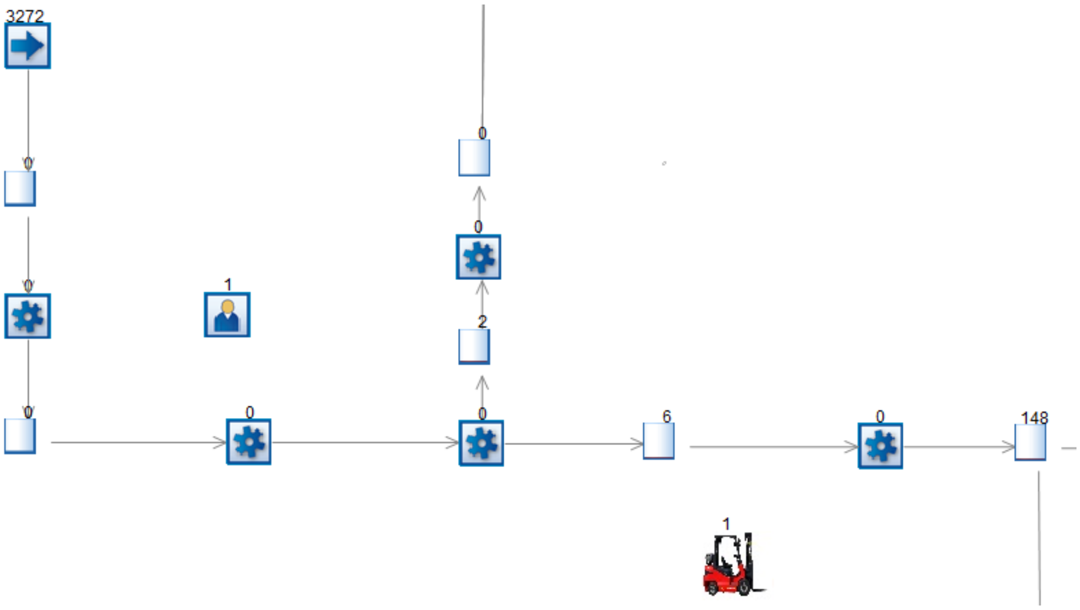

Improving Car Dismantling via Discrete Event Simulation

Master's Thesis in the Master's Programme in Production Engineering

MOHAMAD OMAR MANSOUR
MARCO PEIXOTO MOREIRA

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

This project investigates the car dismantling system of a Swedish company specialized in testing, depollution, dismantling and compression of end-of-life vehicles. A discrete event simulation software called Simul8 was used, where improvements and an implementation plan were proposed based on prioritizing low investment costs, high productivity, minimum work-in-progress and high resource utilization. The scenario manager, an optimization tool in Simul8, was mostly utilized in formulating more than eight different scenarios and optimizing improvements. A triangulated approach featuring Bank's methodology, theory of constraints, interviews with experts and observations were integrated to help improve the system.

The main outcomes of the simulation model were improvement recommendations for the company. The dismantling process appeared to be the system's main bottleneck, where resolving it required shifting capacity to prioritize value cars dismantling over non-value cars depollution, increasing the dismantling efficiency by 5% and eliminating the process of dismantling some parts from non-value cars, which would require renegotiating agreements with some customers. Two approaches were proposed to move forward. The first is hiring an operator temporarily for 53 weeks (16 months), while the second would be combining testing, depollution and dismantling tasks at eight stations. Deciding on which suggestion to follow depends on the company's investment capabilities and its sense of urgency in eliminating the system's most crucial buffer. Nevertheless, applying either solution should be based on two phases yielding a better and more sustainable outcome on the facility as a whole. This includes achieving a productivity increase by a minimum of 6%, drastically decreasing the main work-in-progress by a minimum of 80% and possibly expanding the business to cover other revenue streams.

Key words: Automotive, ELV, Dismantling, Discrete event simulation, Optimization

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Acknowledgement

In this study, a car dismantling system at a Swedish company was improved by using a discrete event simulation software. Modelling and improving the system were carried out from January 2017 to June 2017. The work is part of a multidisciplinary research project that concerns exploring opportunities for further development of the Swedish automotive recycling sector. This thesis is carried out and financed by a Swedish research centre in collaboration with the Department of Product and Production Development at Chalmers University of Technology in Sweden.

This master's thesis could not have been completed without the cooperation of a small but vivid community of persons we worked together with. Special thanks to our project coordinator at the research centre for trusting us with this project and providing insightful guidance from his own experience any time we needed.

We would also like to thank our supervisor at Chalmers Malin Tarrar and examiner Björn Johansson for setting our course and way of working on the right track.

We would like to thank the dismantling company's management for welcoming us to their company and always being available to cooperate and explain their business.

We can only wish but the best to the research centre's project continuation and to the dismantling company to continuously improve and flourish.

Separately,

Mohamad would like to dedicate his work on this thesis to his parents for their belief in him. Special thanks to his brother Ahmad Mansour for his continuous guidance, support and mentorship in always striving to be passionate, ambitious and professional in everything he does.

Göteborg June 2017

Mohamad Omar Mansour

Marco Peixoto Moreira

Notations

CBs	Car bodies. They are value cars whose parts are already dismantled
DES	Discrete event simulation
DOE	Design of experiments
ELVs	End-of-life vehicles. They are vehicles that have no more residual value on the market and little to none reusable spare parts; hence, sent to be compressed eventually
KPI	Key performance indicator
MPC	Manufacturing, planning and control
NVCs	Non-value cars. They are ELVs that contain no parts of value that can be directly reused and sold
NVPs	Non-value parts. These are parts with no value to sell. They are compressed with the car and recycled later
PP	Pick-and-pay. It stands for a car that is depolluted then put into a designated yard for individual customers to dismantle parts directly from, which would allow them to purchase at lower prices
ROI	Return-on-investment
RR	Rate of recycling and reusing the ELVs' weight
RRR	Rate of recycling, reusing and recovering ELVs
TAD	Testing and depollution
TOC	Theory of constraints
VCs	Value cars. They are ELVs that contain parts of value, which can be directly reused by and sold to customers
VPs	Value parts. These are parts that are of value, which can be sold to the customers and reused in good condition
VSM	Value stream map

1 Introduction

Since the last century, vehicles became an essential infrastructure of our daily lives. Almost all manufacturers spend much energy and investment to secure vehicles matching the people's changing needs; for example, by issuing autonomous vehicles that allow people to make the best out of their time while being transported.

Nevertheless, similar to any product, the vehicle has a lifecycle, after which it is deemed as an end-of-life vehicle (ELV). Given that the vehicle itself represents a large stock of materials and spare parts that can be reused, it would be wasteful to completely compress the vehicle as is, shred it and recycle very few basic raw materials from it. Therefore, a strategy for efficient recycling is a necessary step towards a better circular economy.

The major policy for the vehicle recycling system in Europe, the ELV directive (2000/53/EC), specifies that as of 1st of January 2015, the rate of recycling, reusing and recovering ELVs – the RRR rate – in the member countries shall be increased from a minimum of 85% to 95%. Moreover, the rate of recycling and reusing of the ELV's weight – the RR rate – shall increase from a minimum of 80% to 85%. The long-term EU strategy goes beyond simply recovering mass and explicitly aims at maintaining the value of both materials and energy used; thus, striving for functional recycling (EC, 2007).

1.1 Background

Currently, the ELV dismantling in Sweden is relatively small-scaled and labour concentrated (Cullbrand, Fråne, & Jensen, 2015). There exist 330 Swedish certified dismantling facilities; the biggest one processes approximately 4,400 ELVs every year. Since most of these firms are small and ranging from 3 to 20 employees ("Sveriges Bilåtervinnares Riksförbund," n.d.), they may not have undergone the same level of industrialization and development as, for example, the automobile industry.

This thesis falls under a multidisciplinary research project aimed at exploring the opportunities for further development of the Swedish automotive recycling sector. The thesis is included in a work package revolving around developing new and more efficient vehicle dismantling processes by adopting and adapting manufacturing, planning and control (MPC) theories and practices to the special challenges and needs of SMEs within the vehicle dismantling and recycling businesses.

It is good to note that within the same work package, the authors were working hand-in-hand with another team tackling lean process improvements and warehouse optimization techniques at another similar Swedish company (Bergqvist & Islam, 2017), which will be referred to as the lean team or team lean throughout the rest of this report. The purpose of this collaboration from the research centre's perspective was to get a holistic view of the issues encountered in this business and possibly propose improvements that might be complementary. The weekly meetups with the project coordinator at the research centre helped in sharing knowledge about the various aspects of this sector.

1.2 Purpose

The purpose of this project is to use a discrete event simulation (DES) software to model the current dismantling system at a Swedish car dismantling facility. The model will be utilized to investigate improvement opportunities by surfacing the system's problems and their root causes as well as experimenting with several scenarios catered to develop a new and more efficient dismantling system.

1.3 Aim

The thesis aims to establish:

1. A current state value stream map (VSM) of the dismantling system at the Swedish company to be verified and validated with the shop floor manager.
2. A verified and validated simulation model featuring the dismantling system. The model should start when a car enters the facility. It ends when the compressed car body (CB) leaves for shredding, and the dismantled parts are barcoded and ready to be warehoused.
3. Improvement recommendations for the dismantling system by answering the following questions via the simulation model:
    a. How can the system be improved for better productivity and minimum work-in-progress as well as high resource utilization, while maintaining the minimum investment possible? More specifically:
        i. How can the flows between the processes be optimized with regards to system losses?
    b. What are the pros and cons that be concluded from the dismantling process improvements proposed?
    c. What implementation plan can be established for the real system to cope with the proposed improvements?
4. Key takeaways for the ELV dismantling business.

1.4 Case description

With less than 50 employees working, the company deals with testing, depollution, dismantling and compression of ELVs, where dismantled parts are sold to insurance companies and private customers. In the year 2014-2015, the company took in 3,270 cars both from insurance companies and individual owners and sold 52,429 different parts ranging from lamps to doors and engines as well as many parts from other categories.

The company's business revolves around ELVs that are older than 5 years, since cars of this category would be more present on the market. This means that there is considerable demand on these cars' spare parts. With the dismantling company being aware of the individual customers' needs in having lower prices, it features a pick-and-pay yard. Basically, these customers can also come to dismantle themselves value parts (VPs) from ELVs that were already depolluted.

Similar to other car dismantling facilities, the company experiences variation in supply, especially in the type of cars, since any ELV coming inbound should be accepted whatever its condition is. Nonetheless, the company also deals with certain insurance companies who deliver different ELV types in somehow consistent proportions overall. Moreover, it experiences variation in demand, since this line of business in itself cannot decide when a car will be crashed and spare parts will be required. Given these conditions, eliminating the variation that the company can control is of utmost interest, which mainly includes queue congestion and throughput instability within the dismantling system. Understanding the basics of the car dismantling process at the facility will be more elaborated on in later sections.

1.5 Delimitations

The project was to be secured within a period of five months. This meant going deeper into the software's features and the time to spend on improving the current dismantling system were to be set accurately.

In addition, the simulation model will not take into consideration the warehousing process, being logistics assigned to team lean (Bergqvist & Islam, 2017). Rather the focus will be more on the flow of the cars, especially those that have their parts dismantled by operators.

Furthermore, this work is limited to a case study at one company; hence, some of the improvement scenarios were explicitly modelled upon the associated dismantling system. Consequently, some of the suggested improvements may be limited to that company's dismantling system given its characteristics.

In addition, it was not possible to arrange continuous improvement meetings with the shop floor operators due to the limited time to call for such meetings, make them feel comfortable about the authors' collaboration and brainstorm together to come up with experiments that can be simulated. Hence, given more time, this could have helped in compiling new and perhaps different scenarios to test.

Finally, the authors should take into account the fact that the models they simulate will be further used by the research centre in further development of the project. Hence, data should be compiled from and into Excel workbooks, which can be easily updated by other users of the software.

2 Methodology

This project was approached through a real-life case study supported and driven by a research methodology. The latter is based on a triangulated approach, composed of a literature review as well as quantitative and qualitative studies (Berlin & Adams, 2015), which were conducted almost in parallel. This approach paved the way to analyse and improve the case study, which was to be simulated.

Also, data collection was based on the literature and the qualitative parts, since the quantitative studies embodied compilation and analysis of the simulation model's output rather than the input. The following sections discuss in detail the case study conducted, the research methodology used, the project's validity as well as the ethical issues encountered.

2.1 Case study

A case study investigates real-life phenomenon through detailed analysis of a number of events or conditions, and their relationships. It is a methodology that enables researchers to examine data in a specific context, especially when a holistic and in-depth investigation is required. Through a case study methodology, one would be able to go beyond the qualitative and quantitative results and understand the behavioural conditions through the actor's viewpoint (Zainal, 2007).

The case study in this project represents simulating the dismantling system at a Swedish car dismantling company via a DES software called Simul8, and provides optimized improvements to increase the number of parts dismantled, decrease buffer sizes and throughput time as well as maintain high resource utilization while having investment costs to the minimum. Given the complexity of such a system, the authors agreed on making the tolerance limits of the system's output and behaviour as tight as possible but in a reasonable way to convey credible and strong recommendations to the company. Thus, given the limited amount of time to learn the software's features, the authors decided to simulate the real system in a holistic way, rather than going into the extreme details that might not affect the output or the behaviour that much.

Although the main focus was on the system's flow, and since the processes' performance affects the flow, the authors were working hand-in-hand with the lean team to investigate the feasibility of conducting certain scenarios, such as testing the effect of having two operators working on the same dismantling station (Bergqvist & Islam, 2017).

Given the limited amount of time to collect detailed information about the processes, the authors requested relevant information from the lean consultant hired by the company, where he measured quantitative data about the arriving ELVs' distribution, the cycle times and the number of dismantled parts. Although the aim of this study is to assess the current and actual state of the system in the year 2017, the available data provided by the lean consultant goes back to the years 2013 and 2014. However, the number of inbound cars and parts dismantled was benchmarked against that of 2014, since the 2013 data was not available. On the other hand, critical buffer sizes and capacities were derived from the interviews and physical observations via facility visits.

2.2 Triangulated approach

The triangulated approach features the data collection techniques used, which are the literature review and the qualitative studies, and it also includes quantitative studies as will be emphasized below.

2.2.1 Data collection: literature review

The aim of the literature review was to tackle a methodology that would be appropriate to serve as a guide in conducting a DES project as well as to search for state of the art practices in ELV dismantling systems. These two main aspects will be described as follows.

