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Analysis of a Painted Body Storage System

An investigation of buffer capacity and solutions to storage system expansion

Master of Science Thesis in the Programme Systems, Control and Mechatronics

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Göteborg, Sweden, July 2011

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Preface

This report is the result of a 30 points Master of Science thesis at Chalmers University of technology performed during the spring 2011. The work was conducted at Scania CV AB in Oskarshamn with the goal of investigating the demands in buffer capacity as well as alternative solutions for the expansion of the painted body storage system.

This thesis work marks the end of my studies at the masters programme Systems, Control and Mechatronics at Chalmers University of technology. I would like to thank all the people who have contributed to this work and supported me during this period. I would especially like to thank my supervisor at Scania, Sten Gunnarsson, for all his support and many ideas. I would also like to thank John Larsson, Pernilla Zackrisson and all the other employees at Scania who always answered all of my many questions. Finally, I would like to thank my supervisor at Chalmers, Per Nyquist, and my examinator Björn Johansson.

Göteborg, Sweden, July 2011

Abstract

In most automotive factories, storage systems are positioned in between processes in order to enable batching and handle disturbances in the process. Typically, these storages are either conveyor based selectivity banks (SB) or automated storage and retrieval systems (AS/RS).

At the Scania plant in Oskarshamn, where truck cabs are manufactured, a number of storages of AS/RS type are located in between different parts of the plant. One of these is the painted body storage, situated between the paint shop and the trim shop (general assembly). The objective of this storage system is to handle disturbances and the different working hours in the paint shop and trim shop, but also to enable correction of the production sequence. This storage system has been identified as a future bottleneck, and as the company is preparing to increase the production capacity, appropriate measures have to be taken in order to increase the capacity of this storage system.

In this thesis, different solutions on how to increase the throughput and buffer space of the PBS are investigated. The main proposed solution is to expand the AS/RS with a parallel selectivity bank. This thesis describes an example of such a configuration where a number of parallel conveyor lanes are used to increase the throughput as well as the storage capacity of the system. Presented in this thesis is also a developed algorithm for choosing where to store arriving cabs in order to optimize the flow. Simulations results showed that the presented solution could handle large increases of the production rate. However, an analysis of the necessary buffer capacity showed that the available buffer space would have to be increased proportionally to the increase in production rate, thus making a selectivity bank a costly solution.

Keywords: Automotive manufacturing; Storage systems;, AS/RS; selectivity bank; Simulation.

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Abbreviations

AS/RS	Automated storage and retrieval system
S/RM	Storage and retrieval machine
PBS	Painted body storage
SB	Selectivity bank
PSB	Parallel selectivity bank

1. Introduction

1.1 Background

Automotive factories generally consist of five main shops: The press shop, body shop, paint shop, powertrain shop, and trim shop (general assembly). As a result of the very nature of the tasks performed in each shop, they all apply different manufacturing principles. While the body shop prefers to produce batches of products of the same models, the paint shop produces batches of same-colored products. The assembly shop on the other hand, operating by the principles of mixed-model production, focuses on smoothing out the production with a mix of products of different models and with different options. On top of this is a planned sequence which has to be respected in order for the product to be delivered to the customer on time.

In order to handle the different production policies of the shops, intermediate storage systems are placed between shops. These storages enable the production sequence of each shop to be optimized, but they also act as buffers, reducing the effects of disturbances in the process (Ribeiro, Barata, & Sousa, 2009). Three storage systems are considered especially important and are installed in most automotive factories. These are positioned between the body shop and the paint shop, inside the paint shop between the primary coating process and the top coating process, and between the paint shop and the trim shop.

The background of this thesis is ongoing preparations at Scania AB for an increase of the production of trucks. At the plant in Oskarshamn, Scania produces truck cabs, which are then shipped to different locations in Europe for further assembly. The objective of preparing the plant to handle the predefined future production volumes presents a major challenge in identifying all the possible bottlenecks in the process and making necessary improvements. One component in the process which has been identified as a bottleneck is the painted body storage (PBS), located between the paint shop and trim shop. The PBS consists of a one-aisle automated storage and retrieval system (AS/RS) with one storage/retrieval machine (S/RM). The major concern with this storage is the limited throughput, but there is also a question of the size of the storage in order to cope with the different production volumes.

The targeted production volumes are defined as a number of steps presented in Table 1. The numbers specify the average production volumes of the paint shop.

Predefined step	**Production Volume**
Step 3 (Current production capacity)	285 cabs / day
Step 3.5	350 cabs / day
Step 4	410 cabs / day
Step 5	490 cabs / day

Table 1. Predefined production volumes.

The main solution which so far has been considered to the problem of limited capacity of the PBS is to expand the current AS/RS or to build a new one. This is however a very expensive solution which makes it important to investigate other possible solutions as well as to determine the actual demands in terms of buffer capacity.

1.2 Objective and scope

The purpose of this thesis is to investigate the capacity demands of the PBS for the predefined production volumes, as well as to investigate alternative solutions on how to increase the capacity of the buffer. To accomplish these objectives, this work aims to identify the critical factors which are influenced by the performance of the PBS. Control methods also have to be developed in order to demonstrate the feasibility of solutions by the means of simulation. Also, an analysis of the necessary buffer size is to be performed for the future production volumes.

The company is currently working on plans on how to expand and upgrade the process to be able to handle step 3.5. However, a solution which handles this step also has to be expandable to handle larger production volumes. Presented solutions are supposed to act as an alternative to expanding the current AS/RS or building a new one.

Initially it was included in the project scope to update an existing simulation model of the production plant implemented in the simulation software Extend. The idea was to then use this to carry out necessary simulations. However, during the project planning phase it was discovered that this method would not be a very suitable way to reach the stated goals. Therefore, with the consent of Scania representatives, it was decided that tools and methods determined most suitable in order to reach the goals should be used instead.

This work is limited to the PBS. Therefore, all processes in the plant affecting the PBS will be dealt with in their current state. This means that no efforts will be made in trying to improve any other parts of the plant that might affect or be affected by the PBS.

1.3 Methodology

The project started out with an analysis of the system in the form of interviews with technicians and planning personnel in order to gain understanding of the problem at hand. A literature study was then performed with the intention of gaining deeper understanding of the subject and to investigate different approaches to the problem. The project then continued with planning and choosing a method of how to approach the problem. MATLAB was chosen as the main tool for simulation based on the simplicity it provides in writing algorithms and manipulating data. Automod was also used to some extent in order to validate the MATLAB model but also to investigate the effects that the PBS has on adjacent processes.

The input data to the simulation models was for most part gathered in the form of raw data from the company database and filtered to be used as input data. Some data were also measured manually or taken from a parallel simulation project.

1.4 Scania AB

Scania AB is a Swedish manufacturer of heavy trucks, buses and diesel engines. A major part of the company operations is performed in Södertälje, Sweden, where the head office is located and where all research and development takes place. However, production and sales are worldwide with production facilities in Sweden, France, Netherlands Argentina, Brazil, Poland and Russia, and sales and service in over 100 countries. At the Scania plant in Oskarshamn, fully assembled truck cabs are produced for the manufacturing of trucks in Europe. The major owner of Scania is the German automotive company Volkswagen AG, and the company has approximately 35,500 employees worldwide (Scaniakoncernen, 2011).

2. Theory

In this chapter, theory concerning mixed model assembly and different types of storage systems is presented in order to make it easier for the reader to comprehend the work presented in this thesis.

2.1 Sequencing in mixed model assembly

In the automotive industry in general, the customer demand of product variability has led companies to offer a large number of different options, creating a huge variety of models of each product. And since the demand of one specific model is often insufficient to justify the dedication of resources for that particular model, the models have to share resources. This is also the case at the Scania plant, where one large impact of this is in the trim shop, where all the different cab models are assembled on the same lines. The problem with this becomes obvious when you add the fact that the lead times at certain stations in the trim shop varies significantly between different product models and options. The general approach to this problem is to try to avoid or minimize work overload by smoothing out the flow of products to the trim shop. This can be done either by mixed-model sequencing, or car sequencing (Boysen, Scholl, & Woppere).

In mixed-model sequencing, parameters such as operation times, worker movements and station borders are taken into account to generate a detailed schedule for the flow of products. Car sequencing is a more implicit method which aims to minimize work overload by formulating a set of spacing constraints. These constraints are often defined as: At most H products with option O are allowed among N subsequent positions. Work overload can then be minimized by finding a sequence which minimizes the number of broken spacing constraints.

2.2 Storage systems

Typically, storage systems in automotive production plants are either of the type selectivity bank (SB), or automated storage and retrieval system (AS/RS). An AS/RS generally consists of a number of parallel racks divided into a number of bins. In the aisles between the racks, storage and retrieval machines (S/RM) operate in both vertical and horizontal direction. These machines can store or retrieve objects from any of the bins in the racks on either side of the aisles in which the S/RM is operating. Computer systems are used to keep track of the location of stored objects as well as to determine the most suitable location to store an arriving object.

Selectivity banks on the other hand consist of a number of parallel transportation lanes. When an object arrives to the bank, a computer algorithm is used to calculate the most suitable lane in which to store the object. Since the flow of objects in each lane is first in first out (FIFO), it will not be possible to extract the object until all the objects ahead in the same lane have all been extracted. However, in some SB, feedback loops are used to return objects to the entrance to the bank in order to avoid blocking. The major drawbacks with this storage system is that the footprint becomes very large and most importantly, only objects in front position of each lane can be chosen for extraction

Compared to the SB, the AS/RS has the advantages of allowing more candidates to be taken into account for retrieval, and minimizing the footprint of the storage buffer since objects can be stacked vertically in racks. On the other hand, it is very expensive to build. It also has a drawback of limited throughput which is dependent on the operating speed of the S/RM. (Moon, Song, & Ha, 2005). At the Scania plant in Oskarshamn, all of the storage systems are of the type AS/RS.

3. Description of the production process

The production chain of the plant is divided into four primary shops; the press shop, body shop, paint shop and trim shop, as illustrated in figure 1. The first three shops are generally grouped together and categorized as the base process.

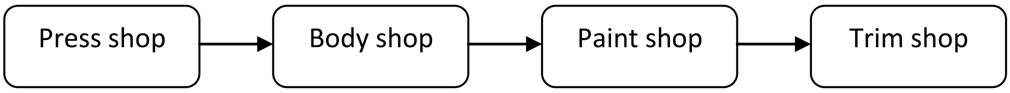


Figure 1. The production chain.

3.1 The press shop

In the press shop, body parts are produced out of steel sheets. A large number of different parts are all produced by a limited number of presses but with different dies. The setup time associated with changing the dies is relatively large, and therefore, the press shop produces batches of each part.

3.2 The body shop

The body parts are fed to the body shop where they are welded together, forming cab shells. Most of the welding is performed by robots on two separate lines. The order of which different models are produced in the body shop is primarily based on the planned sequence. However, the body shop produces batches of cabs shells of the same models. Hence, the order of which cabs are produced by the body shop differs somewhat from the planned sequence. Also, the body shop sometimes experience breakdowns of the welding lines which increases the deviations of the planned sequence.

3.3 The Paint shop

When the cab shells enter the paint shop, they are first subject to a primary coating process where statically charged primer in powder form is sprayed on to the cabs. The cabs are then sent into an oven where the powder melts, forming a layer of paint primer.

After the primary coating process, cabs are sent to the top coating process where they are grouped in color batches. These batches are then spray painted on one of three lines, of which one is fully automated with painting robots. In general, cabs with high frequent colors are grouped in large batches and then painted on the automated line, while cabs with low frequent colors are grouped in smaller batches or painted separately on one of the manual paint lines. The batching in the top coating process is a consequence of the need to purge the painting equipment between each color change, which results in a loss of both time and paint. The batching in the paint shop results in large deviations from the planned sequence. This is especially the case when cabs are painted in metallic colors. The capacity to paint metallic colors in the paint shop is limited to a fixed number per week, resulting in the need to paint some cabs several days in advance. Also, the painting process is of nature such that it is hard to achieve a perfect result each time. As a result, there is a frequent need of manual touch up and sometimes repaint of entire cabs. Before cabs exits the paint shop they pass the insulation line and the anti-corrosion line (ACL). The flow on these lines is first in, first out (FIFO), meaning that the order in which cabs enter the line is the same as the order in which they exit. When cabs exit the ACL line they are subject to an inspection. If the inspection is passed, the cabs are sent to the PBS, otherwise they are extracted from the flow and sent for touch-up.

