at Line 09 would have various implications on the system.

To implement the proposed AGV system, physical changes and movements would have to be made on the production floor. Firstly, the excess amount of headlight boxes contained in suma D would have to be removed to clear up the space in the area. This will free up the space where the AGV paths can be laid and the central holding area can be positioned. Secondly, suma C and suma D should be combined by moving the picking of headlights to suma C. This will result in a larger suma, and will also eliminate the inefficiencies in the current process. The combination of the two sumas and the additional space obtained as a result thereof can be seen in Figure 5.3.

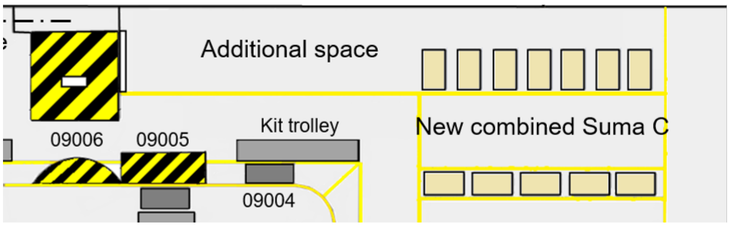


Figure 5.3: Proposed combined suma.

Two AGVs holding areas would have to be incorporated which can be used to store the AGVs when they are not utilised in the process. This area can also be used for maintenance or battery replacement. The first AGV holding area would have to be positioned next to the production line in the newly opened additional space as indicated in Figure 5.4. The second AGV holding area would have to be positioned to the right of the beginning of suma A. Structural barriers would have to be installed to ensure the AGV area is confined. For the AGVs to be able to move around the production floor, magnetic tape would have to be laid on the indicated paths in Figure 5.4 to guide the movement of the AGVs.

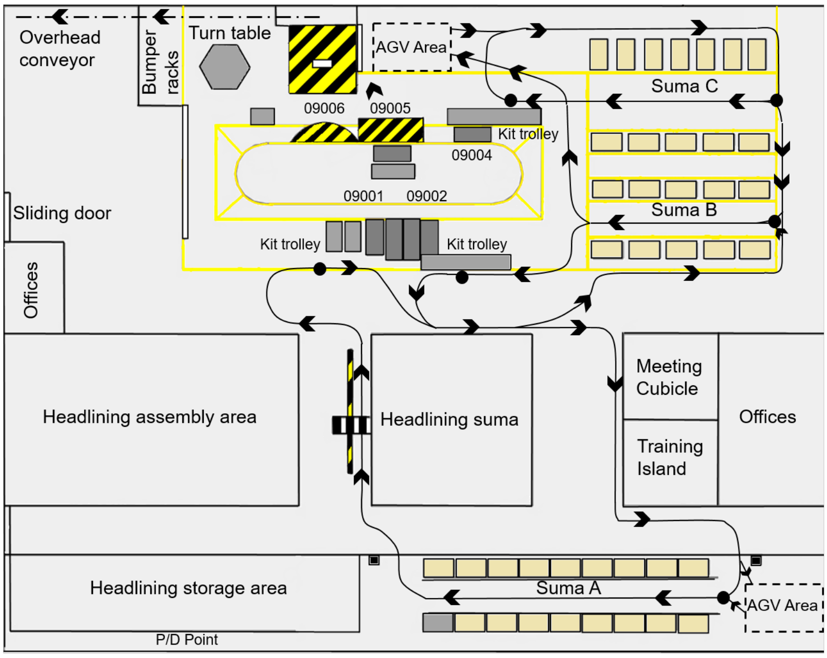


Figure 5.4: Proposed floor layout.

Process changes would also have to be incorporated to account for the movement of AGVs between stations 09001, 09002 and 09004. The biggest process change would be the implementation of the docking concept at the three stations. For this docking concept to be implemented successfully, the trolleys at the stations would require a re-design to incorporate the docking concept. Also, the picking process in the newly designed suma C would have to changed to incorporate the picking of headlights in the suma. The design of the current car kit used to store the parts for the assembly at station 09004 would have to be extended. This is to include the headlights in the car kit, so that the associate performing the assembly only picks the headlights from the car kit. The material supply process would also change as a result of the proposed AGV process. In the current system associates supply stations 09002 and 09004 with parts by walking and pushing part trolley to the stations. In the proposed AGV system, the associated would only handle the car kits and kit trolleys in the suma. After all the parts are picked, the AGV delivers the parts to the station and returns with the empty kits.