2.2.1.1 Steps to follow in a DES project

Establishing an accurate and precise simulation model requires adopting a robust and reliable approach. There are several methodologies stating how to approach a DES project. One of the most popular is that of Jerry Banks', whose model represents a step-by-step guide for building a simulation study (Westling, 2015). This assisted the authors in:

- Identifying exactly the problem to be solved
- Planning all the tasks and activities within the five months thesis period
- Modelling conceptually the facility's dismantling layout
- Collecting data from the shop floor manager and relevant literature about state of the art practices in simulating dismantling facilities
- Simulating the study and analysing the results
- Proposing improvement suggestions for the company's management

The model is illustrated in *Figure 1*, where each step is explained below (Banks, Nelson, Carson, & Nicol, 2010).

Problem formulation: **s**coping what to do and stating the problem clearly is essential to agree upon with the key stakeholders before digging deeper into building the simulation. As the study progresses, the problem may be reformulated.

Setting of objectives and overall project plan: the objectives of the simulation study are set, and a plan is established to organize the tasks needed for reaching the desired outcome. This is done while taking in consideration the:

- Availability of the key stakeholders involved
- Associated costs and budget
- Time required to achieve each work phase
- Results expected at the end of every phase

Model conceptualization: starting with a simple model and using simulation to move forward towards a more complex system that mimics the real one is ideal. The conceptual model should capture the essence of the real system, which requires continuous and direct engagement with the key stakeholders whose input will affect the outcomes of the model.

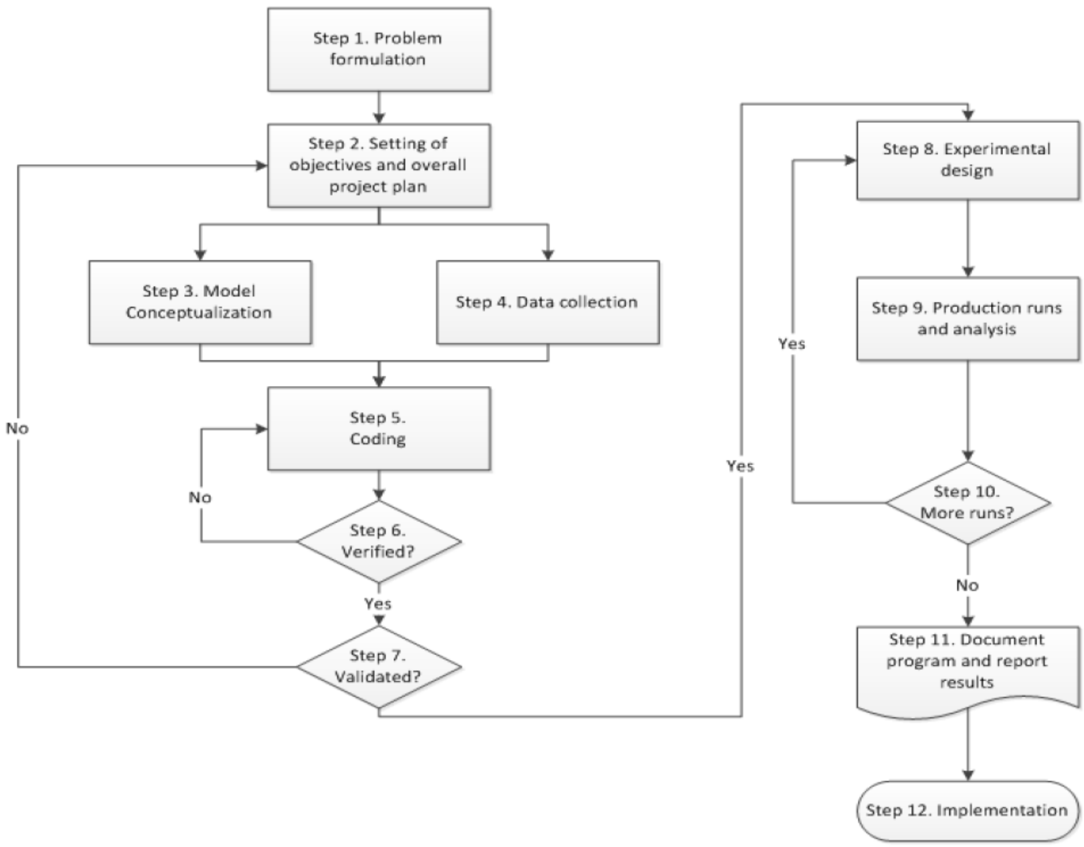


Figure 1. Steps to follow in a simulation study (Banks et al., 2010).

Data collection: this is done in parallel with conceptualizing the model, where the type, number and quality of the collected data becomes of higher importance when the model becomes more complex. Moreover, since 40% of a project's simulation time is dedicated to input data management (Skoogh, 2011), it is advised to classify the data – both quantitative and qualitative - according to three categories; available, unavailable but collectable as well as unavailable and not collectable, see *Table 1* (Robinson & Bhatia, 1995). Furthermore, starting at earlier phases in collecting the data needed is crucial, but the type of data to be collected depends on project's objectives.

Table 1. Data classification (Robinson & Bhatia, 1995).

Category	Data availability
Category A	Available
Category B	Not available but collectable
Category C	Not available and not collectable

Transforming this data into a representative input for a DES model requires adopting a reliable input data management methodology. One of the many methodologies that are used in an industrial DES project can be seen in *Figure 2* (Skoogh & Johansson, 2008).

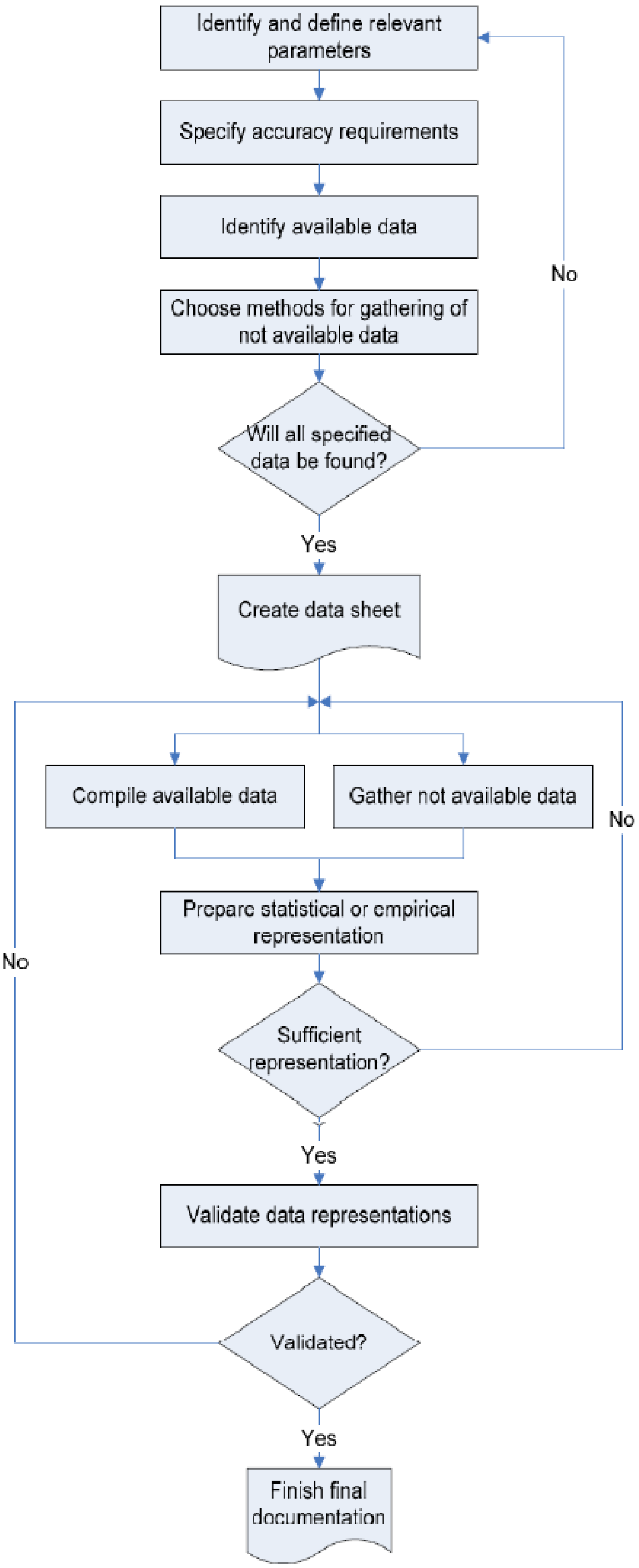


Figure 2. Input data management methodology (Skoogh & Johansson, 2008).

This methodology highlights the importance of identifying relevant parameters, specifying their accuracy requirements as well as choosing the best method for collecting unavailable data. It also emphasizes how crucial it is to create data sheets for proper statistical representations of the information.

Coding: selecting the software should be aligned with the computational capacity of the computers running the simulation as well as the level of complexity the modelers wish to dive into.

Verification: it is important to make sure that the different parts of the simulation model are behaving correctly, which requires a great deal of debugging, if a prominent level of complexity was desired. This requires having the system's behaviour according to acceptable tolerance limits to avoid diminishing returns, where it becomes important to structure the model as well as its input and output parameters in a self-explanatory and organized way (Kapoun & Börjesson, 2015).

Validation: the model is iteratively compared to the real system and adjusted accordingly until accuracy margins are acceptable. Several validation techniques include (Sargent, 2010):

- Observing the model's behaviour graphically as time elapses
- Comparing the results from the simulation model to the real system
- Making several runs and ensuring that the results are consistent

Experimental design: decisions need to be made based on the warmup period, which is the time the simulation will run before collecting results. Therefore, queues and other simulation objects get into conditions that are typical during normal running situations in the system being simulated ("Simul8," n.d.). These appropriate decisions should also be dependent on which parameters to select for the warmup analysis, the length of the simulation run and the number of trials needed for each run. This requires experimenting with the software to fully understand its behaviour.

Production runs and analysis: results from the compiled runs are analysed to check if the system's behaviour has been correctly mimicked; otherwise, more adjustments are needed until satisfying results are achieved.

Documentation and presentation of results: there are two documentation types, which are program reporting and progress reporting. The former requires documenting the key parameters influencing the simulation model in a clear and robust way, which would allow other or future analysts to understand the system and even modify it in a flexible manner. On the other hand, progress reporting should be done continuously to keep track of the objectives achieved and make the key stakeholders close in the loop, which requires documenting what was done already and the decisions made. And since the model should provide the stakeholders with the best information catered for making the best decisions, it is important to compile the results and organize them in a manner that is both understandable and attractive to the stakeholders.

Implementation: the success of this step is highly dependent on the robustness of the previous 11 steps as well as on who takes part in the implementation process. It also depends on how much the model builders included the model users during the simulation process. Hence, high involvement would allow the model user to understand more of what is required during the simulation and what the outcomes will be, leading to successful implementation.

2.2.1.2 State of the art practices in ELV dismantling systems

The aim of this search was to find in detail the most abundant layouts used in car dismantling facilities, the techniques used for their improvement, how DES-based car dismantling case studies were developed and what key performance indicators (KPIs) were used when assessing different improvement experiments in ELV systems. Therefore, careful consideration was provided regarding the search keywords. The text searched for was limited to a combination of the following keywords using Boolean commands: simulation AND (dismantling OR dismantle OR disassembly OR dis-assembly) AND (vehicle OR vehicles OR car OR cars). Public databases were used, which are Google Scholar and Google, as well as other databases supported by Chalmers, which are Scopus and Web of Knowledge.

In addition, light was shed upon recent literature (after the year 2000) tackling mainly the dismantling of ELVs (not only depollution, compression and shredding). This is because of three reasons. First, although the company deals with both value cars (VCs) and non-value-cars (NVCs), the latter contributes less to the business. Therefore, investigating studies on facilities dealing with the former would be more value adding to the project. Second, the European directive issued the increase of a car's RRR rate up to 85% in 2006 (EC, 2007), which might mean that, at that moment, car dismantling facilities started altering their performance and conducting advanced control methods. Finally, there was an interest to pursue cases at a time where advanced DES software packages were utilized, which would have allowed the possibility of modelling complex systems.

2.2.2 Data collection: qualitative studies

The qualitative studies were based on three factors. The first is conducting interviews, and the second is observing the facility's performance via arranged field trips. Both helped in establishing the third factor, which is the VSM.

2.2.2.1 Interviews

Since the company's dismantling system was the main focus of this thesis, it was crucial to understand how the different processes, flows and resources interact with each other. Therefore, two main points of contact at the facility were established, which are the company's CEO and the shop floor manager. The CEO has spent more than 25 years in the business at the company, and the shop floor manager started working there for more than 10 years. As a result, both interviewees possessed both the knowledge and competence to explain in detail the dismantling business in general and the company's performance in detail. More than four interviews of four hours each on average were held between the interviewees and the authors to help understand the company's dismantling system. It is good to note though that the shop floor manager was also available most of the time to collaborate via phone calls.

On the other hand, the company has hired a lean consultant to improve its performance, where he conducted time studies featuring the different stations' cycle times, inputs and outputs. Therefore, a one hour meeting was held with him to clarify his findings, which served as a base for input into the VSM and the simulation model.

Finally, two 30 min interviews were held with two professors at Chalmers, with each specialized on "Lean Production" as well as "Production Logistics". The aim of these two interviews was to investigate the different MPC techniques that can be transferred from a stable environment both in demand and in supply, into an unstable one like that of ELVs. Specifically discussed were topics on sequencing and levelling of the cars being dismantled.

Note that most interviews were conducted face to face and semi-structured. This is because sometimes it was unclear what information might be relevant or not; thus, given the complexity of the dismantling system, it was difficult to know what it is the authors will be looking for exactly, especially when different processes are interconnected. Hence, conducting the interviews in a discussion-like manner while preparing some questions in advance seems like a good chance to explore other issues that might be important, which would provide a more holistic view (Whiting, 2008). The interviews were also recorded and transcribed afterwards to document the key findings.

2.2.2.2 Observations

Along with these interviews, there was a need to physically visit the facility and develop deeper knowledge of the company's dismantling system. Therefore, four visits were scheduled with the CEO and the shop floor manager to show the place around for the authors and physically observe the dismantling system.

2.2.2.3 Value stream map (VSM)

A VSM is a method that illustrates and analyses the logic of production processes, where the flows of material and information are graphically illustrated. It also represents an appropriate base for understanding how operations and activities are connected (Langstrand, 2016). The aim is not only to highlight how the current system works, but also to improve it by easily visualizing the non-value adding activities (Rother & Shook, 2003).