3.4 The trim shop

When it is time for a cab to be assembled, it is retrieved from the PBS and sent to the trim shop. The sequence in which cabs are assembled are primarily based on the planned sequence, but the assembly also apply spacing rules for certain cab models and options. Since there is no possibility to extract a cab from the assembly line, the flow here is always FIFO.

Finally, when a cab has been assembled and it has passed inspection, it is shipped to a different location for final assembly of chassis and power train.

3.5 Buffers

As mentioned earlier there are three main buffers in the process, all of AS/RS type. The objective of the first buffer, situated between the body shop and the primary coating process, is to handle disturbances in the two shops, and to restore the planned sequence after the body shop. The second buffer, situated between the primary coating process and the top coating process, is primarily used for batching of same colored cabs, but also to handle disturbances.

The third buffer, referred to as the painted body storage (PBS), which is the focus of this work, is situated between the paint shop and the trim shop. The objectives of this buffer is to restore the planned sequence, handle disturbances and enable sequencing of cabs to the trim shop, but also to handle the different working times in the base process and the trim shop.

All of these buffers are commonly found in any automotive manufacturing plant. However, it is the PBS that has gained the most attention in literature. A common topic is the resequencing of cars with a PBS of selectivity bank type (Boysen, Scholl, & Woppere).

4. Process Analysis

In this chapter, a detailed description of the AS/RS is described. Other factors needed to model the process is also presented as well as data used in simulations.

4.1 Car sequencing at Scania

The car sequencing method is applied in the trim shop at the Scania plant. The spacing constraints are defined as maximum allowed frequency (f) for certain options and models (O), where a maximum frequency of 3 means that at most every third successive cab is allowed to have option O. Each spacing constraint is assigned a priority, ranging from 1 to the number of rules, where the spacing constraint with priority 1 is the most important not to violate, and so on. A list with the spacing constraints used by the trim shop today and the percentage of cabs having the corresponding options is shown in table 2**.**

Priority	Model/Option (O)	Max Frequency (f)	Cabs with option O
1	P-Cab	3	23.5 %
2	Right-hand drive	3	15.6 %
3	Contrast-tape	2	26.4 %
4	Topline	2	12.5 %
5	Painted plastic details	5	33.7 %
6	Dual tool hatches	3	7.5 %

Table 2. Spacing constraints used in the trim shop and percentage of cabs with corresponding option.

While it is possible for one cab to have several options, some of the options cannot be combined. For example, a cab cannot be both a P-cab and a Topline since these options refer to two completely different cab models.

4.2 The painted body storage AS/RS

The AS/RS in focus of this work consists of one aisle with one rack on each side as can be seen in figure 2. Each rack has 82 bins – 7 vertical levels and 12 horizontal columns, each with a capacity of storing one cab. The input and output to the AS/RS is both on the same side of the aisle and both are on vertical level 2, but on opposite sides of the storage horizontally - the input at column 1 and the output at column 12. The bins above the input and output on level 3 are also unavailable for storage due to technical reasons. There is also an extra combined I/O position at the bottom of the storage at column 9 where cabs can enter or exit. All together there are a total of 163 bins available for storage.

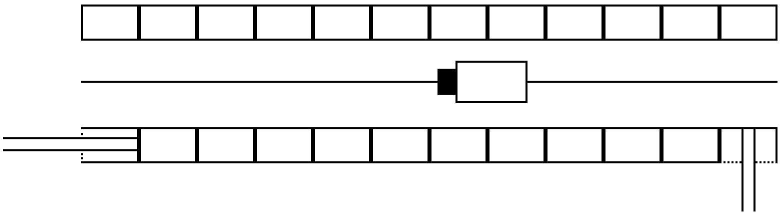


Figure 2. Sketch of AS/RS seen from above.

The storage/retrieval machine S/RM (figure 3) consists of a vertical mast, travelling along two parallel rails which are fixed at the floor and the ceiling of the building. The mast supports a hoisting carriage on which cabs are transported, and a telescopic fork is used to insert and extract cabs in and out of the storage bins and I/O positions.

Figure 3. S/RM transporting a cab.

4.3 Modeling of the AS/RS

In order to properly model the AS/RS, the cycle times for a storage/retrieval operation as well as the storage and retrieval policies had to be determined. Time measurements were taken of the different phases in several storage/retrieval operations. From these measurements, the time needed to insert/extract a cab from or into a storage bin or I/O position could be directly determined, and the acceleration and maximum velocity in vertical and horizontal direction was calculated with the simplistic assumption of linear and equal acceleration and retardation, see Appendix A. A list was then generated with the approximate travel times of all possible travel distances of the S/RM, which can be seen in table 3.

		Vertical direction						
		0	**1**	**2**	**3**	**4**	**5**	**6**
Horizontal direction	**0**	0.0	8.1	13.7	19.2	24.8	30.3	35.9
	1	9.9	8.1	13.7	19.2	24.8	30.3	35.9
	2	11.1	11.1	13.7	19.2	24.8	30.3	35.9
	3	12.8	12.8	13.7	19.2	24.8	30.3	35.9
	4	13.5	13.5	13.7	19.2	24.8	30.3	35.9
	5	15.6	15.6	15.6	19.2	24.8	30.3	35.9
	6	17.1	17.1	17.1	19.2	24.8	30.3	35.9
	7	18.5	18.5	18.5	19.2	24.8	30.3	35.9
	8	19.9	19.9	19.9	19.9	24.8	30.3	35.9
	9	21.4	21.4	21.4	21.4	24.8	30.3	35.9
	10	22.8	22.8	22.8	22.8	24.8	30.3	35.9
	11	23.7	24.2	24.2	24.2	24.8	30.3	35.9

Table 3. Travel times in seconds of all possible travel distances for the S/RM. Distances measured in number of storage bins. For example, moving 4 horizontal positions and 2 vertical positions takes the S/RM 13.7 seconds.

Storage policy

The AS/RS always stores cabs in the lowest vertical level possible and as close to the output position as possible. The reason for this is that vertical travel of the S/RM is much slower than that of horizontal travelling, as can be seen in table 3**.** If the S/RM is to move 4 or more vertical position, the travelling time will always be decided by the time for vertical travel regardless of the horizontal distance the S/RM has to travel.

Order policy

The order policy of the AS/RS is of first-come, first-served type. Whenever an order arrives to the AS/RS it is placed in a queue, and when the AS/RS becomes idle it checks if there are any orders in this queue. If there are orders in this queue, it serves the order that first arrived to the queue.

Sequencing

When retrieving cabs from the AS/RS, two set of parameters are taken into account: Planned sequence and spacing constraints. The retrieval procedure used today is as follows:

1. All cabs available in the AS/RS are sorted based on the planned sequence.

2. A number (usually 16) of the cabs with the least time until due date are then chosen for retrieval.

3. The list of cabs chosen for retrieval is then re-arranged in order to minimize the number of violated spacing constraints. This is done by going through the list one cab at a time and calculating the cost for violating the spacing constraints on the cabs in front of that particular cab. All the cabs further down the list is then investigated in order to find the optimal cab to take over the position of the cab currently being investigated. A more detailed description of this algorithm is found in Appendix D.

4.4 Arrivals

Since simulating the entire plant was not an option in this work, a suitable point in the process had to be found from where data of arriving cabs could be retrieved. It was also necessary that the flow between this point and the buffer was straight and predictable, so that the arrival of cabs to the buffer could be properly modeled. The flow of cabs before the PBS is illustrated in Figure 4. As soon as a cab enters the insulation line, the flow is FIFO all the way to the PBS. Since data of arriving cabs was readily available at this point, this data was chosen as input to the simulation model.

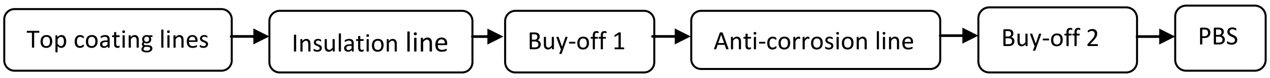


Figure 4. Illustration of the flow of cabs from the top coating process to the PBS.

Data of arrival times of cabs to the insulation line was collected during 8 days and consisted of about 600 samples. According to the data, the arrival times to the insulation line follows an exponential distribution with an additional fixed time constant of 99 seconds, Appendix C. The explanation for the fixed time factor is that the cab is transported down to the insulation line with an elevator with a fixed transporting time.

4.5 Sequence deviations

In order to properly model the sequencing performance of the PBS, the sequence deviations of arriving cabs had to be known. Data of the sequence deviation of cabs entering the PBS was therefore collected from a period of 20 days. Because of the nature of the data, reconstructing the original sequence of cabs perfectly was not possible. This however enabled the possibility to manually determine the size of sequence deviations for a portion of the arriving cabs, thus making it possible to perform a sensitivity analysis of the sequencing performance. The collected data of sequence deviations is presented as a histogram in figure 5, and the sequence deviations of a reconstructed sequence are presented in figure 6.

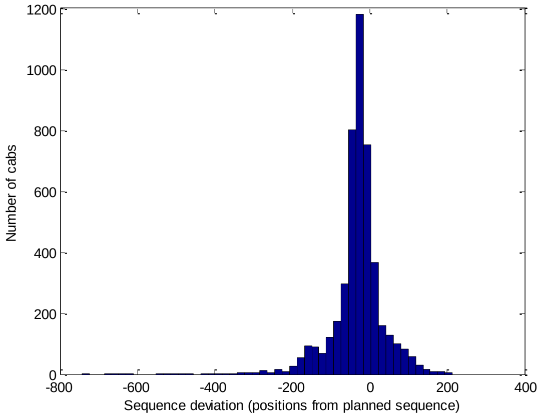


Figure 5.Histogram showing sequence deviations of collected data.

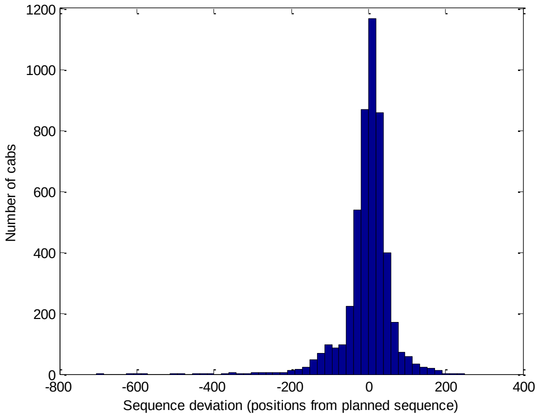


Figure 6.Histogram showing sequence deviations of reconstructed sequence.

The reconstruction of the sequence was performed by inserting one cab at a time in the sequence based on their deviation from the planned sequence. All cabs that could not be inserted this way without overtaking the position of another cab was given a new sequence deviation which was drawn from a normal distribution. These cabs were then inserted into the sequence based on this new value. By the means of experimenting it was found that a normal distribution with a standard deviation of 25 resulted in a fairly accurate reconstruction of the sequence, which can be seen by comparing figure 5 with figure 6. By increasing or decreasing the standard deviation of the normal distribution from which new sequence deviations were drawn, the variance of the set of sequence deviations of all cabs could be increased or decreased respectively.

4.6 Trim shop data

Today, the trim shop has a fixed TAKT time of 199 seconds. However, if the trim shop were to produce at this rate nonstop, the production results would be far greater than the actual results seen today. Therefore, adding downtime in the trim shop to the simulation model was considered necessary. Data of cabs arriving to the first line of the trim shop was collected from two weeks, which consisted of 130 samples of downtime. From this data, the mean time to failure (MTTF) could also be determined. Using the distribution fitting toolbox in MATLAB, the down time data was fitted to a Weibull distribution and the MTTF data was fitted to an exponential distribution, Appendix C. The best-fit evaluation was carried out both by the means of visual comparison as well as by comparing the calculated value of the logarithmic likelihood function, provided by the toolbox, for various fitted distributions.