These physical and process changes might require some work and thorough planning to incorporate in the current process. Also, it might be a slow process to move to a more automated supply concept. But the advantages of the system, apart from the performance as indicated with the solution model and key performance indicators, prove favourable to ensure an efficient system.

The docking concept to be installed at stations 09001, 09002 and 09004 will minimise the associate handling of trolleys, which will reduce waste of excess motions in the process. This would allow the associates conducting the assembly to focus on the assembly instead of moving and shifting part trolleys. In the current system, the associate at station 09001 has to manually attach and detach the trolley from the AGV. Each time the associate leaves his station to attach and detach a trolley, time is lost in production. From the base model it was found that the associate spends on average 9,6 % of his total time in a shift doing non-value adding work of attaching and detaching the trolleys. This is a total roughly 42 minutes lost over the course of an entire production shift. With the implementation of the docking concepts, the process will be eliminated and 42 minutes of assembly time will be retained.

The combination of suma C and D will also lead to process simplification and removes redundant movements by associates. Currently the headlights are being double handled by moving the headlights from the part boxes to the headlight trolleys. From the headlight trolleys to the headlight are moved to an intermediate table, and only thereafter the associate moves the headlight to the line for assembly. This is a risk, as the headlight can easily be damaged in the process. By incorporating the headlight in the existing kit trolley it would ensure that the headlight are handled as least as possible and eliminate unnecessary motions in the process. This would also reduce the total headlight stock on the floor which currently congests the area and solves the problem of over stocking the line.

A problem of the current system after the optimisation of the suma layout, is the excess walking by the associates. In the base model the associate working in suma B and C walks an average of 4800 meters in total during his shift. And this is only looks at the distances he has to walk between the two stations, and between the stations and the sumas. In the proposed new system the walking distance that the associate had to walk decreased. The total walking distance for the associate is on average 3033 meters. This is a 37% reduction in walking distance. The time saved by the associate by less walking can be further utilised in the process.

Because the new system proposes the combination of suma C and D, it would no longer require a relief associate. Currently when the relief associate is not on duty, the associate as suma A had to fill the headlight trolleys. In the proposed system the process would not require an additional associate to assist in the process. Therefore the same operations can be performed more efficiently with two associates. One at suma A, and one at suma B and C.

5.3 Financial consideration

The investment in high capital assets such as AGVs should also be considered as it impacts on the financial standing of the company. Especially if it is an asset that is used to create better efficiencies on the production floor. Currently BMW has two AGVs. One is utilised in the process and the second is idle and used a a backup. The proposed solution found that for the tandem guide path three AGVs would be required.

These AGVs can be purchased as an commercial-off-the-shelf product or can be built inhouse. The aim of the implementation and testing of AGVs in this area of the plant is to ultimately use the concepts and apply to other parts in the whole assembly plant. Therefore the purchase of an AGV should be economically feasible. A commercial AGV would cost BMW between R 220 000 and R 350 000. Therefore to implement the solution at Line 09 they would need to purchase an additional AGV to sustain the process.

They are also in the experiment phase of building their own AGVs. The total estimated cost to build their own AGV would be R 54 000. Other costs include the magnetic tape to be purchased for the AGV guide path, and cost to adjust the kit trolleys at stations to implement the docking concept.

Although the implementation of the AGV require a large capital investment, there are numerous advantages in implementing such a AGV system. This chapter specifically looked at the benefits of an AGV system that can be used to supply materials to the stations. The design of such a system is based on longer term planning, and if implemented correctly it can assure an efficient system. The next section concludes the findings and gives a recommendation on future research.

Chapter 6

Conclusion and recommendations

In any manufacturing environment, raw materials or intermediate components are required at various points in the manufacturing process to ensure continuous production. More so, it is critical that these materials and components are constantly supplied in the right quantities, on the right time. Failing to do so can have negative effects on the production process. It is therefore that this paper looked at the integration of Low Cost Intelligent Automation (LCIA) as a material handling mechanism in a manufacturing environment. More specifically, in the form of Automated Guided Vehicles (AGVs) with which materials are transported with to various points in the process.

The three main AGV system design issues such as the guide path design, number of vehicles and dispatch rule used in the system were the main focus of the research project. For the specific application at BMW Plant Rosslyn it was found that the most applicable guide paths to use are the conventional and tandem guide path systems. The single loop guide path was excluded as the layout of the facility made the single loop impractical. The most appropriate dispatch rules for the system are the Maximum Remaining Outgoing Queue Size (MROQS) and the Modified First Come First Serve (MFCFS).