Both the interviews and the facility visits paved the way to establish a VSM of the current state, which shows how the different processes are interconnected. The VSM was continuously modified until the system was drawn precisely and accurately. It therefore represented a concrete base for the simulation model, where it was important to understand how everything works together before actually modelling the current state using the DES software.

2.2.3 Quantitative studies

2.2.3.1 Software selection

After getting the details of the processes from the lean consultant and establishing the VSM, it was time to model the current system via a DES software that provides the speed, flexibility and support needed for complex systems. A recent study on the ranking of several DES tools for commercial use based on their popularity was conducted and highlighted three main software packages topping the list, which are Arena first, Simul8 second and WITNESS third (Dias, Pereira, Vik, & Oliveira, 2011). The software Simul8 was selected as the DES software for this simulation study for two reasons:

1. The software encompasses drag and drop functionalities, which makes it easier to design and establish a system. Although Simul8 is supported with a coding language specific to it (Visual Logic), there were online references, blogs and tutorials one can always refer to.
2. Although Chalmers already possessed student versions of the software, there was a need to acquire a professional version to design complex processes. The later was relatively cheap against other software packages. Therefore, both of

the simulation members used two student versions and one professional version in total.

2.2.3.2 Bottleneck analysis via Simul8

After establishing the base model, it was necessary to analyse it for bottlenecks to improve it later on. Hence, it was important to utilize suitable analysis tools provided by Simul8. Therefore, two techniques were adopted:

- Visually observing the model's behaviour as time elapses to inspect which buffers are over occupied
- Compiling the results' reports from the processes, queues and resources into excel to inspect them mainly for their utilization and the average waiting times before, during and after them

2.2.3.3 System improvement techniques

Once analysing the system for bottlenecks was conducted, it was crucial at that point to improve the system. Conceptually, improvement scenarios were tested one at a time to assess their effect on the system's output and behaviour. Hence, a design of experiments (DOE) analysis was intrinsically adopted as a way of thinking.

Besides using conceptual techniques for bottleneck improvement through the literature, such as the theory of constraints (TOC), it was important as well to manifest the software's optimization capabilities into improving the dismantling system. Simul8 provides three main optimization tools, which are ("Simul8," n.d.):

- Scenario manager: it provides the possibility to change several parameters for several runs with a single click. Thus, several scenarios can be tested in one go.
- OptQuest: it is an optimization tool that inputs the desired outcome of the system, such as maximizing the number of parts in a warehouse, and outputs the optimized value of a selected variable, such as the cycle time of a dismantling station.
- Sensitivity analysis: it determines how sensitive certain design parameters are in respect to another output parameter. This is done by providing $\pm$ 10% changes in value of the design parameters, and determining the effect on the output parameter.

However, it appeared that the last two tools take so much of the simulation time and the available PCs' RAM capacity, which the authors lacked. Therefore, the scenario manager was adopted as the optimization tool used.

2.2.3.4 Warmup time

The parameter chosen for warmup analysis in all models was the end stock in the warehouse, which stores all parts that are dismantled and barcoded. This is because the main system's output sought after is the parts stored in the warehouse.

Using the warmup time as a condition to benchmark the base model with the scenarios and between the scenarios themselves places every simulation at different initial conditions. Hence, every simulation has its own properties that makes it efficient in its own way. Therefore, it was decided not to integrate the warmup time when comparing simulations against each other.

Rather the warmup time will be integrated when assessing the credibility of the base model, which should be realistic for the company's management to believe in relatively quick and tangible results. Moreover, the warmup time till be used when evaluating and plotting the main buffer's performance in the system. Hence, starting with no work-in-progress provides a misleading indication about the status of a certain buffer if the system's performance was not study.

2.2.3.5 Trials

Trials are a series of simulation runs performed with the same settings for all parameters other than random numbers, which are different number sets allocated to non-fixed distributions. To resemble real life scenarios where variability is almost always associated, running a simulation more than once is a must. Consequently, trials provide more accurate and reliable results with upper and lower bound limits. For example, having a result from one year is not enough; it might be a good year or a bad year. Therefore, running for several times ensures what type of output would be expected in a typical environment ("Simul8," n.d.).

Aspiring to have high levels of accuracy is admiring, but simulating many trials would be time consuming. Deciding on the number of trials was iterative, where two factors were taken into consideration, which are having tight tolerance limits and having a reasonable amount of time to compile these trials. Therefore, establishing a 10 trials run seemed enough as will be shown later in the results.

Applying these trials for every tested scenario may be too time-consuming and would occupy most of the computer's RAM. As a result, this was restricted to the base model, since the results from multiple trials will be benchmarked against the output from the real system for validation purposes. Note that the 10 trials run was conducted with warmup; this is because accuracy and precision were the crucial parameters sought after when being compared to the real system. If warmup was not included, then the model would experience lower values, since it did not initiate from a steady state situation.

2.2.3.6 KPI benchmarking

It is important to establish a quantitative base for comparing scenarios against each other and the base model. After conducting the interviews and going through the literature, it appeared there were four KPIs that needed to be monitored and hierarchically presented according to their level of importance, which are:

1. Investment cost: given that the company is medium-sized with less than 50 employees, it would be much more practical to provide recommendations with the minimum capital investments or running costs possible, unless significant return-on-investments (ROIs) are yielded.
2. Productivity: eventually, the company sells spare parts to customers, and determining whether an investment is worthy or not depends significantly on the profit derived from the number of parts barcoded.
3. Work-in-progress: cars occupy a significant amount of space when clustered together, and this prevents undergoing a smooth dismantling flow if congestion occurs. Therefore, ensuring lower buffer sizes provides better visualization of what is happening around the facility, better communication between the different stations and faster throughput. This allows processing requests quickly and paves the way for opportunities in investment in the emptied areas.
4. Resource utilization: it is important that the workload is levelled amongst the different operators to make sure everyone is pulling in the same direction, where maintaining high utilization rates is crucial to make the best out of every resource, especially the operators. Therefore, shifting capacity with appropriate planning techniques might be necessary to avoid having certain resources being

efficient on some stations, while others pending for work. As a result, this is related to the company's ability in creating value-adding work all the time.

The reasoning behind this hierarchical prioritization is that the company's management always wanted to secure the minimum investment possible, in which that was communicated clearly with the authors. The company then appeared to prioritize productivity, since it is by selling more parts that the company would be paying for the investment costs. Third, the number of ELVs waiting to be processed has a direct relationship with the value parts extraction rate, the speed of processing the customer orders as well as the space present at the facility, all of which are of crucial importance to the company. Finally, the company would like to have a situation of full capacity across its resources so that all marginal costs are justified.

These parameters however will represent a collective benchmarking base when comparing the most significant scenarios against each other. For example, if a certain scenario requires lots of investment costs, that does not mean it should be disregarded completely. Thus, the other three factors should be analysed collectively to indicate how worthy it is to invest in this scenario. The key takeaway therefore should be making the best out of the dismantling system given the same input of the number of cars across all the scenarios tested.

2.3 Project validity

Adopting the triangulated approach helps in giving the project a high level of credibility (Berlin & Adams, 2015). Especially since this was associated with weekly meetings with the project coordinator at the research centre, as well as a midterm evaluation with the supervisor and examiner at Chalmers, the authors' way of working was continuously supported and guided.

Touching on the model's validity, several problems were encountered, which delayed the complete validation for two weeks. This is because of two reasons related to the collected data ambiguity and Simul8's insufficient compatibility with excel.

2.3.1 Data ambiguity

The data received from the lean consultant was sometimes ambiguous for the authors to understand, and in most cases, there were very few inputs to many parameters, like the cycle times and number of parts extracted from the dismantling stations. However, generating suitable representations of quantitative input data should include as much samples as possible, especially for those varying significantly. As a result, collecting at least 230 samples is required to produce statistical distributions that mimic reality (Law, 2007; Skoogh & Johansson, 2008).

For example, some of the data in 2014 did not encompass more than a few sample values. Consequently, merging the data of 2013 with that of 2014 was necessary to establish distribution plots via Stat-Fit, the statistical analysis tool provided by Simul8. Upon consulting with the company's management, the project coordinator and the supervisor, it appeared that this methodology was sound, since not so many changes occurred between the years. This was necessary to do, since being charged by the lean consultant to clarify the data did not seem like a sound option at that time.

2.3.2 Simul8's incompatibility with Excel

Although Simul8's professional version provides advanced features, importing data and exporting functions to excel were not that user-friendly. In most cases, one must input the data manually, while compiling and filtering the output data would require building and coding a specific excel interface. This led to losing time and made the process of modelling and analysing experiments lengthier to perform.

2.4 Project ethics

Abiding by the highest ethical standards was essential to make sure that the results of this thesis are credible and repeatable. The authors however encountered a conflict of interest with the lean consultant hired by the company; however, he was gently requested by the CEO to take an hour of his time to explain his data to them. This thesis work seemed to jeopardise the consultant's role, since he believed he was already being paid for the work being investigated in this project. On one hand, the authors were working more on having better holistic flow improvements rather than pure process improvements, which were the main part of the lean consultant's work. On the other hand, the consultant's concerns were understandable, and this conflict was resolved by seeking guidance from the project coordinator and the supervisor as well as the company's management to figure out the best interpretations of the data. The authors also assured the lean consultant that their role is not to replace him, rather to get a holistic view about improving the system. Given this tension, it was decided to try and make the best out of the current situation without bothering the consultant.

Furthermore, there are four crucial factors to look after when it comes to ethics in a project work, which are invasion of privacy, lack of informed consent, deception and harm to participants (Bryman & Bell, 2015). To ensure the interviewees' privacy was not invaded, they were only contacted during normal working hours and without touching on personal matters rather than business. To prevent deception, all stakeholders were informed about the purpose of this thesis beforehand, what methodologies are used, and what the results will be used for. As with respect to the issues of consent and harm to the participants, permission was sought to record each interview, after which it was transcribed. Finally, confidentiality agreements were signed by both authors to agree on not sharing key information with stakeholders other than:

- The company's CEO and shop floor manager
- Supervisor and examiner at Chalmers
- Project coordinator at the research centre

3 Theory

While trying to approach this project literature-wise, four areas were identified as the most important to search for, which are:

- Identifying what DES is, and why it is suitable for the case study at hand
- Implementing bottleneck identification methods to help improve the dismantling system
- Highlighting the most critical issues to consider when improving flows
- Searching for state of the art practices in improving car dismantling systems via DES

3.1 Discrete event simulation (DES)

Simulation allows fast learning and low cost testing of a system's behaviour (Hosseinpour & Hajihosseini, 2009), rather than conducting real-life experiments for every possible scenario. DES is a type of simulation that is convenient to adopt in a system whose state changes at a particular time point and then remains in that state for some time until it changes again. Hence, key parameters change in discrete times and by discrete steps (Özgün & Barlas, 2009), which is the case for car dismantling, where cars and parts tend to stay in different processes and queues until they pass through other processes again. Moreover, a DES model can handle a system's dynamics to mimic the real processes' states and behaviours (Westling, 2015).

Other simulation types exist, such as continuous simulation, where a system's state changes continuously over time (Özgün & Barlas, 2009), as in the case of evaluating leakage of water tanks ("What is the exact difference between Continuous, discrete event and discrete rate simulation?," 2014).

3.2 Theory of constraints (TOC)

In an effort to continuously improve a system, it is important to define its goals and KPIs first, and then address the system's problems in a structured manner to continuously improve it. TOC serves the latter objective and is based on five steps as follows (Mabin, 1999):

1. Identify the constraint: identify the weakest link, commonly referred to as the constraint or the bottleneck, that is hindering the system's goals and KPIs. Some of the popular methods to identify a system's constraints are (Roser, Nakano, & Tanaka, 2003):
    a. Utilization method: the resource with the highest active time is identified as the bottleneck.
    b. Waiting time method: the waiting time the loads stay in the queues is highlighted, where high waiting times identify the next resource as the bottleneck.
2. Exploit the constraint: achieve the best possible outcome from the constraint by removing unproductive work.
3. Subordinate other activities to the bottleneck: smoothen the workflow and avoid inventory accumulation as well as having the constraint waiting for work.
4. Elevate the constraint: increase the capacity by adding more equipment or operators, etc.
5. If in any of the previous steps a constraint is broken, go back to step 1: evaluate if another operation has become the new constraint.

Applying TOC represents a base for using bottleneck improvement tools and methodologies provided by the software used. Therefore, recognizing the different techniques provided by Simul8 serving this context are important as was presented in Section 2.2.3.2 and Section 2.2.3.3.

3.3 Flow efficiency vs. resource efficiency

Since the aim of TOC is to improve a system's performance, and hence, efficiency, one must recognize the different approaches to do so from an operational strategy viewpoint. There are two approaches mostly touched upon in the literature to reach the optimal state; the first is being flow-efficient and the second is being resource-efficient as shown in *Figure 3*.

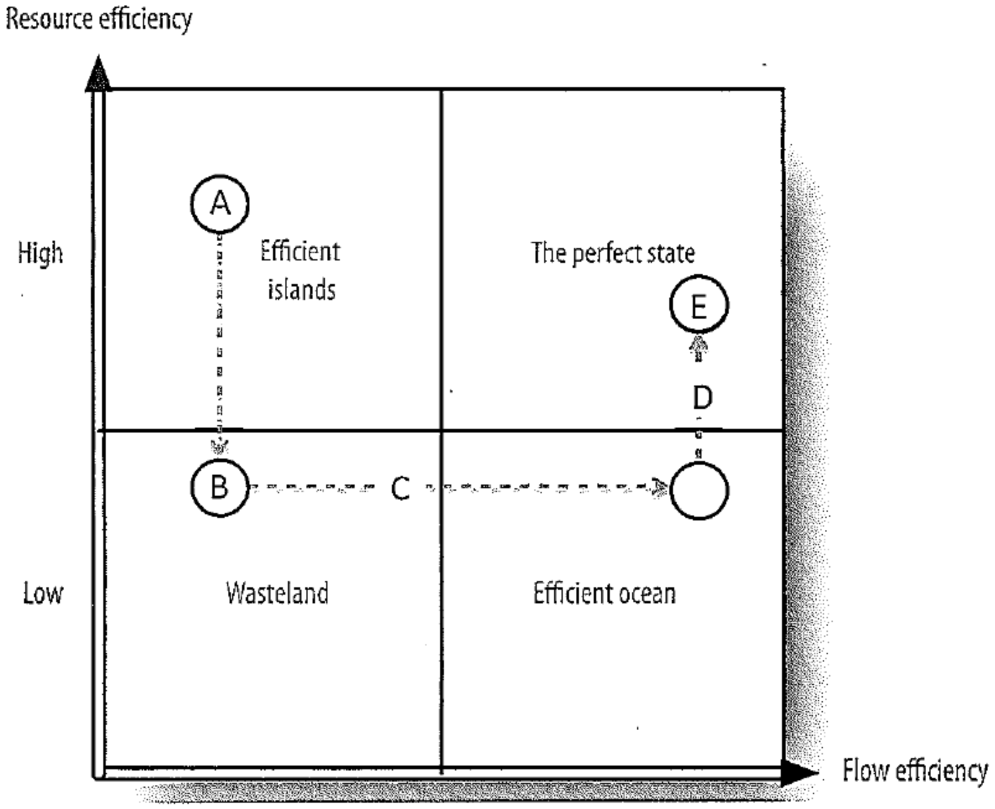


Figure 3. Steps to follow in achieving a lean operation strategy (Modig & Åhlström, 2012).