4.7 Production Schedule

The trim shop is operated in two shifts while the shops in the base process are operated in three. Also, all shops have different working schedules for different days of the week. The result of this is that up to ten percent more cabs than the average production rate are produced on a day with the most working hours. In order to simulate the maximum load on the PBS, the working schedule of Mondays was chosen to be used in simulation, both for the paint shop and trim shop, Appendix B.

Because of the low manpower during the night shift, the TAKT time during the day is different from the TAKT time during the night. However, the planning department has defined production goals, specifying that 216 cabs should be produced on Mondays during the day shifts and 44 during the night shift, resulting in a total of 260 cabs.

If the night shift in the paint shop was to be fully manned, and the TAKT time during the night equal to the TAKT time during the day, a weekly average production rate of 280 cabs / day would be possible. This is also the specified maximum capacity of the plant today.

In the trim shop, the weekly average production rate is only 235 cabs / day. The difference between the production rate of the paint shop and the trim shop is caused by some cabs not entering the trim shop, for example cabs destined for special assembly. Approximately 3.3 percent of the cabs produced in the paint shop never enter the trim shop. These cabs exit the paint shop right before the point where cabs are transported to the PBS.

The Monday production goal in the trim shop is 254 cabs which based on the effective working time would result in a mean production time of 212 seconds. However, because of downtime in the process, the fixed TAKT time in the trim shop is set to 199 seconds. Since the actual production results sometimes exceeds the production goals, the production rate that the PBS has to be able to handle in simulations was defined as 10 % more than the average production rate.

5. Throughput analysis

The first part of the analysis focuses on the throughput of the PBS. As a first step, the performance of the existing system is investigated. Solutions are then presented and analyzed step by step for the investigated production rates. In the second part, an analytical approach is used to investigate the capacity requirements of the PBS for different production rates.

5.1 Performance analysis of the AS/RS

The first step in the analysis was to determine the maximum performance of the existing system. In order to do so, a model of the AS/RS was first implemented in MATLAB.

The store and retrieval policies, as well as the travelling times of the S/RM and the times for picking and storing a cab was modeled as described in chapter 3.3. The production rate of today was then simulated with the buffer level initiated to 90 % of maximum capacity. Simulations showed that the cycle time of the S/RM followed a normal distribution with a mean cycle time of 93.5 seconds and a standard deviation of 10 seconds. According to the maintenance department, the average cycle time of the S/RM is 1.5 minutes, which indicates the validity of the model.

By knowing the cycle time of the S/RM, it is possible to calculate the maximum number of cabs that the AS/RS can handle during one day of production. The theoretical maximum production rate can then be approximated by taking into account the production schedule as well as the difference in production pace during the day and night shift, as stated in 3.7.

However, because the arrival of cabs is not evenly distributed over time, simulation is necessary to determine the maximum throughput of the PBS. A model of the process, including the anti corrosion line (ACL), the PBS and the trim in buffer was therefore implemented in Automod, figure 7.

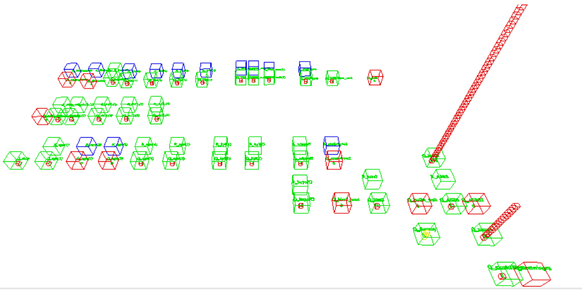


Figure 7. Automod model.

Simulation of PBS throughput

Two different scenarios were tested for the existing system; a fully manned nightshift, and a night shift with the manpower corresponding to that of today. The simulation results for a number of production rates without a fully manned night shift are presented in figure 8 and 9.

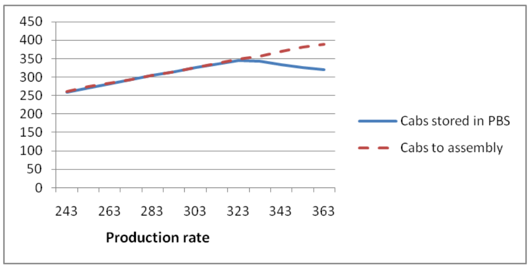


Figure 8. Simulation results for existing system – System throughput.

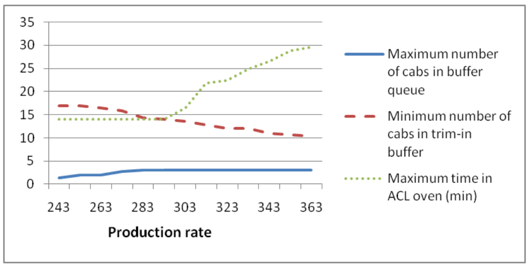


Figure 9. Simulation results for existing system – Blocking and starvation.

The results of the simulations show that the number of cabs stored in the buffer start to decrease at a production rate of approximately 320 cabs / day. The reason for this is a combination of blocking caused by the AS/RS, and limited throughput of the ACL. However, when examining the maximum time that cabs spend in the ACL oven, it is found that this number increases rapidly when the production rate exceeds only 300 cabs / day. This is a consequence of blocking caused by the AS/RS which might lead to the damaging of painted cabs.

Simulation of fully manned night shift

Given the same production rate, a fully manned night shift results in a somewhat slower production pace during the day compared to when the night shift is not fully manned. In simulations, this results in a maximum production output up to a production rate of about 340 cabs / day. However, it can still be seen that blocking of the ACL begin to occur at a production rate of approximately 310 cabs / day, resulting in a prolonged residence time in the ACL oven, figure 10 and 11.

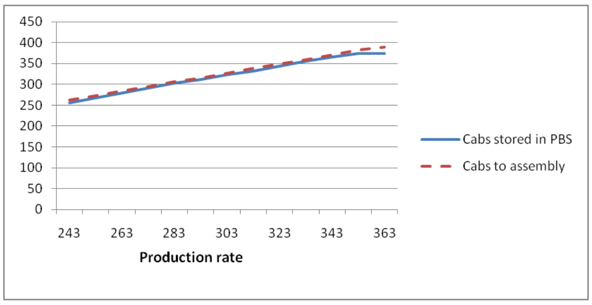


Figure 11. Simulation results for existing system with fully manned night shift – System throughput.

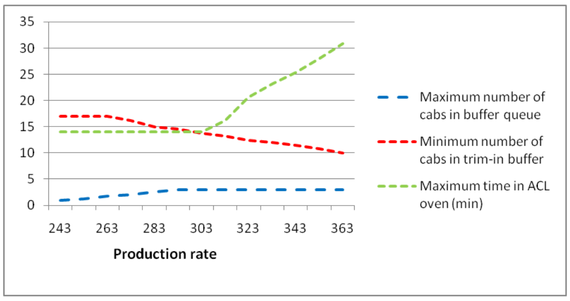


Figure 10. Simulation results for existing system with fully manned night shift – Blocking and starvation.

5.2 Optimization of the AS/RS

In order to address the problem of limited throughput, the S/RM was separated from the actual storage (racks) and treated as a separate process, as illustrated in figure 12. This creates a chain of processes where the S/RM is the critical process.

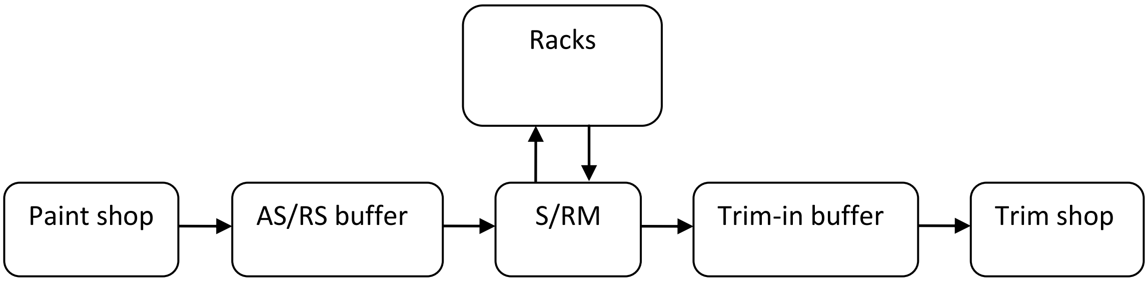


Figure 12. Process chain with the S/RM as a separate process.

Now, the throughput of a critical link in a production chain can be increased by installing a feeding buffer in front of the process and a shipping buffer after the process. These buffers already exist in form of the AS/RS buffer and the trim-in buffer but by increasing the size of these buffers, it is possible to increase the throughput (Stein, 2003).

Another approach to the problem of limited throughput is to decrease the cycle time of the S/RM. Efforts have previously been made in order to try to speed up the S/RM but without success. Another way of decreasing the cycle time would be to move the input or output positions of the AS/RS. In order to really reduce the cycle time, the input and output should be positioned next to each other, or at the same position in opposite sides of the aisle, and as close to the middle of the AS/RS, both vertically and horizontally. This way, the mean distance from the input and output positions to all the bins in the racks as well as the distance between the input and output positions would be minimized. However, it is likely that the cost of such a reconstruction would be far greater than the actual gain, and therefore it was not further investigated.

A sketch of a solution which incorporates both of these methods has previously been produced with the intention of a bypass to the AS/RS in case the S/RM would break down. The sketch shows the possibility to add a number of conveyors parallel to the AS/RS system, and to move the input position to the horizontal position 9, three positions away from the output. This construction is illustrated with a rough sketch in figure 13. Double conveyor lanes are introduced as a way of increasing the storage capacity of the buffer.

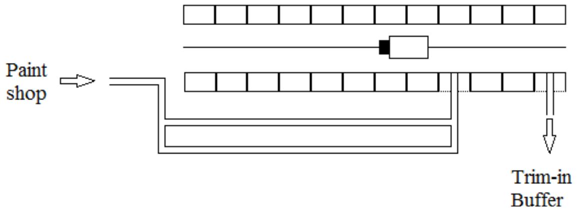


Figure 13. AS/RS extended with two conveyor lanes.

The reason for choosing position 9 instead of position 12 is because of the construction of the AS/RS building. Also, the vertical level 2 is chosen to avoid installing vertical lifts.

Simulations of the MATLAB model show that the cycle-time of the S/RM is reduced to about 87.5 seconds with this reconstruction. This means that the S/RM now can perform up to 686 cycles during the time of the day shifts, corresponding to an average production rate of approximately 375 cabs / day.

Simulation of moved input

In order to investigate the effects of the reduced cycle-time, the Automod model was first simulated without the addition of the additional buffer queue space. The results of simulations with the reduced cycle time are presented in figure 14 and 15.

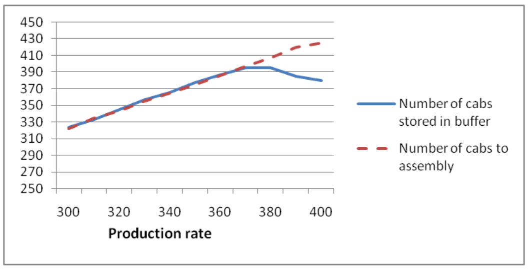


Figure 14. Simulation results with moved input position– System throughput.

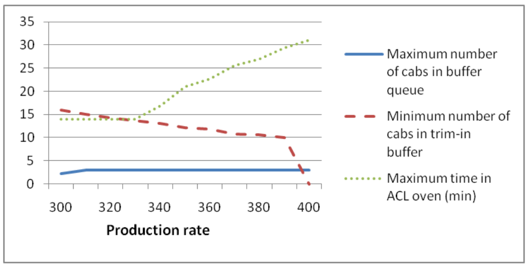


Figure 15. Simulation results with moved input position– Blocking and starvation.

The simulation result indicates that with the input position of the AS/RS moved to the new position, the AS/RS can handle a production rate of 330 cabs / day without causing any blocking or starvation. However, the number of cabs in the trim-in buffer can be seen to remain quite high. In order to avoid starving the trim shop, the number of cabs in the trim-in buffer cannot drop below a certain limit because of the time it takes for a cab to travel from the AS/RS through the trim-in buffer. This time amounts to approximately 500 seconds, making it possible to calculate the limit for the minimum number of cabs in the trim-in buffer. By knowing this limit, the AS/RS can be set to prioritize cabs arriving from the paint shop as long as the number of cabs in the trim-in buffer is higher than the limit. If the number of cabs in the trim-in buffer drops below this level, orders from the trim shop should be prioritized instead. The simulation results with this store policy are presented in figure 16 and 17.