The four scenario models proved valuable insights into the performance of the guide paths under different dispatch rules for various number of AGVs in the system. Of the main performance indicators, the total system throughput was a leading indicator as the first objective of the production line is to ensure that it meets the required demand.

For the total output, both types of guide paths, under each dispatch rule showed how the system throughput increases as the number of AGV increases. For all models there was a deflection point at four AGVs in the system. The results when using three AGVs and four AGVs in the system gave similar results for all of the models. The reason being that there are three stations connected by AGVs in the system, and a fourth vehicle did not improve performance that much. Similarly, the throughput of the AGV system followed the same trend as the total output of the line. The sizes of buffer kits at stations also increased as the number of AGVs increased in the system. The results showed how the output distributions of the buffer sizes broadened in dispersion with an increase in AGVs

The system utilisation, proved that for all of the models the utilisation decreased as the number of AGVs increased. The biggest drop in utilisation were between three and four AGVs.

From the performance indicators it was identified that the most efficient combination is the tandem guide path system which operates under the MFCFS dispatch rule. The optimal number of AGVs was found to be three. This system provided a consistent output of 135 front and rear end bumpers produced in comparison to the aimed output of 136. The utilisation of AGVs in this system was as high as 85% and all of the buffer sizes were continually filled to ensure smooth production.

When compared to the current system, the implementation of the new system reduced total walking distance of 4800 meters to 3033 meters for the associate picking parts at suma C and D. This is a total reduction of 37%. The new system also retained 9.6 % of the time the associate currently spends doing non-value adding work by attaching and detaching the part trolley from the AGV. This was done by incorporating a docking concept at each station, and results conclude that this is a advantageous prospect that BMW Plant Rosslyn can consider. For the implementation of the proposed system, it would require to purchase an additional AGV for Line 09. Also, suma C and D would have to be re-arranged to incorporate the AGVs in the assembly operations.

The main findings of the report conclude that with the new system, BMW would be able to produce at a higher output than the current system, the process would require less associate involvement and handling of materials which increases the quality of their product as there are less damages. As set out in the problem statement, this system reduces the total walking distance and ensures that stations are continually stocked with the right quantities at the right time to avoid over stocking stations, but at the same time ensure smooth and continual production.

For future research more comprehensive scenarios can be evaluated which incorporate more design issues such as dispatch rules in the system. In AGV system design, there are many different decision variables that need to be taken into consideration, and for a more comprehensive result practical problems that might be encountered such as break downs and battery management can be incorporated in the analysis. This would give a more probable depiction of the AGV environment. In terms of results it would be advantageous to be able to run each scenario more than 100 times. This would give a more complete and rounded depiction of the data. It would also provide for better distributions that can be used to assist decision making.

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Appendix A

Industry Sponsorship Form

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
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Department of Industrial & Systems Engineering
Final Year Projects
Identification and Responsibility of Project Sponsors

Final Year Projects may be published by the University of Pretoria on *UPSpace* and may thus be freely available on the Internet. These publications portray the quality of education at the University, but they have the potential of exposing sensitive company information. It is important that both students and company representatives or sponsors are aware of such implications.

Key responsibilities of Project Sponsors:

A project sponsor is the key contact person within the company. This person should thus be able to provide guidance to the student throughout the project. The sponsor is also very likely to gain from the success of the project. The project sponsor has the following important responsibilities:

1. Confirm his/her role as project sponsor, duly authorised by the company. Multiple sponsors can be appointed, but this is not advised. The duly completed form will considered as acceptance of sponsor role.
2. Review and approve the Project Proposal, ensuring that it clearly defines the problem to be investigated by the student and that the project aim, scope, deliverables and approach is acceptable from the company's perspective.
3. Review the Final Project Report (delivered during the second semester), ensuring that information is accurate and that the solution addresses the problems and/or design requirements of the defined project.
4. Acknowledges the intended publication of the Project Report on UP Space.
5. Ensures that any sensitive, confidential information or intellectual property of the company is not disclosed in the Final Project Report.

Project Sponsor Details:

Company:	BMW Group
Project Description:	The application of low cost intelligent automation to assembly operations using a discrete event simulation
Student Name:	Ruan van Loggerenberg
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