Being resource-efficient implies making the best out of each process alone, without taking into consideration how the other processes connected to it are performing. Being flow-efficient suggests connecting the different processes in an efficient way to have a smooth flow, and hence having no congestion, to make the best out of the system as a whole.

Prioritizing the former is essential to apply a lean operation strategy to balance capacity utilization, ensure flexibility, have a stable workload and establish robust control over the system. This requires a base that promotes teamwork, creation of routines, standardization and visualization (Modig & Åhlström, 2012).

In addition, focusing on the flow and reducing inventory as well as work-in-progress allows lean plants to occupy less space (Dickson, Singh, Cheung, Wyatt, & Nugent, 2009). This is essential in car dismantling facilities, where the number of cars present must be controlled due to cost and space restrictions. This helped in figuring out the essential KPIs when comparing different improvement scenarios, see Section 2.2.3.6.

3.4 Layout optimization in car dismantling via DES

3.4.1 Dismantling flow types

In general, there are two types of ELV dismantling systems, the first one is the disassembly line type, as shown *Figure 4* on the left hand side, and discrete muli-point disassembly type, as shown on the right hand side below (Zhou, Dai, Cao, & Guo, 2006).

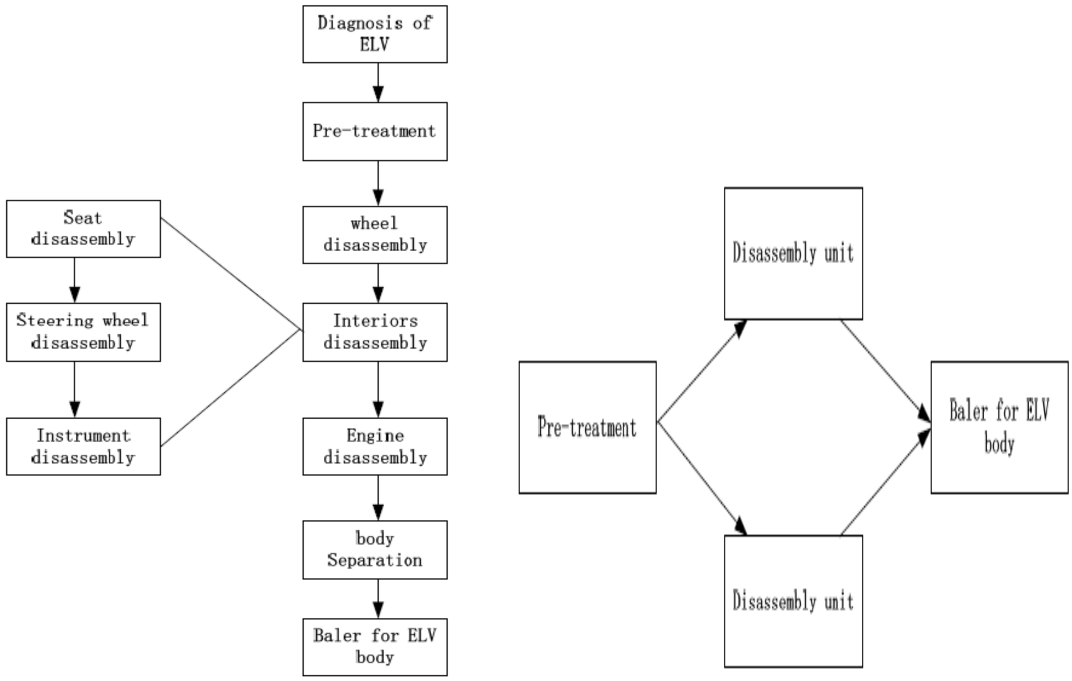


Figure 4. Disassembly layouts for ELV dismantling systems; line type on the left and multi-point type on the right (Zhou et al., 2006).

There is limited literature on the actual layout details that are presented in modern car dismantling facilities. One study designed a dismantling system using the software Arena to build nine consecutive work-stations constituting of (Sohn & Park, 2014):

- Reception: ELVs are received, parts are selected and the dismantling sequence is planned.
- Pre-treatment: fluids are drained and tyres as well as batteries are removed.
- Pre-station: airbags, hood and glass are removed.
- Station-1: outer parts are extracted, such as doors, lamps and bumpers.
- Station-2: inner parts are removed. This includes steering wheels, dashboards, seats and belts.
- Station-3: parts in the engine compartment are extracted, such as radiators, A/C, alternators and oil/water pumps.
- Tilting station: parts in underbody are removed. This includes axles, shock absorbers, starts motors and fuel tanks.
- Part station: parts are registered.
- Press station: the ELV is compressed for shredding.

Nonetheless, the system was not fully implemented as there were no reported results about the system's efficiency and performance, especially when comparing the simulated model with real-life applications.

Although there appears many efforts regarding layout optimization of vehicle assembly using DES (Ferreira et al., 2012), all proposed layouts in the dismantling literature appear to share the following stages and sequence (Acaccia, Michelini, Penzo, & Qualich, 2007; Sohn & Park, 2014):

- Reception and inspection of ELVs
- Depollution of fluids
- Parts dismantling
- Scrap body compression
- Assessment and management of reused parts

3.4.2 Challenges facing dismantling facilities

An analysis of one of the biggest dismantling stations in Poland was conducted using VSM, SIPOC (suppliers, input, process, output and customer) diagrams and RPA (rapid plant assessment). The paper highlights that there are two key challenges that faced the facility, which are (Kosacka & Golińska, 2014):

- Unnecessary stock elimination
- Reducing the dismantling cycles by eliminating waiting times and unnecessary transport

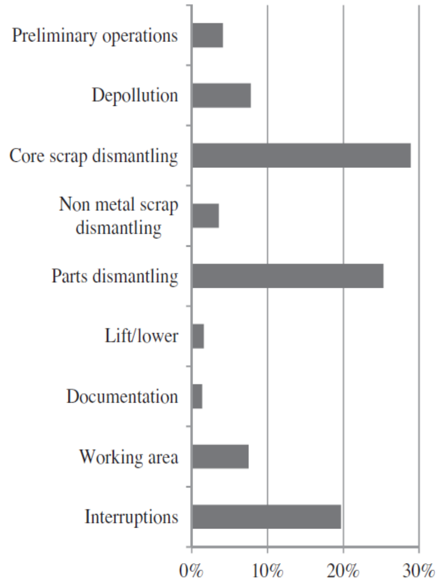
Moreover, and upon a detailed study lasting three months of 70 different ELVs passing through depollution and dismantling processes in different facilities, it is highlighted that the time and resources needed to peerform each operation is one of the most critical parameters influencing the ELVs' treatment. This is affected by the vehicle's class, brand, year of production and conditions. Therefore, high flexibility is needed within the facility to keep the plant's performance robust. It is worthy to note that the plants inspected had their ELVs processed in a single station or in a two-step process (e.g. first depollution then dismantling). The paper also highlights the time allocation percentages across the different value-adding treatment phases, see the VSM in Appendix I, where dismantling comes first with approximately 53%, while depollution comes second with approximately 8% as shown in *Table 2* (Berzi, Delogu, Giorgetti, & Pierini, 2013).

On the other hand, another model was built within Arena by comparing four different existing disassembly layouts to come up with a new system for productivity improvements. The layouts share the following sequence of disassembly operations, where operation times and number of workers are presented in *Figure 5* (Sim, Kim, Park, & Park, 2005):

- Operation 1: checking components for disassembly
- Operation 2: explosive components disposal (e.g. airbags)
- Operation 3: setup for fluids draining
- Operation 4: draining of fluids, such as oil, fuel, refrigerant, coolant and brake fluid
- Operation 5: exterior disassembly, such as bumpers
- Operation 6: interior disassembly, such as seats
- Operation 7: engine and transmission disassembly
- Operation 8: CB compression

Table 2. Total time allocation of treatment phases (Berzi et al., 2013).

Category	Description	Operation detail
A	Preliminary operations	Removal of other waste Visual Examination
B	Depollution	Fuel removal Battery removal Lubricant drainage Fluids drainage
C	Core scrap and mechanics dismantling	Wheels removal Radiator removal Catalytic converter removal Engine removal Suspension removal
D	Non-metal scraps removal	Glasses Bumpers Other
E	Parts dismantling	Selection and catalogation Mechanics Body Interiors
F	Lifting and lowering operations	Up Down Adjustments
G	Documentation compiling	Starting Reporting
H	Working area management	Vehicle removal Cleaning Parts removal
I	Interruptions	Personal break Hitch Other job



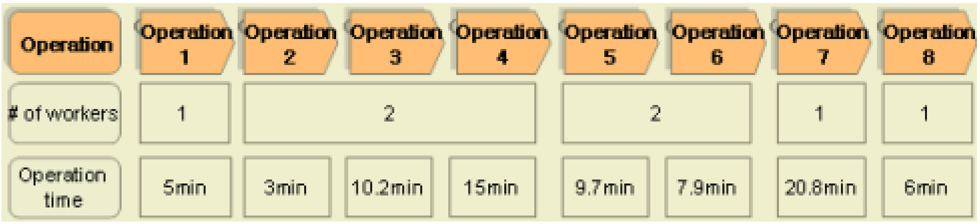


Figure 5. Line layout disassembly composition (Sim et al., 2005).

Three of the layouts are line-oriented, while one of them is cell-based. The layouts also differ in how cars move between stations, for example using forklifts, hangers or cart-on-track conveyor system.

The proposed simulated disassembly system appoints non-powered carts to move the vehicles, and pushing machines to load them into compression in a line layout dismantling system. The proposed improvements were based on increasing the capacity of the bottleneck operation 7, the engine and transmission disassembly, and balancing out the workloads as shown in *Figure 6*. Nevertheless, no quantitative assessment of the new system's potential in increasing productivity was provided.

Although there were efforts on studying line layout dismantling systems, it is mostly emphasized that they would experience critical inventory and scheduling issues due to the high degree of uncertainty between the parts' demand and the type of dismantling output (Tang & Zhou, 2001). As a result, sequencing and leveling of products may not be possible in unstable environments (Jonsson & Mattsson, 2011).

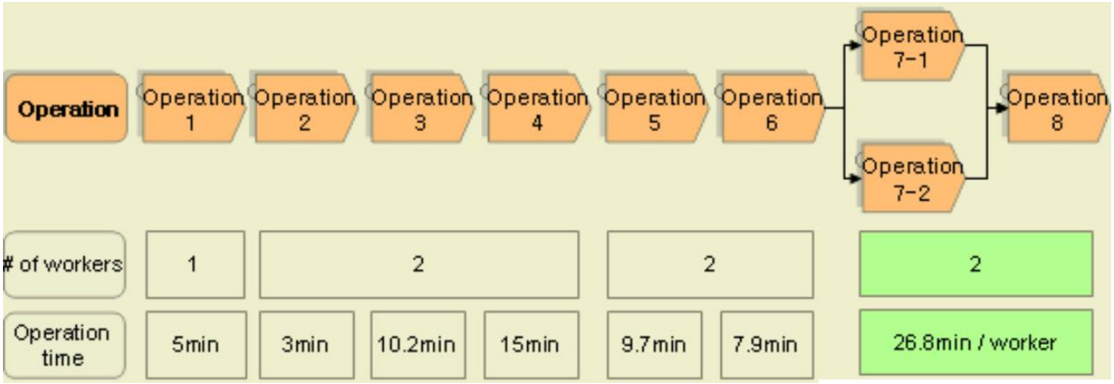


Figure 6. The proposed line layout (Sim et al., 2005).

This is why for systems experiencing a relatively low volume with high variances, a flow shop – and not a line flow or job shop – should be adopted as shown in position number 2 in the product-process matrix below (Olhager, Rudberg, & Wikner, 2001).

		Product mix type: I. low volume, non-standard, one-of-a-kind	II. low volume, many products	III. high volume, few major products	IV. high volume, standard, commodity
Process type	I. Job shop	①			
	II. Flow shop/ batch		②		
	III. Line flow			③	
	IV. Continuous line				④
Characteristics	Typical order winner[1]	Flexibility	←	→	Price
	Typical order penetration point[2]	Engineer-to-order	Make-to-order	Assemble-to-order	Make-to-stock
	Capacity strategy[3]	Lead	←	→	Lag
	Planning strategy[3]	Chase	←	→	Level

Figure 7. Product-process matrix (Olhager et al., 2001).

This is supported by another theoretically case-based simulation study using Arena and OptQuest. The study recommends the island type dismantling system (the multi-point disassembly type) as the most appropriate configuration for a dismantling system after considering processing amount, economical efficiency, effectiveness and limited capacity. This is because the island type does not require big initial investments and is not affected by the car's variant model, unlike the line layout. The design characteristics of dismantling ELVs using both types is presented in *Table 3* (Park & Sohn, 2004).

Table 3. Island type vs. line type ELV dismantling systems (Park & Sohn, 2004).

	Island type	**Line type**	**Automated system**
Feeding	forklift	conveyor	conveyor
Platform	lift	work station	workstation
Handling	hoist, forklift	rotating facility	rotating facility
Operator	human	human	sensors/auto, mechanism
Draining	individual tool	drain station	drain station
Information	vehicle	vehicle/process	optimal process
Merits	flexibility/economic	speed	speed/ unmanned

4 Results and Analysis

In the following sections, the results are first presented by touching on the interviews conducted with the professors at Chalmers. Second, the base model results will be highlighted starting from establishing the VSM, defining the simulation objects within Simul8, stating the associated assumptions and finally elaborating on the simulation model. Third, the scenarios will be explained, analysed and concluded by summarizing their key findings.