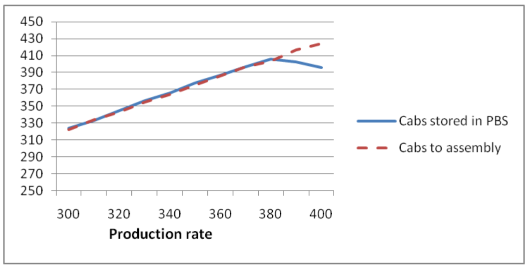


Figure 16. Simulation results with moved input position and order priority – System throughput.

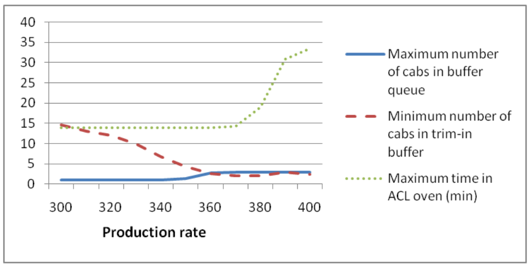


Figure 17. Simulation results with moved input position and order priority – System throughput.

These results show that with the input position moved to the new location, and with this new store policy, a production rate of 370 cabs / day can be handled without adding extra positions to the buffer queue or trim-in buffer. This means that all the added extra space in the buffer queue can be used as extra buffer space, instead of having to be free in order to accumulate blocking caused by the PBS.

5.3 Parallel selectivity bank

If the production rate is to be further increased to levels up to 410 or even 490 cabs / day, the single AS/RS alone will not be able to achieve necessary throughput without significant modifications. Also, which will be discussed in section 5, the size of the buffer will have to be significantly increased. Obvious solutions to these problems would be to either construct a new parallel AS/RS, or expand the current system with a new aisle and S/RM. However, such constructions are very expensive, mainly due to the large building required.

A possibly less expensive solution could be to add a parallel selectivity bank (PSB) with a number of conveyor lanes through which some of the flow is directed. The selectivity bank would also provide additional buffer space. An example of such a configuration is shown in figure 18.

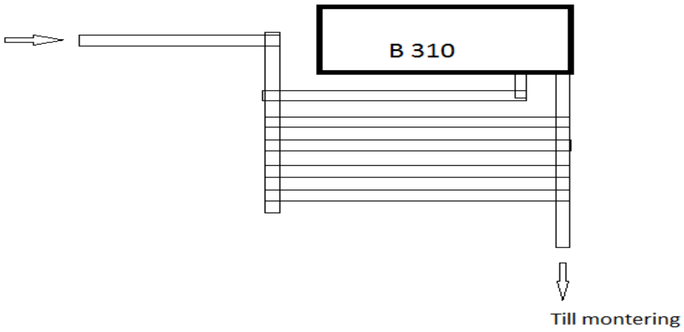


Figure 18. PBS expanded with a parallel selectivity bank.

This configuration is basically an expansion of the configuration with the moved input position. In this configuration, cabs are stored either in the AS/RS or in one of several conveyor lanes. For this system it is possible to use the same retrieval policy as today with some modifications. However, when it comes to finding a good store policy, the problem becomes somewhat more complicated.

Modeling of AS/RS – PSB configuration

In order to be able to experiment with different control methods for the new system, the MATLAB model of the AS/RS was extended with a model of a parallel SB. The production schedule, disturbances in the trim shop, as well as deviations of the planned sequence was also implemented. A choice was made not to incorporate the insulation and anti-corrosion lines in the MATLAB model. Instead, cabs arrived directly to the PBS. This meant that the distribution of arrival times used in previous simulations could no longer be used as direct input.

To solve this, the cycle time of the process in the anti-corrosion line with the highest cycle time was chosen as a fixed component of the arrival time. This amounted to approximately 60 % of the mean arrival time of the present production rate. The remaining component of the mean arrival time was chosen as the scale parameter of an exponential distribution.

The model was validated without the PSB to make sure that the output of simulations in terms of throughput and correctness of sequence of cabs sent to the trim shop corresponded to the company data. It was then simulated with different sizes of the PSB, and different policies for storage and retrieval was evaluated.

Retrieval policy

The retrieval policy has two main objectives:

- Minimize violations of spacing constraints
- Minimize deviations of the planned sequence

Both of these objectives were handled well by the currently used retrieval policy, and thus, it was decided that this policy was to be used in the new system. However some modifications had to be done to the old retrieval policy. The main difference now was that it had to be assured that the order in which cabs were retrieved from the selectivity bank would not be in conflict with the order in which they were arranged in the conveyor lanes.

The new retrieval policy can be described as follows:

1. All cabs that are stored in the AS/RS are placed in a list and then sorted in order of planned sequence.

2. Each cab in the selectivity bank is inserted in the list based on their planned sequence, but not higher than cabs positioned ahead on the same conveyor lane.

3. A number of N cabs positioned highest in the list are then chosen for retrieval.

4. The list of cabs chosen for retrieval is then re-arranged using the same algorithm as before with the addition of one extra step, see Algorithm 1, Appendix D.

Store policy

The two main objectives of the store policy is to:

- Minimize deviations from the planned sequence by storing an arriving cab in an appropriate position.
- Minimize the flow of cabs through the AS/RS.

From experiments with the simulation model it could be seen that the location of cabs in the selectivity bank were relatively unimportant for attaining few constraint violations. However, if the deviations from the planned sequence were to be minimized, the location of cabs in the selectivity bank is critical. For example, if a cab which is already late for assembly is positioned behind a cab which has arrived early in a conveyor lane, the cab which is already late will become ever more so.

Besides minimizing deviations from the planned sequence, a large part of the flow of cabs had to be directed through the selectivity bank. If the flow through the AS/RS becomes too large, significant blocking of the ACL line or starvation of the trim shop might occur.

The main problem when trying to find a good store policy which handles both of these objectives is the large variations in the arriving cabs deviations from the planned sequence. This results in that the two objectives becomes very much in conflict with each other.

Choice of conveyor lane

Before the decision is made of whether to store an arriving cab in the AS/RS or the selectivity bank, the selectivity bank is investigated in order to find the most suitable conveyor lane in which to store the arriving cab. The method which was used was to calculate a cost based on the difference in planned sequence between the arriving cab and the cabs at the rear of each conveyor lane. A more detailed description is found in Appendix D.

Choice of storage system

With the goal of fulfilling both of the two main objectives of the store policy, a number of different methods for deciding where to store arriving cabs was created and tested. When evaluating the different methods, one very simple approach seemed to be quite effective. This method looks at the cost calculated when searching for the best suited conveyor lane. It then specifies that if this cost is less than a predefined limit (β), then the arriving cab can be stored in the selected lane in the selectivity bank.

Simulation of AS/RS – PSB configuration

The buffer levels during a three day simulation of a production rate of 410 cabs / day, and with a 4*10 selectivity bank, using the described policies are presented in figure 19.

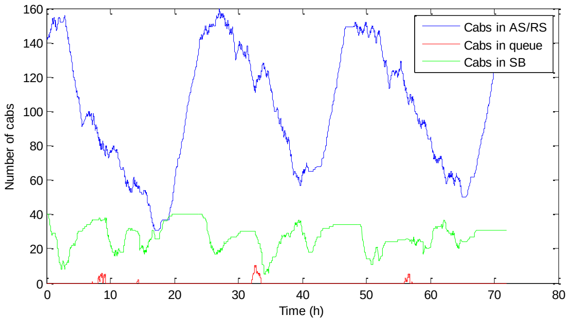
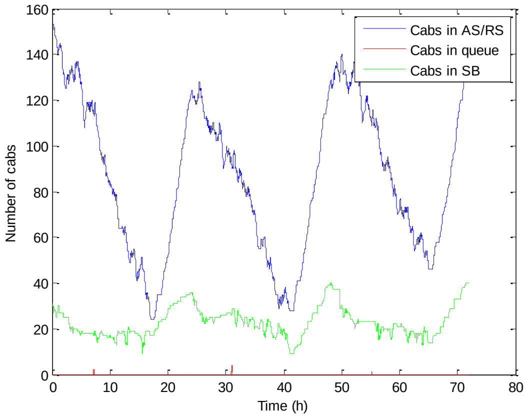


*Figure 19. Simulation results with the PBS expanded with a 4*10 selectivity bank using a fixed-limit control method for a production rate of 410 cabs / day.*

During the simulation, queue build up can be seen to occur at a few occasions. One of the reasons for this is that β is fixed. Because of the large variations of the sequence deviations of arriving cabs, the fixed value of β results in that there are times when very few cabs are stored in the SB. Another reason is that most cabs during the night shift are stored in the AS/RS. Generally, most of these cabs are scheduled within a confined sequence window, resulting in a large number of consecutive cabs being retrieved from the AS/RS during a period of time the next day. Even if many cabs are stored in the selectivity bank during this period, the selectivity bank will eventually fill up, with the consequence of blocking the ACL line.

The solution to this problem is to keep the number of cabs in the selectivity bank relatively low during the day so that it can be filled up during the night. In order to do so and still handle the main objectives, a new control method was developed. This method seeks to keep the number of cabs in the selectivity bank as close to a predefined number as possible during the day by constantly adjusting the value of the cost limit β based on the flow of cabs. The control method is explained in more detail in Appendix D.

This control method was evaluated with two different sets of data for arriving cabs; one with less sequence deviations than normal, and one with more sequence deviations. The simulation result of a production rate of 410 cabs / day with a 4*10 SB is presented in table 3, and the buffer levels during three days simulation is shown in figure 20 and 21.



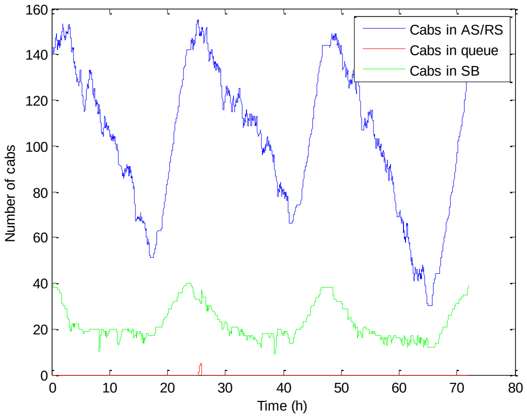


*Figure 20. Buffer levels during simulation with the PBS expanded with a 4*10 selectivity bank, improved control method and low amount of sequence deviations.*

*Figure 21. Buffer levels during simulation with the PBS expanded with a 4*10 selectivity bank, improved control method and high amount of sequence deviations.*

As can be seen in table 3, some queue build-up occurs, but in the figures 20 and 21 it can be seen that it is quite rare, and it is unlikely that it would cause any large problems. It is clear that with a configuration such as this, the number of cabs delivered to the trim shop in correct sequence is going to decrease. The drop is however not that significant and it might therefore be acceptable. Also, the size of the SB used in simulation is most likely too small in terms of additional buffer capacity. In order to increase the buffer capacity, more conveyor lanes would have to be added to the SB, which in turn would result in more cabs being delivered to the trim shop in correct sequence. For the sequencing part, this configuration performs relatively well compared to an improved AS/RS. There are a few more violations of the spacing constraints with the highest priority, but this can be solved by increasing the length of the list of retrieval.

Configuration	**Variance of arriving cab sequence**	**Cabs delivered in correct sequence**	**Flow through SB**	**Maximum queue build up**	**Violations of spacing constraints (%), Options 1-6**
AS/RS + 4*10 SB	6200	93.9 %	24.4 %	6	1.0/2.2/4.8/0.6/5.0/8.5
Improved AS/RS	6200	97.4 %	-	-	0.3/0.6/3.5/0.8/8.2/4.6
AS/RS + 4*10 SB	3300	96.8 %	28.3 %	5	0.8/0.9/3.8/0.6/7.1/7.0
Improved AS/RS	3300	98.0 %	-	-	0.5/0.6/3.3/0.8/4.4/3.0

*Table 3. Simulation results with the PBS expanded with a 4*10 selectivity bank and an improved control method for a production rate of 410 cabs / day.*

For a production rate of 490 cabs / day, simulations showed that at least 8 conveyor lanes with 10 positions each was necessary to achieve necessary throughput. The simulation results with two different sets of data of arriving cabs is presented in table 4**,** and the buffer levels during three days of the simulation is presented in figure 22.