4.1 Expert input

As illustrated in Section 2.2.2.1, two interviews were conducted with two professors featuring lean production and production logistics. As the authors came across the application of many different MPC techniques from vehicle assembly businesses, it was interesting to investigate how these techniques can be transferred from assembly to disassembly.

The interviewees highlighted that the common MPC techniques featuring for example sequencing and scheduling as well as pull methods, such as Kanban and CONWIP, normally require a stable environment to be applied. The interviewees thus emphasized the importance of this simulation, since improvement approaches in this setting require a more holistic understanding of how the car dismantling business works in supply, production and demand. This made it interesting to actually try and plan the work environment in a robust way, especially when it comes to shifting capacity between different workstations.

Nonetheless, both stressed upon the importance of talking to the operators working in the facility, especially the blue-collar workers, to develop a deeper understanding of how processes work, how they are connected and the best possible ways for improvement. Consequently, adopting the values of teamwork and respect for people, which are the cornerstones of lean thinking, may be much more applicable in this context than the methods and tools that are usually followed.

4.2 Base model

4.2.1 VSM

To understand the basics of the car dismantling system at the company, a VSM was compiled as shown in *Figure 8*. Since there are two main entities combined, which are the cars from one side and parts extracted from the cars on the other, it did not seem suitable to visualize the lead times and the processing times that are usually presented under common VSMs as shown in *Figure 9* (Carmignani, 2017).

There are three main paths that constitute the VSM at the company, which are:

- Car inbound path
- VCs path
- NVCs path

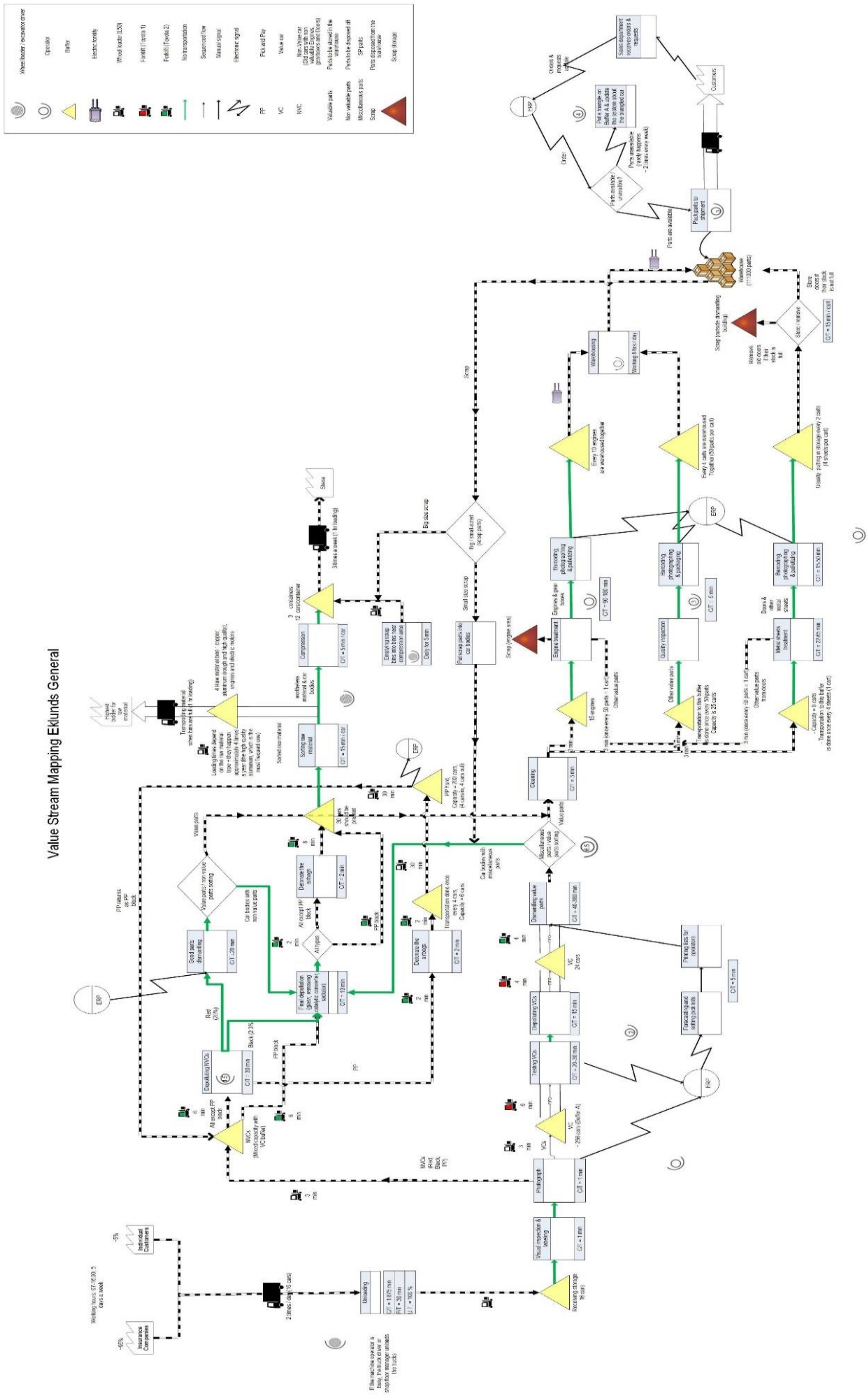


Figure 8. A VSM of the dismantling system at the company (thick green lines indicate processing within the same station).

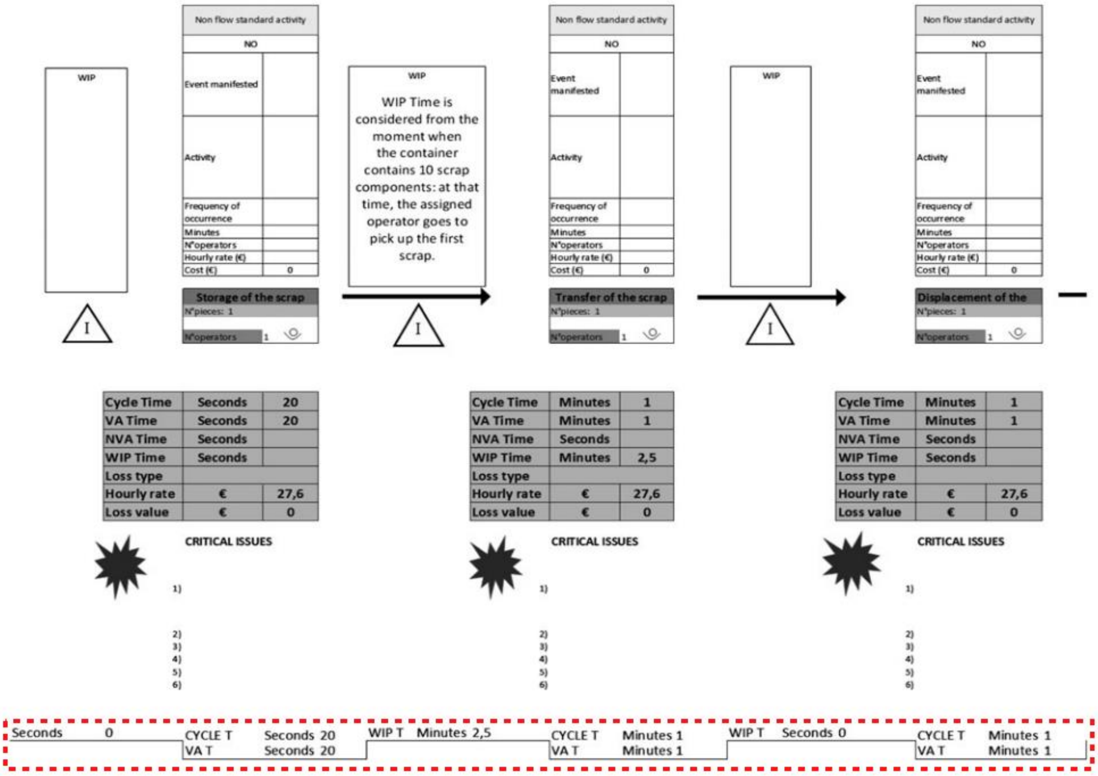


Figure 9. A typical VSM with lead time and processing time indicators as shown in red (Carmignani, 2017).

However, before explaining the paths, it would be convenient at this point to show briefly the facility's layout. *Figure 10* illustrates the layout of the facility composed of the most critical buffers and stations.

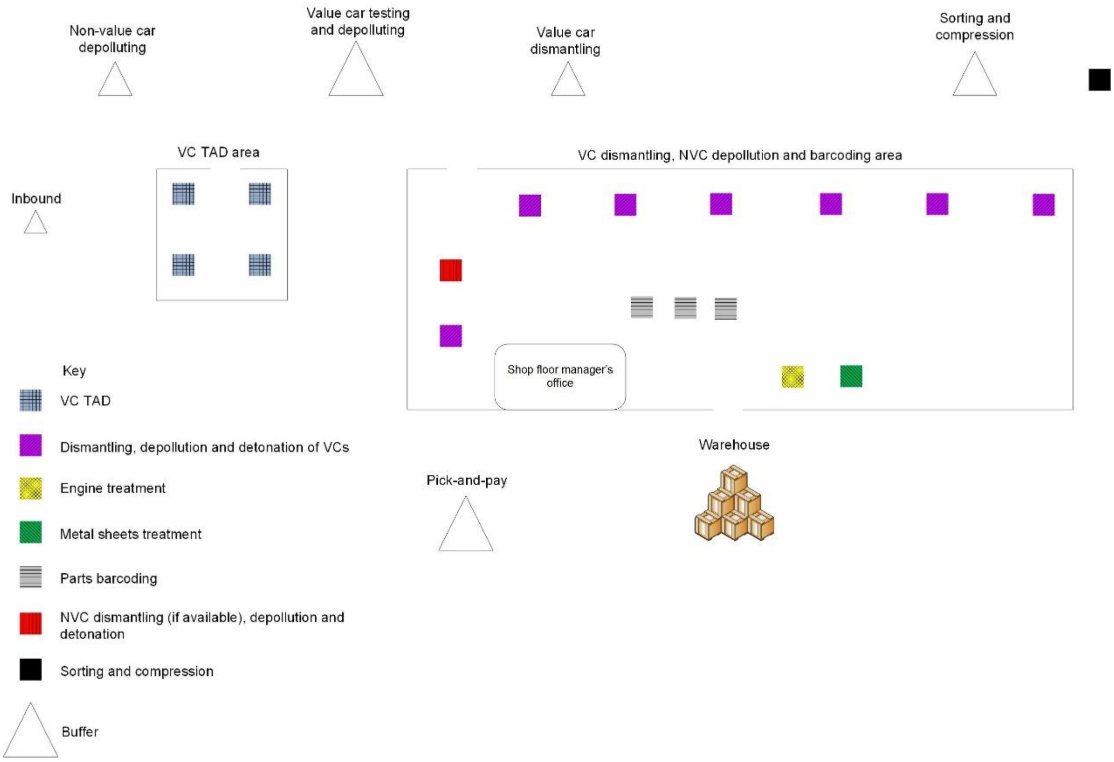


Figure 10. The facility's layout.

The facility consists of two main buildings. The first one stands for testing and depollution (TAD) of VCs, where there are four main stations. While the sorting and compression area is outside, the other building encompasses dismantling of VCs, barcoding VPs as well as depollution of NVCs. Basically, it consists of:

- Seven dismantling stations for VCs
- One NVC depolluting station
- Three barcoding stations
- One metal sheet treatment station
- One engine treatment station

Due to the unavailability of architectural drawings, the layout was drawn by illustrating as much as possible the composition of both buildings.

4.2.1.1 Car inbound path

Two trucks arrive two times a day at 13:00 and 15:00 o'clock with 8 vehicles each. The truck is unloaded into a receiving storage by either the wheel loader driver if he is not busy, or by the truck driver or the shop floor manager. After that, the shop floor manager will inspect, label and photograph the vehicles. In the labelling process, vehicles will be divided into distinct colours according to their status, where the picklist is set by evaluating and forecasting the sales and requests of VPs. All ELVs would be categorized as in *Table 4*. Note that VCs and NVCs will follow different paths since they pass through different processes.

Table 4. Types of ELVs arriving at the company.

ELV type	ELV category	Description	Percentage (%) of inbound cars
Blue	VC	The first car of a certain model that is dismantled for VPs. Everything is taken out and documented carefully. They have the highest number of VPs	2.29
Yellow	VC	The car will be dismantled for VPs	16.19
White	VC	The car will be dismantled for VPs, but the engine will not be dismantled	54.49
PP (Pick-and-pay)	NVC	Cars that are depolluted then put into a yard for some time for private customers to dismantle parts directly from, where they can purchase at lower prices	10.51
Black	NVC	Cars that are depolluted then compressed with their non-value parts (NVPs)	6.01
Red	NVC	Like black cars, but operators are given 20 min to find and dismantle as many VPs as they can	10.51

4.2.1.2 VCs path

After photography, VCs will be taken by the wheel loader and its driver to a VC testing and depollution buffer, where they will stay until a manually guided red forklift comes to pick them up and bring them to the VC TAD area. The VC TAD area employs two operators with two stations each. Here, each operator inspects the condition of different VPs in the car by following a list provided by the shop floor manager. Afterwards, he connects the cables for depollution, leaves the car to drain its fluids, and executes the same process on another car while waiting for the first car to finish draining. After fluids draining, the cables are disconnected and the car is carried with the same forklift to the VC dismantling buffer preceding the dismantling area. The area features seven stations with:

- Three employees dedicated to dismantling of VCs. Being dedicated means that the operators work fully on that process without assisting in other stations.
- Four employees doing dismantling and other activities as follows:
    - One operator helps in engines and gearbox dismantling when the inbound buffer of that station exceeds 15. He also assists in barcoding small parts when the inbound buffer exceeds 800 (about 16 carts).
    - One operator helps in the NVC depollution if the NVC depollution buffer exceeds 21 NVCs.
    - Two operators work in VC TAD area, and they help in dismantling when the buffer preceding VC dismantling is more than 24 VCs.

To start the dismantling process, the operator brings the vehicle inside with a manually guided green forklift. The dismantling process experiences many variations, from car model to type of crash; consequently, the dismantling process can take from 40 mins to several hours. This results in two distinctive paths, one for newly dismantled VPs, including small parts, metal sheets, engines and gearboxes, and the other for CBs whose parts were dismantled.

The VPs will be transported in carts for cleaning and from there, they will be split into three categories as follows and as shown in *Figure 11*:

- Engines and gearboxes: they will be disassembled, barcoded, photographed and put into pallets in the engine station for warehousing. The station features one dedicated operator and another operator who helps out.
- Metal sheets: this includes doors and non-door parts, such as bumpers and hoods. The same process is repeated similar to that of the engine station; however, only one operator is employed.
- Small parts: they are parts that do not belong in the first two categories, such as lamps and shock absorbers as well as small parts extracted from the doors, engines and gearboxes. These parts will pass through any of three barcoding stations featuring two dedicated employees and one who helps out, where each operator does quality check followed by barcoding, photography and palettizing.

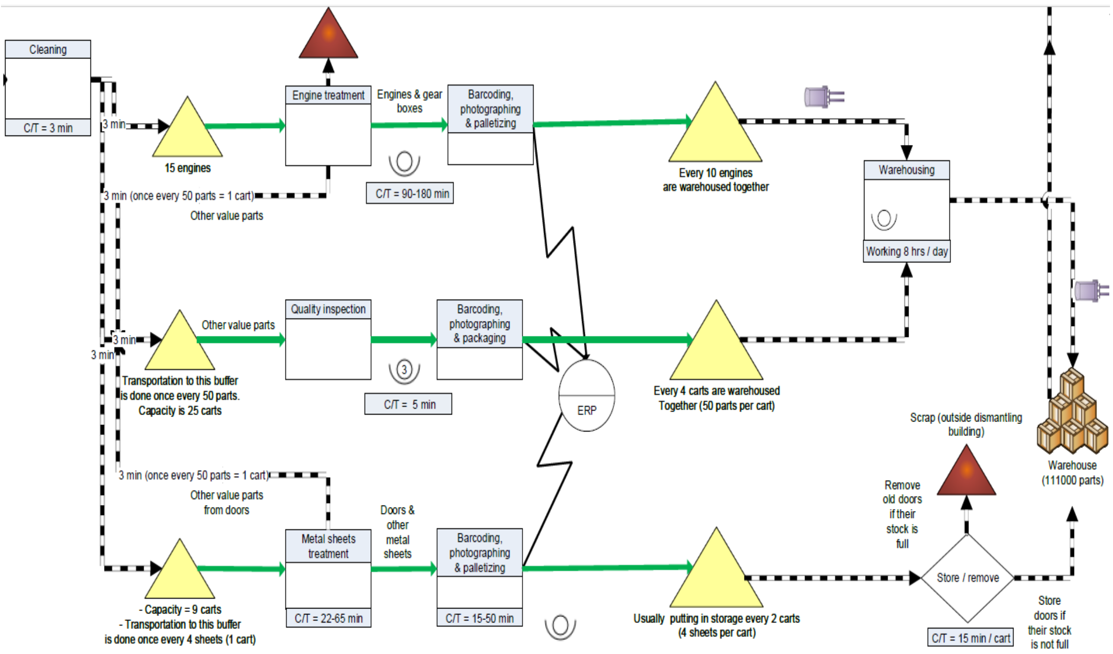


Figure 11. Barcoding paths of all parts at the company.

All VPs will stay in a buffer after every barcoding station, until they are finally transported to the warehouse by a warehousing operator. This is except for the metal sheets, where the operator of that station does the warehousing himself, and removes old metal sheets which do not fit anymore to be put in special bins.

The CBs with their NVPs stay in the dismantling station, while the same operator does the final depollution. This includes removing the glass windows, catalytic converter and the radiator. After that, he drives the CB outside, detonates the airbags and leaves it for the wheel loader driver.

From there, the wheel loader driver uses an adapted excavator to extract raw material, such as copper and aluminium, which are deposited in their proper bins. These materials are then sold and loaded to the highest bidder. After that, he puts the CB in the compressing machine to be compressed along with other parts he gathered from special bins, which includes parts extracted from the car but of no value, such as leftovers from engines and gearboxes, and old doors that do not fit in the warehouse anymore. The result is a cube of metal that is stored in a specific container, waiting for Stena, a Swedish recycling company, to collect it with a truck.

4.2.1.3 NVCs path

After labelling, the NVCs will be taken by the wheel loader to the NVC depollution buffer, after which they will be depolluted. The area employs one dedicated employee along with another operator who works in dismantling of VCs, but helps out if the NVC depollution buffer exceeds 21 cars. The car will stay in that buffer until it is picked by the green forklift into the NVC depolluting station. The type of processing after depollution depends on the NVC's type as follows:

- Red cars: the operator spends 20 min to look for parts he might think are worth dismantling. The parts will be put on a cart then cleaned to be further transported to the barcoding area. After this process, the car follows the same procedure of that of VCs when it comes to final depollution, airbag detonation, raw material sorting, compression and shipment.

- Black cars: they follow the same process as red cars; however, the operator will not spend time to search for parts worthy of dismantling.
- PP cars: the operator detonates the airbags and uses the green forklift to place the car in a buffer. When that buffer reaches four PP cars, the wheel loader driver comes and picks them up via the wheel loader to put them in the PP yard. In turn, the wheel loader driver takes other four cars out of that area, since the capacity of the yard is only 200 cars, and transports them again back to the NVC depollution buffer for final depollution then raw material sorting, compression and shipment.

4.2.2 Base model objects in Simul8

Any simulation in Simul8 builds on connecting some objects together (“Simul8,” n.d.). The most important which are relevant to be elaborated on are:

- Start point: this identifies the type of loads (work items) entering the system and when that happens.
- Queue: this is the place where work items wait to be processed.
- Activity: it embodies processing the work items.
- Resource: it can be an operator or machine, etc.

In an effort to display the results in a well-presentable way, and to highlight which parameters mostly changed between one scenario and another, it is important to agree upon certain abbreviations featuring the most important objects. *Table 5* and *Table 6* elaborate on the abbreviations related to the associated resources and queues respectively. However, some of these abbreviations might be different from the simulation model names, see Appendix II, to make it easier for the reader to understand the main idea behind these abbreviations, and for other users of the simulation models to know what has changed.

Table 5. The most significant resource abbreviations assigned to the base model.

Resource abbreviation	Description
R_TruckDriver	The driver of the truck bringing cars into the facility
R_ShpFlrMngr	The shop floor manager
R_WL_Driver	The wheel loader driver
R_pool	A pool of the resources R_TruckDriver, R_ShpFlrMngr and R_WL_Driver, in which one of these idle operators helps in unloading cars at the inbound parking area using the wheel loader
R_WL	The wheel loader
R_Forklift1	The red forklift used in VC TAD
R_TAD_Dism	One of the two operators responsible for VC TAD. He helps in VC dismantling if the inbound buffer to dismantling exceeds 24 cars
R_Dism	One of the three dedicated operators responsible for VC dismantling
R_Barc_Eng_Dism	The operator responsible for the first dismantling station. He helps in barcoding if the buffer preceding barcoding exceeds 800 parts. He also helps in engine and gearbox dismantling if the inbound buffer to that station exceeds 15
R_NVC_Dism	The operator in charge of VC dismantling. He also helps in NVC depollution if the inbound to that buffer exceeds 21 cars
R_Eng_Trtmnt	The dedicated operator responsible for engine and gearbox treatment, dismantling and barcoding

R_Barc	One of the two dedicated operators responsible for barcoding parts
R_MS_Trtmnt	The dedicated operator responsible for metal sheets treatment and barcoding as well as further dismantling of doors
R_Warehouse	The warehousing operator
R_Forklift2	The green forklift used in the depollution of NVCs and in VC dismantling
R_NVC	The dedicated operator responsible for NVC depollution
R_Excavator	The excavator used to sort raw material from the ELVs prior to compression
R_Compressor	The compressor machine used for compressing the cars into metal cubes

Table 6. The most significant queue abbreviations assigned to the base model.

Queue abbreviation	Description
Q_Receiving	The inbound storage. It has a capacity of 16 cars
Q_NVC_Depol	The buffer preceding depollution of NVCs. It has a capacity of 21 cars.
Q_PreTAD	The buffer preceding VC TAD. It has a capacity of 256 cars
Q_PreDism	The buffer preceding dismantling. It has a capacity of 24 cars
Q_PreYard	The buffer containing the PP cars waiting to be transported into the yard. It has a capacity of 4 cars
Q_PP_Yard	The PP yard. It has a capacity of 200 cars
Q_PreBarcParts	All small parts waiting to be barcoded. It has a capacity of 25 carts (1,250 parts)
Q_PreEng_Trtmnt	The buffer containing the engines and gearboxes to be dismantled. It has a capacity of 15 engines
Q_EngParts	The buffer containing the small parts extracted from the engines and gear boxes
Q_PreMS_Trtmnt	The buffer containing the metal sheets to be barcoded and/or further dismantled. It has a capacity of 9 carts (36 metal sheets)
Q_MS_Doors	The buffer of small parts that were dismantled from the doors
Q_PostBarcParts	The buffer of parts waiting to be warehoused
Q_Warehouse	The warehouse stock
Q_PreSorting	The buffer containing the cars to be sorted from raw material then compressed. It has a capacity of 30 cars
Q_Containers	The containers containing the compressed metal cubes post compression

To make testing scenarios robust, certain fixed numbers were assigned to variables for easier modification later on via the scenario manager. Therefore, the following variables are assigned in the table below.

Table 7. The most significant variables assigned to the base model.

Variable abbreviation	Description
Var_NVC_Depol	It has a value of 21. It stands for the condition when R_NVC_Dism helps in depollution of NVCs given that Q_NVC_Depol exceeds 21 cars
Var_PreDism	It has a value of 24. It stands for the condition when the two operators, R_TAD_Dism, help in VC dismantling given that Q_PreDism exceeds 24 cars
Var_ PreBarcParts	It has a value of 800. It stands for the condition when R_Barc_Eng_Dism helps in parts barcoding given that Q_PreBarcParts exceeds 800 parts

Building on these definitions, *Figure 12* illustrates the layout of the facility composed of the abbreviations of the associated buffers. Thus, this will be useful for the reader when referring to the buffers' names in later sections.

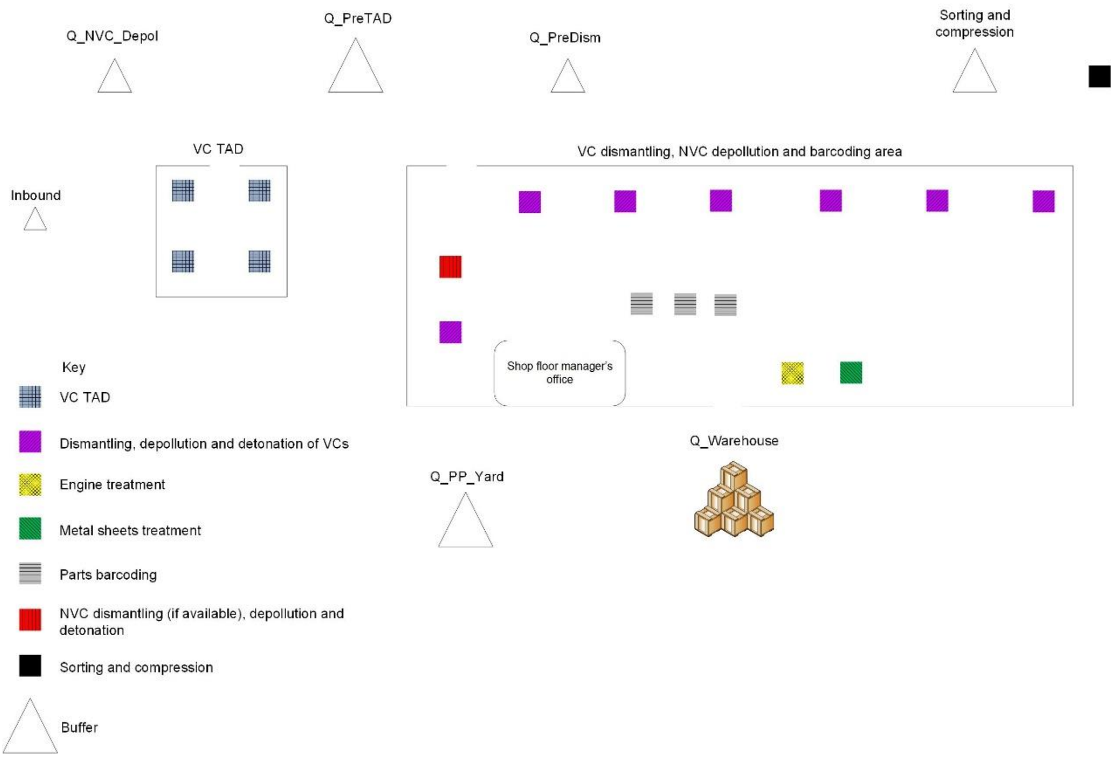


Figure 12. The facility's layout with the buffers' abbreviations.

4.2.3 Assumptions

The current dismantling system is a flexible one. The majority of the operators know how to perform at all the different stations. Depending on their availability, the shop-floor manager must adjust and allocate the operators every day to keep the system levelled. The major assumptions coded into the model are as follows to mimic the real behaviour of the system:

- Three operators work dedicatedly at the dismantling area.
- One operator from the VC dismantling area will help in NVC depollution when Q_NVC_Depol is more than 21 cars.
- One operator will operate at three different stations, depending on buffer sizes. If Q_PreBarcParts is bigger than 800, then he will do barcoding. If

Q_PreEng_Trtmnt exceeds 15, then he will work at the engines station. Otherwise, he will do dismantling.