Configuration	**Variance of arriving cab sequence**	**Cabs delivered in correct sequence**	**Flow through SB**	**Maximum queue build up**	**Violations of spacing constraints (%), Options 1-6**
AS/RS + 8*10 SB	6200	93.3 %	55.3 %	5	3.3/0.7/3.0/1.5/9.0/6.1
Improved AS/RS	6200	97.4 %	-	1	0.5/0.0/2.3/0.4/6.2/3.4
AS/RS + 8*10 SB	3300	95.5 %	57.5 %	7	2.1/0.9/4.8/2.0/7.7/7.9
Improved AS/RS	3300	99.4 %	-	1	0.0/0.0/2.1/0.8/3.7/1.4

*Table 4. Simulation results with the PBS expanded with a 8*10 selectivity bank and an improved control method for a production rate of 490 cabs / day.*

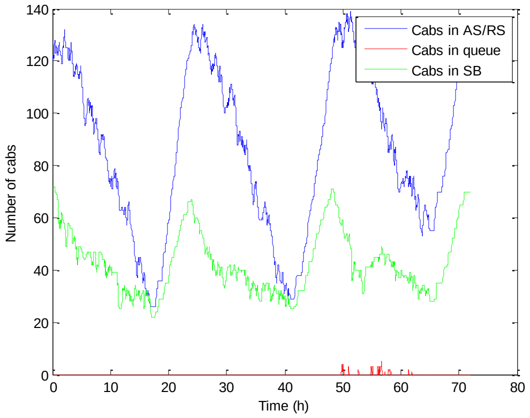


*Figure 22. Buffer levels during simulation with the PBS expanded with a 8*10 selectivity bank for a production rate of 490 cabs / day.*

From these results, it can be seen that this system performs well in comparison to an expanded AS/RS. There are some more violations of the spacing constraints, which however could be solved by increasing the length of the LOR, and the correctness of sequence of cabs delivered to the trim shop is somewhat poorer which is to be expected. The store policy also proved to be robust against different sizes of sequence deviations of arriving cabs. The parameters of the store policy that was set for the first simulation was also used in all subsequent tests for different production rates, different sizes of the PSB and different variances of the arriving cab sequence. This means that there is little importance of fine tuning the parameters, and when appropriate parameters for one condition has been found, there is no need to change the parameters when the conditions changes. The parameters used in simulation can be found in Appendix D.

With the results presented here, the necessary throughput of the PBS can be handled. However, as can be seen in figure 22, the PBS is close to full at the start of the day shift, and almost empty at the end of the evening shift. This means that with the buffer capacities used when simulating the throughput, there is very little margin for disturbances in the process.

6. Buffer capacity

The PBS in focus in this thesis has three main objectives; Handle the different working hours in the paint shop and trim shop, handle disturbances in the process, and restore the planned sequence of cabs. It also has a fourth objective which is to handle the lead times for material logistics in the trim shop.

The demands on necessary buffer space that follows from the first objective can be derived by simply calculating the number of cabs that is to be produced in the paint shop during the night. With the working schedules used today, and with a fully manned night shift, this amount to approximately 28 % of all cabs produced during one day.

When investigating the need of buffer space to handle disturbances, all factors which affect the buffer level of the PBS has to be taken into account. Some of these are:

- Downtimes and low utilization of resources in the paint shop.
- Cabs having to be repaired or repainted.
- Very few or very many of the painted cabs are sent to other destinations, for example special assembly, and thus not entering the PBS.
- More or less stop time than normal in the assembly lines.
- Disturbances earlier in the process, for example in the body shop or primer process.
- Active decisions taken by the management, for example overtime.

6.1 Difficulties with simulation

When determining appropriate buffer space for an in-process buffer, simulation is often a valuable tool. However, there are some cases when simulation is not appropriate. For example when the system behavior is too complex or cannot be defined, the model cannot be validated, or when the problem can be solved analytically (Nelson, Banks, & Nicol, 2000). In some ways, simulation of the PBS relate to all three of these situations.

For the production rates of 410 and 490 cabs / day, it is unknown what modifications will have to be made in the process and what effect these modifications will have. This of course makes it difficult to validate any models of these scenarios, but it might still be possible to simulate such scenarios by making reasonable assumptions.

The main problem however when trying to investigate the necessary buffer capacity is that the buffer level is highly influenced by operative decisions made by the management. In the real world, the reason for any larger disturbance in the process is generally known. This means that decision of countermeasures, i.e. overtime, can be taken based on knowledge of the disturbance. For example, if a robot breaks down on the main paint line it is possible to predict the size of the disturbance (time before the robot is fixed) and take appropriate countermeasures in order to reduce the effect of the disturbance.

In simulations on the other hand, disturbances are generated by random numbers without any underlying cause. This means that rules for calling overtime can only be defined based on the simulation outcome.

6.2 Buffer levels

Today, the specified normal buffer level after the night shift, including the trim-in buffers 19 positions, is specified to 140-175 cabs. If the buffer level drops below 140, a decision is taken of whether to call overtime in the paint shop. The reason for this level being so high is because of the large sequence deviations of cabs leaving the paint shop, but as a consequence, the trim shop rarely experience starvation.

If the upper buffer limit is exceeded, cabs can be transported to an external storage area located outside the factory building for temporary storage. However, because the cabs have to be taken out of the building and transported by truck to this storage area, this is not considered to be an optimal solution. Also, when the upper buffer limit is reached, it is up to the management to decide if the extra storage area should be used or if production should be stopped.

Some buffer space in the in-house buffer is always left empty in case cabs that are late for assembly were to arrive from the paint shop.

6.3 Statistical analysis

With the assumption that the availability of all resources in the process will remain the same in the future, it is possible to approximate the necessary buffer capacity of future production rates by determining necessary buffer space for the current production rate. In order to do so, two different approaches were used;

Observed buffer levels

First, the buffer levels during a period of 18 weeks were examined in order to investigate the variations caused by disturbances. In figure 24 and 23, the number of occurrences and the number of cabs in which the buffer level has exceeded the upper and lower limit respectively is presented.

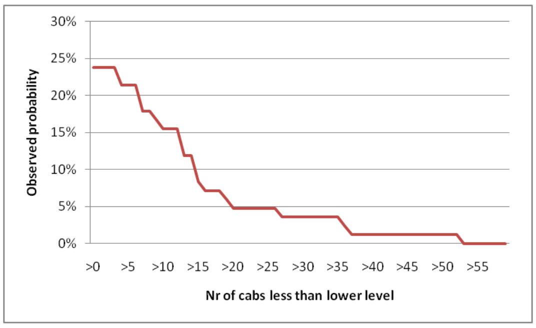


Figure 24. Observed probability of the buffer level exceeding the lower limit.

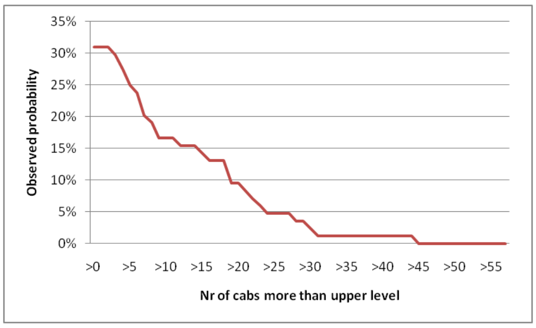


Figure 23. Observed probability of the buffer level exceeding the upper limit.

From this data it can be seen that buffer levels of more than 37 cabs less than the lower limit only occur about 1 % of the time and likewise for buffer levels of more than 31 cabs above the upper limit. The highest and lowest buffer level noted were 53 cabs less than the lower limit and 45 cabs more than the higher limit. The advantage of directly studying the buffer levels is that it reflects the dynamics of the entire process.

Disturbance probability

The goal with the second approach was to calculate the probability of buffer level variations of different sizes based on statistics of production outcome.

Data of the achieved production result in percentage of the planned production goals was collected from a period of five months. These data were then fitted to a normal and Weibull distribution for the paint shop and trim shop respectively. With these distributions, the probability that a buffer level variation is larger than a given value could be calculated, see Appendix E.

However, in order to determine necessary buffer space to handle disturbances, it is necessary to also look at variations over a period of two days. The reason for this is that one days notice is needed in order to call overtime.

By assuming equal probability for the buffer level to take on any value within the normal interval, the probability of the buffer level exceeding the upper or lower limit as an effect of disturbances over two days was calculated, figure 25 and 26. These figures are calculated for the current production rate, for other predefined production rates, see Appendix E.

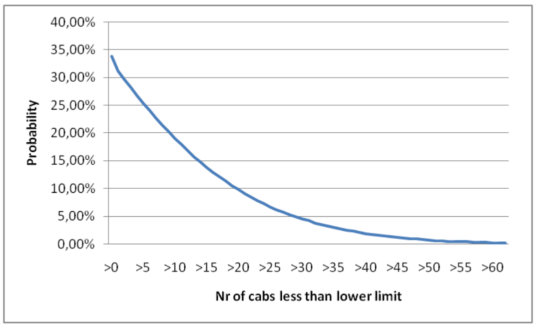


Figure 26. Probability of the buffer level exceeding the lower limit as a consequence of disturbances over two days.

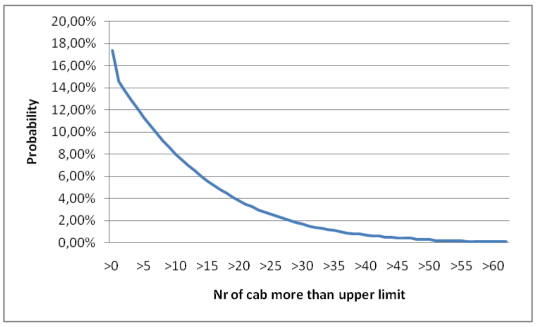


Figure 25. Probability of the buffer level exceeding the upper limit as a consequence of disturbances over two days.

The probabilities presented in these figures only refer to when the buffer level is inside the normal interval. In reality however, it would take some time after a large disturbance for the buffer level to return to the normal interval. Therefore, these calculated probabilities cannot be directly compared to the observed buffer levels where the probabilities of large deviations from the normal interval are expected to be smaller.

However, by matching the observed buffer levels to the calculated probabilities, an estimate of necessary buffer space for higher production rates could be calculated.

Estimation of necessary buffer space

From the observations of the buffer level it can be seen that the difference between handling the variations of the buffer level in 99 % of the time and handling the variations 100 % of the time is quite large in terms of needed buffer space. Also, failing to handle a disturbance in 1 % of the time, and thus losing a small amount of the production output might be a very small cost in comparison to allocating a significant amount of extra buffer space.

The observed buffer levels representing a 1 % probability of occurrence are thus chosen and compared to the values in figure 25 and 26. The probability for disturbances causing buffer level variations of this size is calculated to 2.5 % for a decreasing buffer level, and 1.5 % for an increasing buffer level.

By assuming that the size of the normal interval will have to be increased proportionally to the increase of production rate, as the normal fluctuations of the buffer level is likely to increase in size, the necessary buffer space in order to handle disturbances is calculated, as presented in table 5.

Production Rate	Starvation buffer	Blocking buffer	Normal interval	Total
243 cabs / day	37	31	35	103
350 cabs / day	52	42	50	144
410 cabs / day	60	49	59	168
490 cabs / day	73	58	70	201

Table 5. Calculated buffer space necessary in order to avoid starvation in 1 - 2.5 % of the time and to avoid blocking in 1 - 1.5 % of the time.

6.4 Total necessary buffer capacity

The PBS can be divided into five sub-buffers according to figure 27.

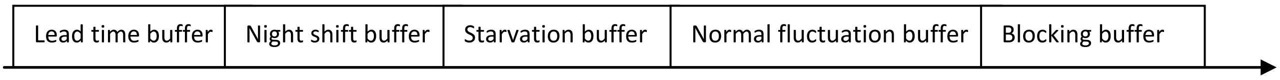


Figure 27. Buffer components of the PBS.

The lead time buffer today consists of a number of cabs corresponding to one hour production in the trim shop. This lead time is necessary since sequence material has to be collected for each individual cab. In the future however, the number of cabs in the lead time buffer might have to be increased to correspond to two hour of production in the trim shop.

The night shift buffer today consists of approximately 45 cabs but since future production rates might require a fully manned night shift, the night shift buffer will have to be able to store approximately 28 % of the cabs produced during one day.

By adding these requirements of buffer space to the figures presented in table 5, an estimate of the total necessary buffer space for the predefined production steps can be determined. These estimates are presented in table 6 and are based on the assumptions of unchanged availability in the process, a proportionally increasing normal interval and a fully manned night shift.

Production Rate	Total buffer space (1 h lead time)	Total buffer space (2 h lead time)
243 cabs / day	187	205
350 cabs / day	264	291
410 cabs / day	310	340
490 cabs / day	370	407

Table 6. Estimated necessary buffer space for predefined production rates.

These calculations presented here are based solely on a statistical analysis. However, for disturbances in the trim shop, it is not simply a question of the size of disturbances, but also a question of how the plant is operated. Since Scania has a policy of client-driven production, one might argue that the paint shop should stop producing if there no longer is a demand of cabs from the trim shop. However, this might result in both the trim shop and the paint shop having to call overtime, instead of just the trim shop. Still, based on operating principles it is possible to choose not to incorporate (or reduce) the buffer space dedicated to handle disturbances in the trim shop, thus reducing the total buffer space needed.

In the presented calculations of total necessary buffer space, no respect has been given to the resequencing of cabs. This might cause problems at the end of the evening shift when the buffer level is at its lowest point. If the paint shop has experienced disturbances, there might be very few cabs in the buffer to choose between, resulting in a poor sequence to the trim shop. It might therefore be of interest to consider allocating additional buffer space for this purpose. On the other hand, in the event of large disturbances in the process, a poor sequence might be acceptable.

7. Conclusions

It has been shown in this work that it is theoretically possible to increase the throughput of the PBS without having to expand the current AS/RS, and that it is possible to do so in a number of steps in which the throughput could be increased gradually to meet the production volume. It was also shown that with the presented solutions, the sequencing performance, both in terms of minimizing spacing constraints and following the planned sequence, would not be significantly reduced.

However, the main solution presented is based on storing cabs in conveyor lanes. The disadvantage with such a storage system compared to an AS/RS is that the footprint becomes very large. And even though the sizes needed for such a system in order to increase the throughput might be competitive to expanding the current AS/RS, it is unlikely that it would be beneficial or even possible to construct a conveyor based system large enough to provide enough buffer space for the predefined future production volume of 490 cabs / day.

An example where a large 15-lane selectivity bank was chosen as PBS instead of an AS/RS can be found at GM Holden (Kline Jr, 2000). The reason for choosing a selectivity bank in this example however was mainly due to the fact that the building required to house the bank already existed, and the objective of the PBS was not so much to provide buffer space as to provide high throughput and sequencing possibilities.

In the final chapter, it was shown that given an unchanged availability in the process, a fully manned night shift and with the operating procedure of today, a production rate of 490 cabs / day requires at least that the amount of buffer space in the PBS is doubled.

8. Discussion

The analysis of necessary buffer space showed that with the given assumptions, the buffer space would have to be increased proportionally to an increase of the production rate. Approximately half of the necessary buffer space follows from the demand of lead time and from the night shift in the paint shop and can hardly be questioned.

The other half on the other side comes from the need to handle disturbances and is exposed to a number of uncertainties. For example, both engineers and management at the company doubt that the size of disturbances will increase proportional to the increased production rate. Also, the analysis used a purely statistical approach where both the paint shop and trim shop were black-boxed. This means that dynamics of the system was not taken into account. In order to be able to make a better estimation of necessary buffer space, the change of size and frequency of disturbances in the process for higher production rates should be investigated. Simulation of the entire process might be a good way to achieve this.

Finally, before any decision is taken on expanding the PBS, an economical analysis of course has to be performed. For example, the cost of creating extra buffer space should be weighed against the cost of having to stop the production. As a support in this work, the calculated probabilities of the buffer level exceeding the normal interval might be useful. These are presented in Appendix E for all predefined production rates.

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Appendices

For a deeper understanding of the results presented in this thesis, algorithms, calculations and data representations are presented in these appendices.

Appendix A – AS/RS data and calculations

The measured and estimated travelling times of the S/RM in vertical and horizontal direction are presented in figure 28 and 29.

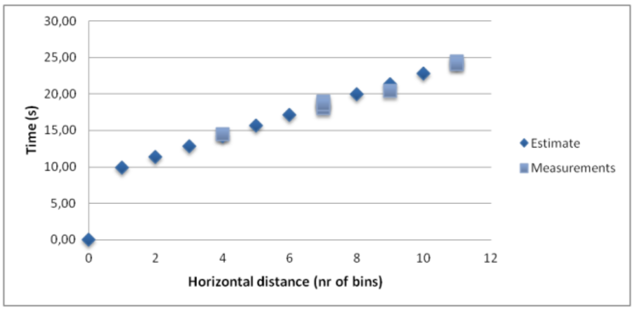

Figure 29. Measured vs estimated travelling times of S/RM in horizontal direction.

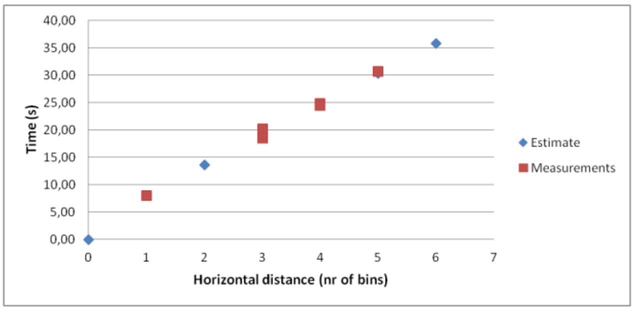

Figure 28. Measured vs estimated travelling times of S/RM in vertical direction.

The estimation of the travelling times is based on a few measurements of two different travelling distances d_1 and d_2, both of which considered large enough for the S/RM to be able to reach maximum velocity. The maximum velocity V_m of the S/RM is then calculated as:

$$V_m = \frac{d_1 - d_2}{T_1 - T_2} \tag{A.1}$$

Where T_1 and T_2 are the measured times it takes for the S/RM to travel the distances d_1 and d_2 respectively.

Assuming a constant acceleration and retardation and that the S/RM reaches maximum velocity, the distance travelled can be expressed as:

$$d = V_m\left(T - T_{a_1} - T_{a_2}\right) + \frac{a_1 T_{a_1}^2}{2} + \frac{a_2 T_{a_2}^2}{2} \tag{A.2}$$

Where T is the measured time it takes for the S/RM to travel the distance d, T_{a_1} and T_{a_2} are the acceleration and retardation times, and a_1 and a_2 are the acceleration and retardation constants for the S/RM.

With the assumption that the acceleration and retardation are equal, we have:

$$T_{a_1} = T_{a_2} = T_a \tag{A.3}$$

And

$$a_1 = a_2 = a \tag{A.4}$$

With the assumption of constant acceleration and retardation we also have:

$$a = \frac{V_m}{T_a} \tag{A.5}$$

Using (A.1) – (A.5), the travelled distance can now be expressed as:

$$d = V_m(T - 2T_a) + V_m T_a = V_m(T - T_a) \tag{A.6}$$

From (A.6) we then have:

$$T_a = T - \frac{d}{V_m} \tag{A.7}$$

The time for the S/RM to insert or extract a cab into/from a storage bin was measured to 27 seconds.

Appendix B – Working schedules

The working schedules of the paint shop and trim shop is presented in table 8 and table 7 respectively.

Shift	Time	Break time (min)
Shift change	06:24	1
Shift 1	08:29	19
Shift 1	11:29	31
Shift 1	13:47	13
Shift change	15:08	6
Shift 2	17:44	31
Shift 2	20:44	13
Shift end	23:09	2
Extra hour reserved for overtime		
nightshift start	00:00	2
nightshift	undefined	18
nightshift	undefined	12
Shift change	06:23	1

Table 8. Working schedule of the paint shop.

Shift	Time	Break time (min)
Shift start	06:24	1
Shift 1	07:30	3
Shift 1	08:42	18
Shift 1	12:00	30
Shift 1	13:36	10
Shift change	15:09	2
Shift 2	16:15	3
Shift 2	18:00	30
Shift 2	21:00	12
Shift end	23:11	1

Table 7. Working schedule of the trim shop.

The resulting total working time is 23.2 hours for the paint shop and 16.8 hours for the trim shop. The effective working time is 20.8 and 15 hours respectively. The night shift in the paint shop corresponds to approximately 28 % of the total working time in the paint shop.

Appendix C – Data representation

Arrival times

By calculating the mean of the data of arrival timed and subtracting the 99 second time constant, the scale parameter of the exponential distribution could be determined to 162.9. The data with the time constant removed is presented in figure 30, along with the probability density function of the exponential distribution.

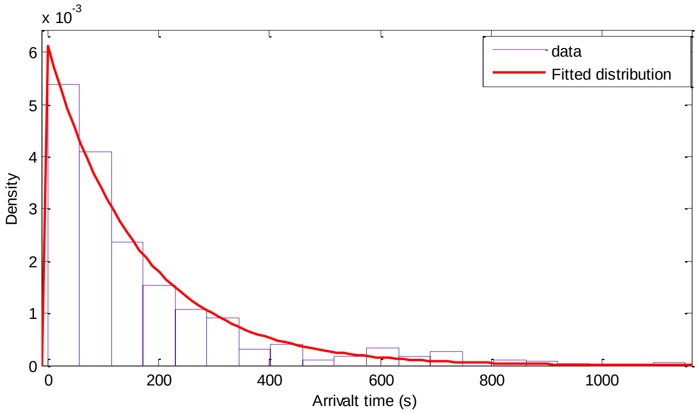

Figure 30. . Exponential distribution fitted to data of arrival times.

Down time and MTTF in the trim shop

The Weibull and exponential distributions fitted to the down time and MTTF data respectively is presented along with histograms of the collected data in figure 32 and 31.

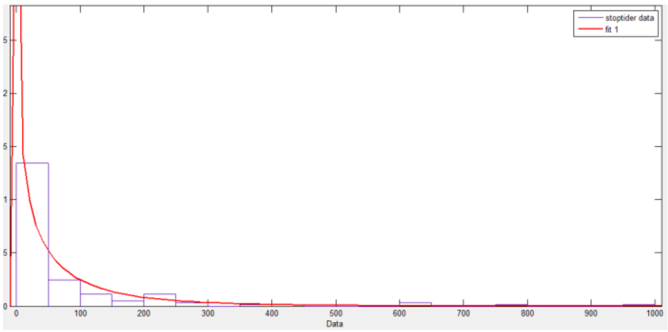

Figure 32. Weibull distribution fitted to down time data.

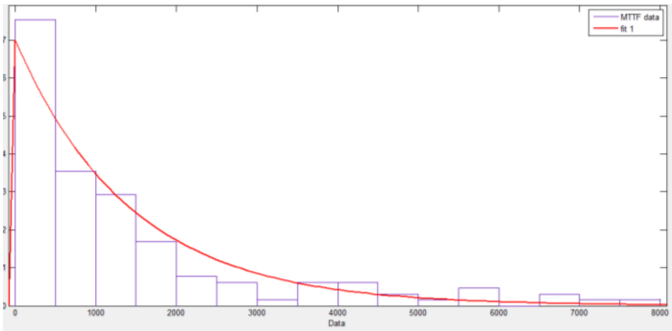

Figure 31. Exponential distribution fitted to MTTF data.

Appendix D - Algorithms

Algorithm 1 - Sequencing Algorithm

The following algorithm is currently used for sequencing of cabs to the trim shop. In simulations of a configuration with a parallel selectivity bank, the third step is slightly modified. For better understanding of how the algorithm works, an example describing the various steps of the algorithm can also be found in this appendix.