- The two operators from VC TAD will do dismantling when Q_PreDism is more than 24.
- Q_PreTAD has the initial condition of having 80 VCs; this value was iterated in the base model to end up having a value at the end of the simulation close to 256 cars, which is the current situation at the company and the maximum capacity of that buffer. The reason that the buffer was set not to have 256 initially is that it took lots of instability in the real system to reach the current state of 256 cars. Hence, the shop floor manager shuffles the capacity continuously to maintain that level, which is not possible to model using DES. As a result, the normal way of working was what is intended to model. The colour distribution of the 80 VCs was set according to *Table 4*, where the blue cars comprise 3.13% of all VCs, the yellow cars 22.19% and the white cars 74.68%.
- The real system's values that will be used to benchmark against the simulation models feature the following data received from the lean consultant:
  - The number of inbound cars is 3,270.
  - The number of barcoded parts is 52,429.
- Although a normal year at the company constitutes of 52 working weeks, the real system experiences non-documented variation in some weeks regarding the supply number and type of cars as well as the number of dismantled parts. To resolve the issue of modelling the number of cars arriving every week, the shop floor manager was consulted to provide reasonable approximations to be an input to the simulation model. He approximated that 16 cars arrive every day in two trucks. Given five working days a week, it would take the simulation model 40.95 weeks to reach the real system's annual inbound of 3,270 cars. As a result, from now on, one year according to the real system will equal 40.95 weeks in the simulation model. To eliminate the confusion about the time unit used, the number of months will be mostly communicated. Conversely, it was agreed with the project coordinator that benchmarking the simulation model's output against the total number of parts barcoded would be more realistic on an annual basis rather than on weekly basis, due to the same issue of variation. Hence, plotting the number of inbound cars and barcoded parts for the real system every week was not possible.
- Even though the real system is composed of 17 workers (4 in VC TAD, 7 in VC dismantling, 1 in NVC depollution, 3 in barcoding, 1 in engine dismantling and 1 in metal sheets dismantling), according to the shop-floor manager, three operators are absent on average due to parental leave or sickness. Given that the availability option in the software is individual-oriented focusing on when each operator is available rather than collective unavailability of individuals at a certain point in time, it was modelled that three operators are always sick, two in dismantling and one in barcoding. The shop floor manager acknowledged this approximation, which led to his justification of why the two VC TAD operators help out in dismantling and one dismantling operator helps out in barcoding. Therefore, the model is made up of 14 operators with an availability of 100%.

4.2.4 Simulation model

4.2.4.1 1 Trial without warmup: Model Zero

Model Zero refers to the base model without warm up time. This model is utilized for benchmarking with other scenarios, since a prerequisite for comparing scenarios is to have the same initial conditions at all the entities of the simulation. The following table presents the KPI summary results for Model Zero, where:

- Items entered stands for the total items that entered the buffer.
- Current contents represent how many items there are in the buffer at the end of the simulation.
- Maximum queue size emphasizes the maximum number of items that stayed in the buffer throughout the simulation time.
- Average queue size stands for the average number of items that are present in the buffer throughout the simulation time.

Table 8. KPI summary results for Model Zero.

Simulation Object	Performance Measure	Run Result	% Deviation from real system's output
Q_Warehouse	Items Entered	53,640	2.31
Q_PreBarcParts	Current Contents	784	-
	Maximum Queue Size	1,041	-
Q_PreDism	Current Contents	22	-
	Maximum Queue Size	24	-
Q_NVC_Depol	Current Contents	0	-
	Maximum Queue Size	8	-
Q_PreTAD	Current Contents	194	-
	Maximum Queue Size	206	-
	Average Queue Size	114.78	-

Also, *Figure 13* highlights that the model reaches a steady state on week 11 based on the number of parts entering the warehouse stock (Q_Warehouse), see Section 2.2.3.4. Further analyses showed that all the scenarios took 11 weeks (three months [i]) to reach steady state; hence, this warmup time can be adopted as standard for all the scenarios. It is good to note that the real system's input and output data per week was unavailable, see Section 4.2.3; hence, plotting the simulation model's data against the real system's data on a weekly basis was not possible. Consequently, only annual comparisons and benchmarking were adopted.

[i] Since 40.95 simulation weeks indicate a full year of 12 months, then 11 simulation weeks would correspond to 3.2 months, or approximately 3 months when rounded up.

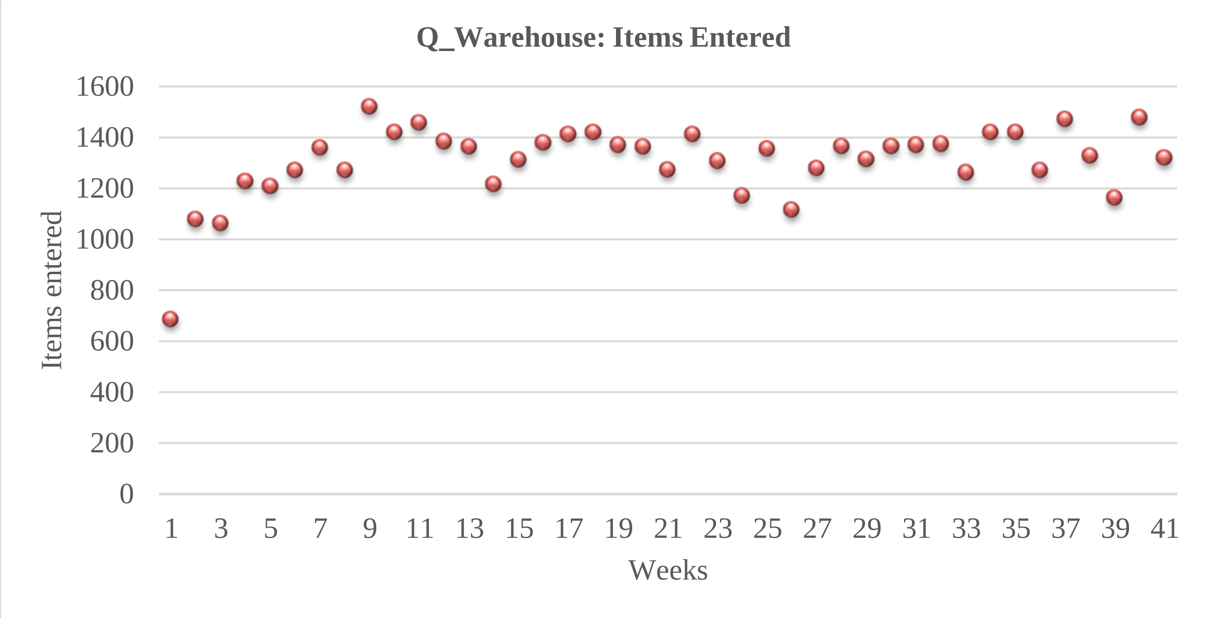


Figure 13. Parts delivered to the Warehouse every week.

4.2.4.2 1 Trial with warmup

When run for 1 trial with warmup, the base model has an output of 54,587 parts annually, where other KPIs as well are presented below.

Table 9. KPI summary results for the base model with 1 trial and warmup.

Simulation Object	Performance Measure	Run Result	% Deviation from real system's output
Q_Warehouse	Items Entered	54,587	4.12
Q_PreTAD	Current Contents	221	-
	Maximum Queue Size	229	-
	Average Queue Size	156.39	-

The following figure also illustrates the development of the average size of Q_PreTAD every week throughout the year with warmup.

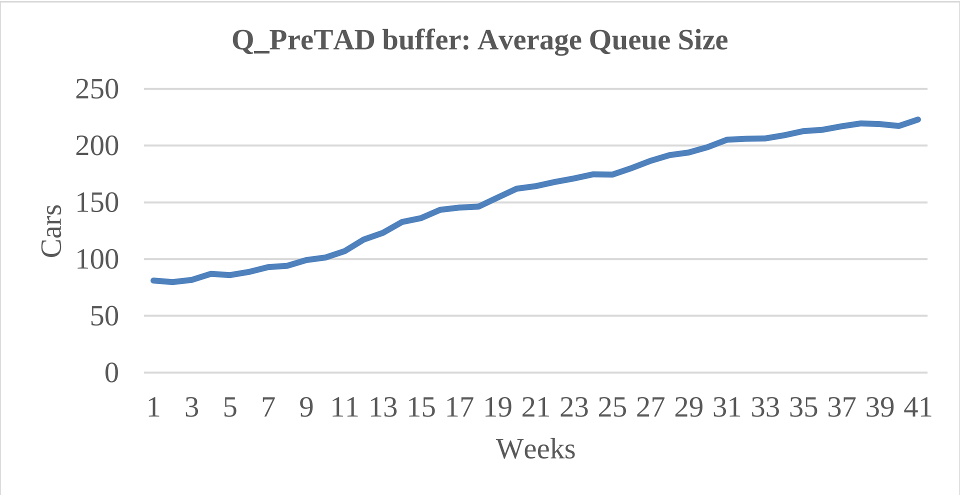


Figure 14. Development of the average queue size of Q_PreTAD with time.

As mentioned in Section 4.2.3, Q_PreTAD will keep on rising from 80 to reach a maximum value close to 256. This means that if the current capacity of that buffer is doubled, it would be completely full within one year.

All Q_PreTAD charts on this point forward will be compiled with 1 trial and warmup. This is so that the normal behaviour of the buffer would be observed. Otherwise, the 1 trial without warmup would show a significant decrease in the buffer size in the first 11 weeks (three months), which only makes sense since there is no other work-in-progress in the system. This significant decrease would make it unrealistic to analyse Q_PreTAD's behaviour over a longer period of time, see Section 2.2.3.4.

4.2.4.3 10 Trials with warmup

By running a series of 10 trials, the goal is to have the simulation result resemble the real-life case and its behaviour including its variability. The table below shows the KPI summary results within 95% confidence intervals, where the average output is 55,014 parts per year, which is a deviation of 4.93% from the real system.

Table 10. KPI summary results for the base model with 10 trials and warmup.

Simulation Object	Performance Measure	-95% confidence	Average	95% confidence
Q_Warehouse	Items Entered	54,554.67	55,014.00	55,473.32
Q_PreTAD	Current Contents	220.77	243.40	266.02
	Maximum Queue Size	232.24	253.60	274.95
	Average Queue Size	148.21	164.34	180.46

4.2.5 Base model analysis

4.2.5.1 Result steadiness and accuracy

The system's output with 1 trial and warmup is 54,587, which is a small deviation by only 4.12% from the real system's output of 52,429. Also, the 10 trails run with warmup indicate that the model's average (55,014) is bounded by tight 95% confidence interval limits ranging from 54,554 to 55,473, where it deviates by 4.93% from the real system's output, which is acceptable. Given these outcomes and with tight confidence limits, it can be confidently implied that the simulation model is both accurate and precise. More importantly, the 1 trial without warmup result of 53,640 (Model Zero) experiences a slight deviation of 2.31%. This means that benchmarking the scenarios against Model Zero can be pretty much considered as benchmarking against the real system.

Furthermore, the warmup period of three months sounded logical and not so lengthy for the system to reach steady state, after which there seemed to be no significant fluctuations, see *Figure 13*.

4.2.5.2 Bottleneck analysis

Figure 14 demonstrates that the average queue size of Q_PreTAD grows constantly through the year. If the model started with 256 cars initially, as is the case of the real system, the buffer would have increased beyond 400 cars, which does not represent how the real system behaves. Thus, having 256 cars in Q_PreTAD buffer in the real system can be attributed to two reasons. The first is that it took some time – which is unfortunately undocumented – to reach this state of 256 cars. The second reason is that the operators are shifted continuously and in an unstructured way to try and keep the buffer from not exceeding its maximum capacity of 256 cars. Therefore, it would have been extremely complex to model the real system with such randomness. As a result, assumptions were taken about the normal way of working, which ended up in abiding by 80 cars in Q_PreTAD and not 256.

Furthermore, the analysis of the resources' utilization shows that most dismantling resources are fully utilized, with values over 99%. Other resources experienced medium utilization (75-85%), such as the engine treatment operator (R_Eng_Trtmnt), the metal sheets treatment operator (R_MS_Trtmnt) and the wheel loader driver (R_WL_Driver). Some resources were underutilized with rates below 50%, such as the forklifts, the wheel loader and the dedicated operator conducting NVC depolluting (R_NVC). All values can be observed in the following table.

Table 11. Resource utilization in Model Zero (high utilization with bold, medium utilization underlined, and low utilization in italics).

Resource	Utilization Rate (%)
R_Barc_Eng_Dism	**99.69**
R_TAD_Dism	**99.62**
R_Dism	**99.44**
R_Barc	**99.27**
R_NVC_Dism	**99.23**
R_Eng_Trtmnt	<u>85.53</u>
R_MS_Trtmnt	<u>75.67</u>
R_WL_Driver	<u>74.68</u>
R_NVC	*40.75*
R_Forklift2	*35.28*
R_Forklift1	*23.25*
R_WL	*19.95*

The analysis of the system indicates that the dismantling area is the main bottleneck, which is compatible with the literature findings about the main challenges facing ELV dismantling systems, see Section 3.4.2. This can be attributed to:

- The continuous and steep rise of the main buffer before it (Q_PreTAD)
- Having Q_PreDism constantly reaching full capacity, and having the operators working in VC TAD always participating in dismantling
- The resources post the dismantling area, specifically R_Eng_Trtmnt and R_MS_Trtmnt are not always fully utilized

4.3 Tested scenarios

Since a prerequisite for comparing scenarios is to have the same initial conditions at all the entities of the simulation, unless other conditions are mentioned, every scenario is run for 40.95 weeks (12 months) without warmup time and an initial capacity of 80 cars in Q_PreTAD. In total, there were eight main scenarios that were tested as will be shown below; however, other scenarios were also compiled, see Appendix III.

4.3.1 Scenario A results

In Model Zero, the resource R_NVC is responsible only for processing NVCs with a current utilization of 40.74%. Scenario A was created to increase the utilization of this resource by establishing the same condition as that of R_NVC_Dism, who mainly does VC dismantling and helps in NVC depollution when Q_NVC_Depol reaches a value of 21 cars, signified as Var_NVC_Depol.

One of the optimization tools of Simul8, the scenario manager, was utilized as shown below to reach the ideal value of Var_NVC_Depol, which is Q_NVC_Depol's capacity, under which the operators would leave NVC depollution to VC dismantling.