N_r : The number of cabs chosen for retrieval.
N_O : Number of options used in the sequencing.
C_i : Cab at position i in the list of retrieval (LOR). (LOR $= \{C_1, C_2, \dots, C_{N_r}\}$, $i = 1,2, \dots, N_r$)
$C_i.O_k$: Option k for cab i. True if the cab has that option, false otherwise. $(k = 1, \dots N_O)$
S_k : Spacing constraint for option k.

```
1.  For each option $\mathrm{O_k}$:
            Count the number of cabs from the end of the list of “frozen” cabs that do not contain
            that option. Save the result in a set H.
2.  $\mathrm{v} = 1$
3.  For $i = \{v, v+1, \dots, N_R\}$:
            Calculate the cost for $\mathrm{C_i}$ by comparing the values in H with the spacing constraints:
            for $\mathrm{k} = 1, \dots, \mathrm{N_O}$
              if $\mathrm{H_k} < S_\mathrm{k} - 1$ & $\mathrm{C_i.O_k}$ == true
                  $\mathrm{C_i.cost} = \mathrm{C_i.cost} + 2^{\mathrm{N_O - k}}$
            Take the number of options that $\mathrm{C_i}$ has and subtract it from the cost:
            for $\mathrm{k} = 1, \dots, \mathrm{N_O}$
              if $\mathrm{C_i.O_k} == \mathrm{True}$
                  $\mathrm{C_i.cost} = \mathrm{C_i.cost} - 1$
            In the modified version of the retrieval algorithm used for the configuration with a
            parallel selectivity bank, the following lines are added to the algorithm:
            If $C_v$ and $C_i$ are in the same conveyor lane
                $C_i.cost = 2^{No}$
4.  Pick the $\mathrm{C_i}$ with the smallest cost and insert it in front of $\mathrm{C_v}$ in the list (at index v). If several
    candidates with equally small cost exist, pick the $\mathrm{C_i}$ with the smallest index $i$.
5.  Increment all values in H: $\mathrm{H} = \mathrm{H} + 1$
6.  For each option $\mathrm{O_k}$
    If $\mathrm{C_v.O_k} == \mathrm{True}$
        $\mathrm{H_k} = 0$
7.  $\mathrm{v} = \mathrm{v} + 1$
8.  If $\mathrm{v} == \mathrm{N_r}$
        Exit the algorithm and return the now rearranged LOR.
    else
            Go to step 3.
```

Example 1 of a sequencing operation – AS/RS

Step 1 – Initialize the set H by counting the consecutive number of “zeros” from the bottom of each row in the list of frozen cabs, figure 33**.**

Planned sequence	**Option 1**	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**
:	:	:	:	:	:	:
80	0	1	0	0	1	0
86	0	0	1	0	0	0
83	1	0	0	0	0	1
84	0	1	1	1	0	0
85	0	0	0	0	0	0

Figure 33. The figure shows the last 5 cabs in the list of retrieval and their corresponding options.

H_1	H_2	H_3	H_4	H_5	H_6
2	1	1	1	4	2

Figure 34. The values in H – one for each option.

Step 2 – Set $v = 1$, meaning that the set H “belongs” to the first position of the list of retrieval and the cab scoring the lowest cost in this iteration will overtake the first position in the list.

Step 3 – Calculate the cost each cab in the list of retrieval (figure 36) would score if it was to be moved to position $v = 1$ in the list, by comparing the maximum frequency of each option (spacing constraints) to the set H. If a cab has an option O_k and the value of H_k is less than the value of the maximum frequency – 1, corresponding to that option, then a violation cost is added for that option according to figure 35**.** In this iteration, cabs with option 2 will receive a violation cost since $H_2 < 3 - 1$. The total number of options of each cab is then subtracted from the cost.

	Option 1	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**
Max frequency	3	3	2	2	5	3
Violation cost	2^5	2^4	2^3	2^2	2^1	2^0

Figure 35. The maximum allowed frequency for each option and the cost for violating the constraints.

Planned sequence	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Calculated cost
32	1	0	0	0	0	0	-1
87	0	1	0	0	0	0	$2^4 - 1 = 15$
92	1	0	1	0	1	0	-3
93	0	1	1	0	0	1	$2^4 - 3 = 13$
94	0	0	1	0	0	0	-1
95	0	1	1	0	0	0	$2^4 - 2 = 14$
96	1	0	0	0	0	0	-1
97	0	0	0	1	0	0	-1
98	0	0	0	0	0	1	-1
99	0	0	0	0	0	0	0
100	1	0	1	0	0	0	-2
101	0	0	1	0	0	0	-1
102	0	0	0	1	0	0	-1
103	0	0	0	0	0	0	0
104	1	0	0	0	0	0	-1
105	0	0	0	0	0	0	0

Figure 36. The figure shows the list of retrieval during the first iteration with the costs calculated for each cab. The violated spacing constraints are marked in the table.

Step 4 – The cab with planned sequence 92 scored the smallest cost and is therefore moved to the first position in the list.

Step 5 and 6 – All values in H is incremented except those corresponding to the options of the “winning” cab which are set to zero. H now “belongs” to the second position of the list of retrieval. From the new values of H it can be seen that all cabs with options 1,3 and 5 will receive violation costs during the next iteration, figure 37.

H_1	H_2	H_3	H_4	H_5	H_6
0	2	0	2	0	3

Figure 37. The values in H during the second iteration.

Step 7 – The iteration variable v is incremented and the procedure starts over again at step 3. This time the cabs “compete” over the second position of the list and the first position is thus ignored. Figure 38 shows the list of retrieval during the second iteration with the “winning” cab of the previous iteration in first position and with the costs calculated. This time there are several candidates with equally low cost, but since the cab with planned sequence 87 is highest in the list (lowest index) of the candidates, it will overtake the second position in the list.

Planned sequence	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Calculated cost
92	1	0	1	0	1	0	
32	1	0	0	0	0	0	2^5-1
87	0	1	0	0	0	0	-1
93	0	1	1	0	0	1	2^3-3
94	0	0	1	0	0	0	2^3-1
95	0	1	1	0	0	0	2^3-1
96	1	0	0	0	0	0	2^5-1
97	0	0	0	1	0	0	-1
98	0	0	0	0	0	1	-1
99	0	0	0	0	0	0	0
100	1	0	1	0	0	0	2^5+2^3-2
101	0	0	1	0	0	0	2^3-1
102	0	0	0	1	0	0	-1
103	0	0	0	0	0	0	0
104	1	0	0	0	0	0	2^3-1
105	0	0	0	0	0	0	0

Figure 38. The list of retrieval during the second iteration. The "winning" cab of the first iteration is now first in the list.

Step 8 – When the iteration has reached the end of the list, the algorithm exits and returns the rearranged list, figure 39.

Order of retrieval	Planned sequence	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
1	92	1	0	1	0	1	0
2	87	0	1	0	0	0	0
3	94	0	0	1	0	0	0
4	32	1	0	0	0	0	0
5	93	0	1	1	0	0	1
6	97	0	0	0	1	0	0
7	100	1	0	1	0	0	0
8	98	0	0	0	0	0	1
9	95	0	1	1	0	0	0
10	96	1	0	0	0	0	0
11	101	0	0	1	0	0	0
12	102	0	0	0	1	0	0
13	104	1	0	0	0	0	0
14	99	0	0	0	0	0	0
15	103	0	0	0	0	0	0
16	105	0	0	0	0	0	0

Figure 39. The rearranged list of retrieval.

Example 2 of a sequencing operation – AS/RS with parallel selectivity bank

An example of a list of retrieval where cabs to be retrieved are stored either in the AS/RS or in one of the conveyor lanes of the selectivity bank is shown in figure 40. The same list after rearrangement is shown in figure 41.

Planned sequence	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Conveyor lane/ AS/RS
626	0	0	1	0	0	1	2
632	1	0	0	0	0	0	AS/RS
634	0	0	0	0	0	0	3
636	1	1	1	0	0	0	3
622	0	1	0	0	0	1	3
614	0	0	1	0	0	0	3
628	1	0	1	0	0	0	3
637	0	1	1	0	0	1	3
638	0	0	0	0	0	0	AS/RS
639	0	0	1	0	0	0	4
635	0	1	1	1	1	0	4
641	0	0	1	1	0	0	AS/RS
642	0	0	0	0	0	0	AS/RS
643	0	0	1	0	0	1	AS/RS
644	1	1	0	0	0	0	AS/RS
645	0	0	1	0	1	1	4

Figure 40. List of retrieval before sequencing.

Planned sequence	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Conveyor lane/ AS/RS
626	0	0	1	0	0	1	2
644	1	1	0	0	0	0	AS/RS
641	0	0	1	1	0	0	AS/RS
634	0	0	0	0	0	0	3
636	1	1	1	0	0	0	3
638	0	0	0	0	0	0	AS/RS
643	0	0	1	0	0	1	AS/RS
632	1	0	0	0	0	0	AS/RS
622	0	1	0	0	0	1	3
614	0	0	1	0	0	0	3
642	0	0	0	0	0	0	AS/RS
628	1	0	1	0	0	0	3
637	0	1	1	0	0	1	3
639	0	0	1	0	0	0	4
635	0	1	1	1	1	0	4
645	0	0	1	0	1	1	4

Figure 41. List of retrieval after sequencing.

From figure 41 and 41 it can be seen that the sequencing algorithm does not behave completely satisfactory in the sense that it is possible to further improve the sequence by switching the positions of some cabs. For example, cab number 628 could switch position with cab number 642 in order to get one less violation of the second spacing constraint. The problem here is that the algorithm only checks for candidates further down the list.

A simple way of improving the sequencing is to first run the algorithm backwards from the bottom of the list to the top, and then run it as normal, from the top to the bottom. The resulting improvements can be seen in figure 42, where there are no longer any violations of the second spacing constraint, and fewer violations of the third spacing constraint. The number of violated constraints can be further decreased by choosing a larger number of cabs for retrieval. In this situation for example, this would have been necessary since the number of cabs with option 3 is more than half the length of the list of retrieval. However, increasing the length of the LOR comes with the cost of increased deviations from the planned sequence.

Planned sequence	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Conveyor lane/ AS/RS
626	0	0	1	0	0	1	2
644	1	1	0	0	0	0	AS/RS
641	0	0	1	1	0	0	AS/RS
634	0	0	0	0	0	0	3
636	1	1	1	0	0	0	3
638	0	0	0	0	0	0	AS/RS
643	0	0	1	0	0	1	AS/RS
622	0	1	0	0	0	1	AS/RS
614	0	0	1	0	0	0	3
632	1	0	0	0	0	0	3
639	0	0	1	0	0	0	AS/RS
642	0	0	0	0	0	0	3
635	0	1	1	1	1	0	3
628	1	0	1	0	0	0	4
645	0	0	1	0	1	1	4
637	0	1	1	0	0	1	4

Figure 42. List of retrieval after sequencing. The sequencing algorithm is first run backwards, resulting in less violations of spacing constraints.

Algorithm 2 - Algorithm for choosing conveyor lane

The following algorithm is used in simulation for selecting a conveyor lane for storing an arriving cab.

δ_i – Difference between the scheduled sequence position of the cab to be stored and the rearmost cab in lane i:
$\delta < 0$ – The cab to be stored is scheduled for assembly $|\delta|$ work cycles earlier than the rearmost cab.
$\delta > 0$ – The cab to be stored is scheduled for assembly δ work cycles later than the rearmost cab.
γ – User defined parameter
$Lmax_i$ – Maximum capacity of lane i.
L_i – Number of cabs in lane i.
$Nlanes$ – Number of lanes in the selectivity bank.

```
1. If there is an empty lane
     Cost = 0
     Choose the empty lane for storing the cab and exit the algorithm.
2. $i = 1, cost = 1000.$
3. If $\delta_i < 0$
     $tempcost = \gamma * |\delta_i|$
   Else
     $tempcost = \delta_i$
4. If $tempcost < cost$ AND $L_i < Lmax_i$
     Cost = tempcost
     k = i
5. If $i = Nlanes$
     Choose lane k for storing the cab and exit the algorithm. The Cost variable is also returned.
   Else
     $i = i + 1$
     Go to step 3.
```

Several values of the parameter γ were tested in simulations. It was then set to 0.5 which resulted in a good balance between deviations of the planned sequence to the trim shop and flow of cabs through the selectivity bank.

Control Method

The control method described here is used in simulations to determine if a cab should be stored in the AS/RS or the selectivity bank. Every time a cab is stored or retrieved from the buffer, the parameter β is updated using (D.5) – (D.9). When a cab arrives to the buffer, the cost calculated in algorithm 2 is compared to β. If the calculated cost is smaller than β, the cab is stored in the chosen lane in the selectivity bank. Otherwise it is stored in the AS/RS.

In the PBS, there are two main events occurring which are triggered from outside the PBS and therefore considered uncontrollable in this thesis. These are when cabs enter the PBS and when cabs are retrieved from the PBS. This control method is only used when a cab enters the PBS and therefore this event is used as the time instant, denoted k.

The number of cabs stored in the selectivity bank during a time of Δk can be expressed as:

$$\Delta X_{Sb}(k) = X_{SB}(k) - X_{SB}(k - \Delta k) \tag{D.1}$$

The number of cabs retrieved from the selectivity bank during a time of Δk can be expressed as:

$$\Delta Y_{Sb}(k) = Y_{SB}(k) - Y_{SB}(k - \Delta k) \tag{D.2}$$

The change in the number of cabs in the selectivity bank can then be expressed as

$$\Delta V_{SB}(k) = V_{SB}(k) - V_{SB}(k - \Delta k) = \Delta \mathrm{X}_{\mathrm{SB}}(k) - \ \Delta Y_{SB}(k) \tag{D.3}$$

Using a proportional control approach, we can based on the desired buffer level μ, express a desired change of the buffer level of the selectivity bank as:

$$\Delta V_{sb}(k) = (\mu - V_{sb}(\mathrm{k} - \Delta\mathrm{k})) * \alpha \tag{D.4}$$

Where α is a gain parameter.

From (D.3) and (D.4) we get the desired input to the selectivity bank $Rx_{SB,D}(\mathrm{k})$.

$$Rx_{SB,D}(\mathrm{k}) = \Delta \mathrm{X}_{\mathrm{SB}}(k) = \Delta V_{sb}(k) + \Delta Y_{SB}(k) = \left(\mu - V_{sb}(\mathrm{k} - \Delta\mathrm{k})\right) * \alpha + \Delta Y_{SB}(k) \tag{D.5}$$

The control variable β is then updated by comparing the desired input $Rx_{SB,D}(\mathrm{k})$ with the desired input $\mathrm{X}_{\mathrm{SB}}(\Delta\mathrm{k})$ and using an appropriate value on the step size Φ:

$$\beta = \beta + \phi * \left(\mathrm{Rx}_{\mathrm{SB}} - \Delta\mathrm{X}_{\mathrm{SB}}(\mathrm{k})\right) \tag{D.6}$$

In order to avoid negative or too small values as well as too large values of beta, limits are also defined for β according to:

$$\beta_{\min} \ \leq \beta \leq \beta_{\max} \tag{D.7}$$

By using the control method described above during the day and evening shifts, the number of cabs in the selectivity bank during the start of the night shift should be approximately equal to $\mu * Cap_{SB}$. During the night shift it is desirable that the selectivity bank is filled up at an even pace so that it gets full at approximately the same time as the night shift ends.

The desired input to the selectivity bank during the night shift thus becomes:

$$Rx_{SB,N}(\mathrm{k}) = \Delta X(k) * \frac{(1-\mu) * Cap_{SB}}{E_N} \tag{D.8}$$

Where E_N is the estimated number of cabs to be produced during the night shift and Cap_{SB} is the total capacity of the selectivity bank.

In order to avoid large queue build-up, the reference level is increased proportionally to the number of cabs currently in queue according to:

$$\mu_r = \mu * (1 + \eta * Q_B) \tag{D.9}$$

Where Q_B is the number of cabs waiting in queue to the PBS and η is a gain parameter.

Parameters used in simulation: $\beta_{init} = 20, \alpha = 12, \phi = 2, \gamma = 0.5, X(\Delta t) = 10, \mu = 0.3, \eta = 0.5$

Appendix E – Buffer capacity

Data representation

The fitted normal and Weibull distributions fitted to the data of production results in the paint shop and trim shop respectively are presented in figure 43 and 44 along with a histogram of the collected data.

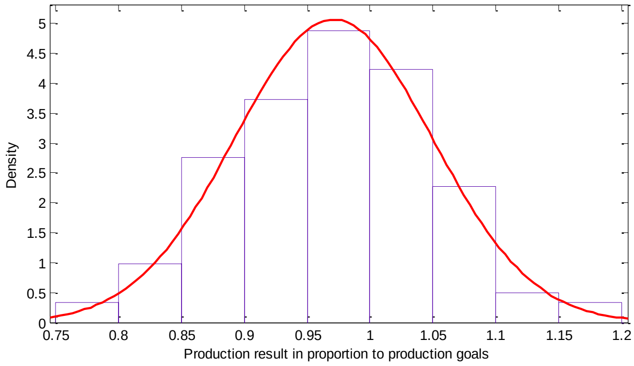

Figure 43. Normal distribution fitted to data of production results in the paint shop.

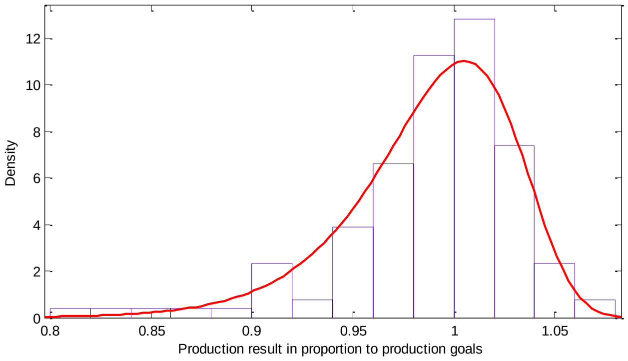

Figure 44. Weibull distribution fitted to data of production results in the trim shop.

Calculations of probability of buffer variations

The change in buffer level during one day is calculated as $Z = X - Y$, where Z is the change in buffer level, X is the production result in the paint shop, and Y is the production result in the trim shop. With the distributions of the production results of the trim shop and paint shop, the probability of a given variation of the buffer level over one day is calculated as: (Grinstead & Snell, 1997)

d < 0 :

$$P(Z < d) = \sum_{k=0}^{\infty} P(X < k) P(Y > k - d) \tag{E.1}$$

d > 0 :

$$P(Z > d) = \sum_{k=0}^{\infty} P(X > d + k) P(Y < d) \tag{E.2}$$

In order to find the probability of the variation of buffer level over two days, the distribution resulting from (E.1) and (E.2) has to be summed with itself which according to Grinstead & Snell is performed by convolution:

$$P(Z_2 = \delta) = \sum_{k=-\infty}^{\infty} P(Z = \delta) P(Z = \delta - k) \tag{ E.3}$$

Where:

$$Z_2 = \delta: \left\lfloor \begin{matrix} Z_2 > d & \delta > 0 \\ Z_2 < d & \delta < 0 \end{matrix} \right\rfloor$$

The probability that the upper or lower buffer limit is exceeded by d number of cabs is given by:

d < 0:

$$P(Z_3 < d) = \frac{1}{N_{Ni}} \sum_{k=0}^{N_{Ni}} P(Z_2 < d - k) \tag{E.4}$$

d > 0:

$$P(Z_3 > d) = \frac{1}{N_{Ni}} \sum_{k=0}^{N_{Ni}} P(Z_2 > d + k) \tag{E.5}$$

Where N_{Ni} is the number of cabs in the normal interval.

Probability of buffer variations

The probability of the buffer level exceeding the upper or lower limit with a given number of cabs is presented in figures 45 - 50 for the production rates of 350, 410 and 490 cabs / day.

Production rate of 350 cabs / day:

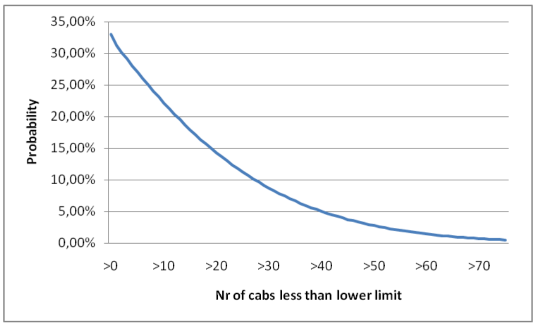

Figure 45. Probability of the buffer level exceeding the lower limit as a consequence of disturbances over two days.

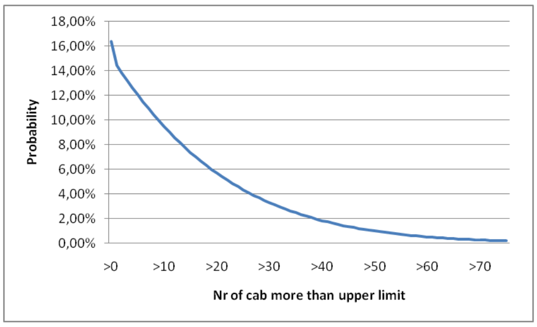

Figure 46. Probability of the buffer level exceeding the upper limit as a consequence of disturbances over two days.

Production rate of 410 cabs / day:

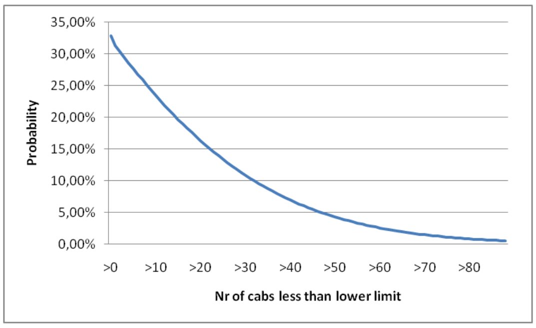

Figure 47. Probability of the buffer level exceeding the lower limit as a consequence of disturbances over two days.

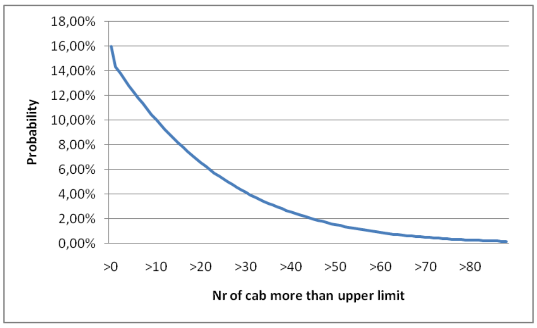

Figure 48. Probability of the buffer level exceeding the upper limit as a consequence of disturbances over two days.

Production rate of 490 cabs / day:

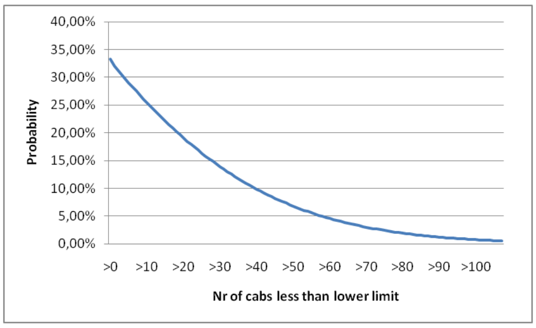

Figure 49. Probability of the buffer level exceeding the lower limit as a consequence of disturbances over two days.

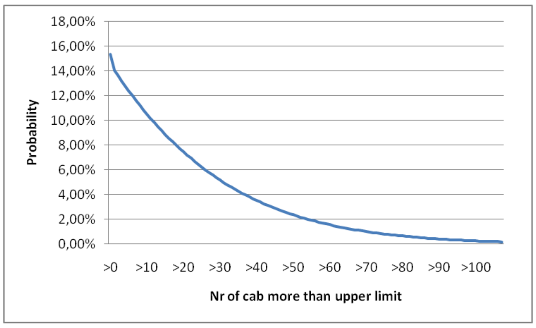

Figure 50. Probability of the buffer level exceeding the upper limit as a consequence of disturbances over two days.