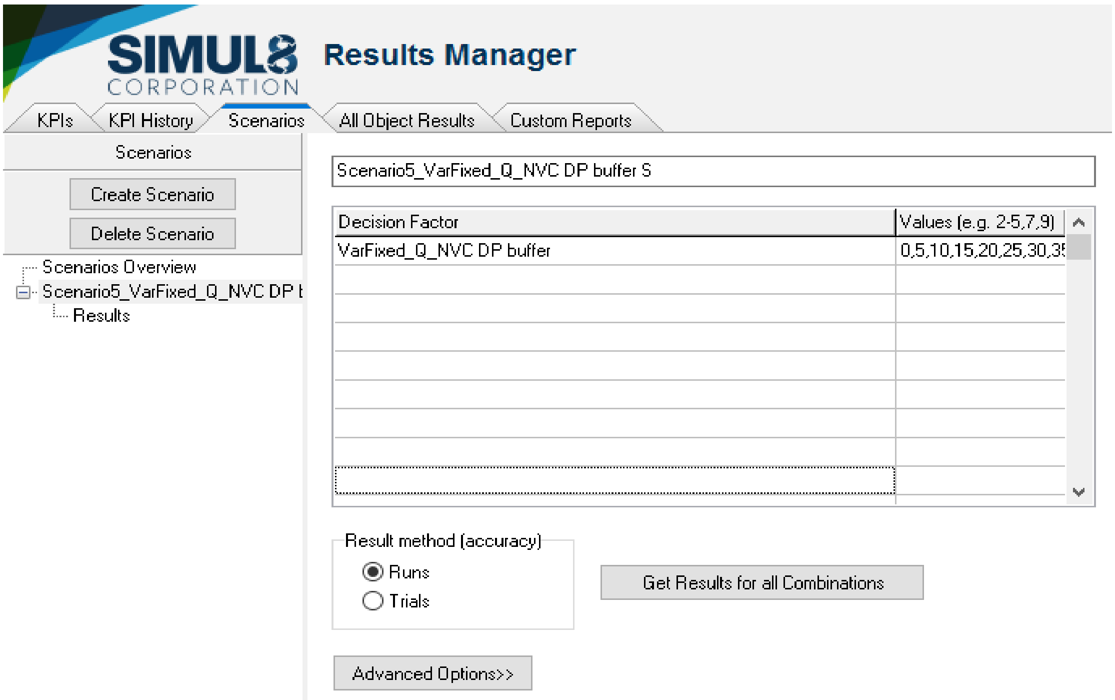


Figure 15. Using the scenario manager to find the optimal value for Var_NVC_Depol.

The iterations revealed that the best productivity was obtained with the value of 47 cars. The KPI summary results for scenario A are displayed below.

Table 12. KPI summary results for scenario A.

Simulation Object	Performance Measure	Run Result	% Difference from Model Zero
Q_Warehouse	Items Entered	56,464	5.26
Q_PreTAD	Average Queue Size	45.20	-60.62
R_NVC	Utilization %	92.63	127.37

Due to the importance of Q_PreTAD and its effect on the system, one run was compiled to observe its behaviour throughout the year as shown in the figure below.

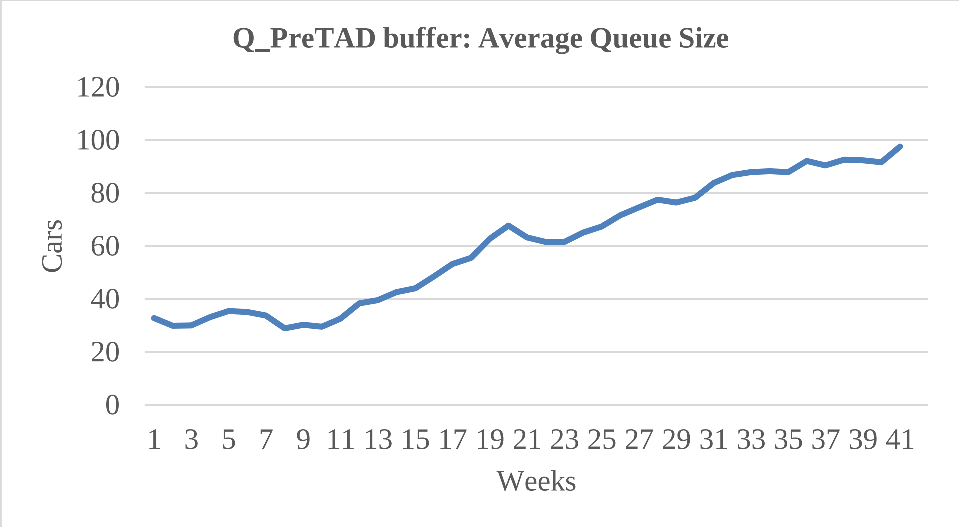


Figure 16. Effect of scenario A on Q_PreTAD.

It is good to note at this point that any other scenario starting with the initial "A" implies that it was based on scenario A. For example, scenario AB would imply that based on scenario A, new tests were made. And thus, the same rule applies for other scenarios with different initials.

4.3.1.1 Scenario A analysis

Since dismantling appeared to be the system's constraint, it deemed necessary to allocate underutilized resources to it in a planned manner. Since R_NVC is responsible only for processing NVCs, with a current utilization of 40.75%, scenario A was created to increase the utilization of this resource. This was done by establishing the same condition as that of R_NVC_Dism, who does dismantling along with NVC depollution if Q_NVC_Depol is below 21.

Nevertheless, the previous way of working is understandable and rational, where the shop floor manager keeps shifting capacity to focus on dismantling by having more buffer space for VCs to be depolluted in Q_PreTAD, where this is done by maintaining Q_NVC_Depol at an acceptable small size of 21 NVCs.

However, the relatively low volume of 21 somehow indicates that NVC depollution was more prioritized than dismantling VCs, although they were quicker to be processed in the system. Consequently, this condition was iterated, which yielded the necessity to change the value to 47 to achieve higher productivity and resource utilization.

Upon this scenario, Q_Warehouse increased by 5.26% and the average size of Q_PreTAD decreased from 115 to 45 cars by 60.62%. Moreover, the utilization rate of R_NVC increased by 127.373%.

From these results, it can be observed that part of the reason Q_PreTAD decreased is the fact that the operators responsible for the NVC path started prioritizing VC dismantling, allowing Q_NVC_Depol to increase until 47. Since both buffers are situated in an open-air field, where cars are subject to alternating weather conditions, and consequently, to possible erosion, prioritizing the cars with VPs and postponing the depollution of NVC by leaving them outside seems to be a more appropriate strategy.

Hence, increasing Q_NVC_Depol's capacity from 21 to 47 (i.e. by 123%) is necessary to have efficient VC dismantling.

Although these results seemed satisfactory initially, it was important to investigate how Q_PreTAD's behaviour changes over time in comparison to Model Zero. Therefore, the following chart was compiled to show the difference in the average size of Q_PreTAD for three years.

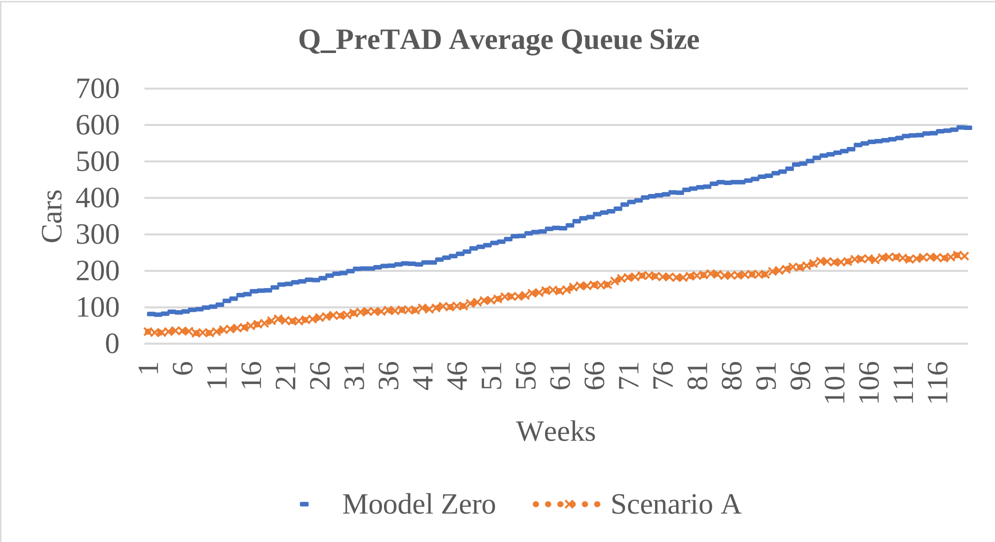


Figure 17. Comparing Model Zero with scenario A regarding the average queue size of Q_PreTAD for three years.

This scenario requires no investment costs, yields higher productivity and includes higher resource utilization rates; however, Q_PreTAD keeps on growing but at a slower pace. This means that building other scenarios on scenario A would be a promising idea to stabilize and possibly diminish Q_PreTAD.

4.3.2 Scenario AB results

With same conditions set as scenario A, scenario AB grows on the idea of having testing, depollution and dismantling in the same station. This includes eight operators as follows:

- The two operators in VC TAD
- The two operators in NVC depollution
- The operator doing dismantling, barcoding and engine treatment
- The three dedicated operators in the dismantling area

The operators therefore would have the chance to work in the VC dismantling building without adding extra stations, where the VC TAD building can be shut down. Given these conditions, there is no transportation from VC TAD to VC dismantling. Consequently, it appears that Q_PreDism diminishes in size, where the KPI summary results for scenario AB can be seen below.

Table 13. KPI summary results for scenario AB.

Simulation Object	Performance Measure	Run Result	% Difference from	
			Model Zero	Scenario A
Q_Warehouse	Items Entered	57,293	6.81	1.47
Q_PreTAD	Average Queue Size	43.96	-61.70	-2.73

The behavior of Q_PreTAD throughout the year can also be viewed in the figure below.

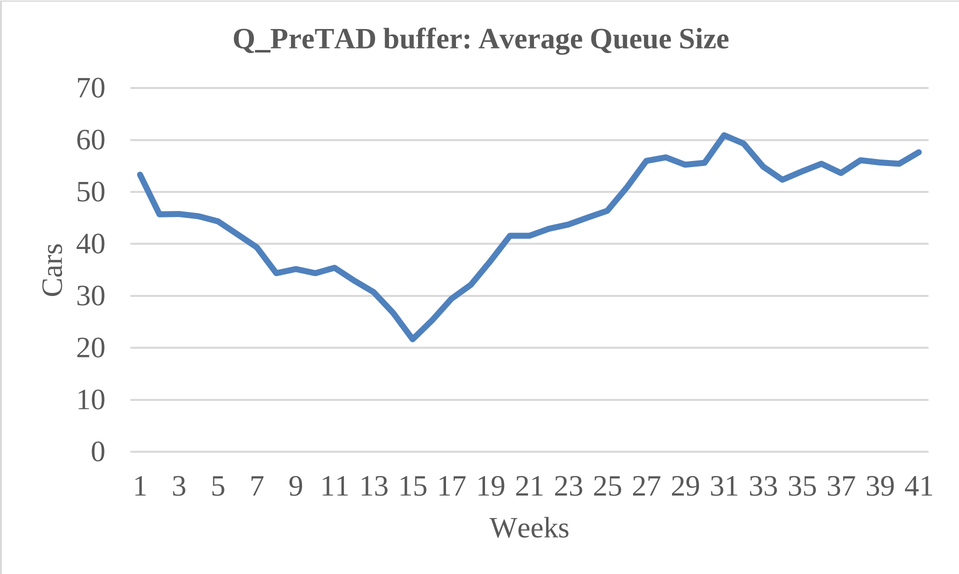


Figure 18. Effect of scenario AB on Q_PreTAD.

Note that the sudden decrease in the buffer's size from week 1 till week 15 can be explained by the fact at some point in time, the system received more NVCs than VCs, which would ease the congestion in Q_PreTAD. Hence, although the inbound generation of ELVs in the model follows the colour distribution in *Table 4*, the type of cars arriving every day is not always the same. As a result, the overall distribution of ELVs across the whole time period of 40.95 weeks follows the distribution in *Table 4*, but not explicitly every week. Conversely, the up shifts from week 15 till week 31 can be attributed to the fact that more VCs arrived during that time period along with the fact that the dismantling area is the bottleneck. This justification also applies to the different plots of Q_PreTAD that will be seen later on.

4.3.2.1 Scenario AB analysis

In this scenario, all eight stations in the big building conduct, testing, depollution and dismantling. Hence, the transportation between VC TAD and their dismantling disappears, where Q_PreDism does not exist anymore. This was designed to test several of the challenges facing ELV dismantling systems in general, which are eliminating waiting times and unnecessary transport, see Section 3.4.2.

The final output of 57,293 parts represents an increase by 1.47% compared to scenario A and an increase by 6.81% from the base model. The plot of Q_PreTAD average size over three years comparing scenario A and scenario AB with Model Zero is presented below, since the one-year plot in *Figure 18* was not conclusive enough due to the unobvious trend in fluctuations occurring throughout the year.

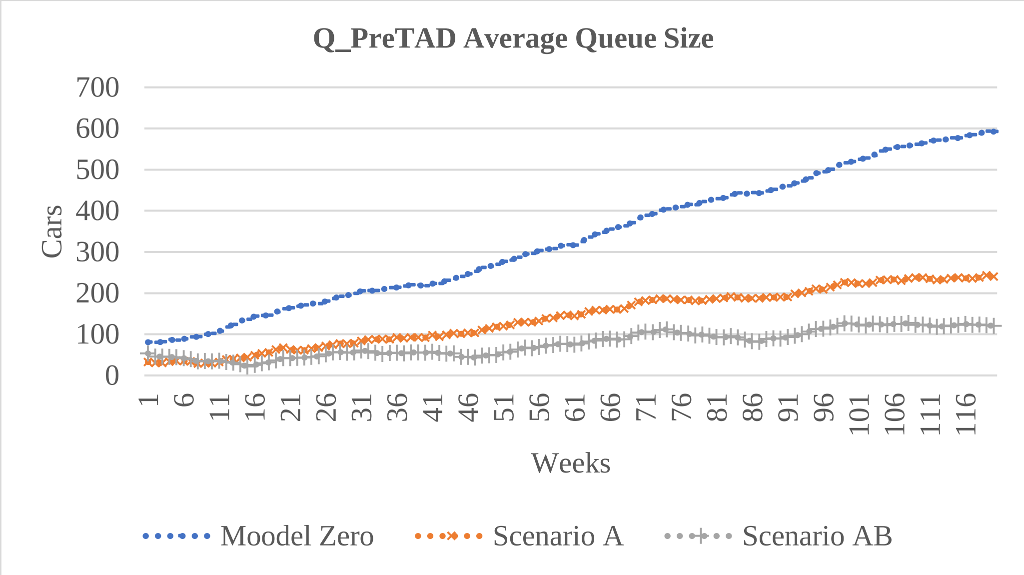


Figure 19. Comparing Model Zero with scenario A and scenario AB regarding the average queue size of Q_PreTAD for three years.

This plot seems to indicate that structuring the layout in a job shop/fixed position is slightly better than having everything processed in a cell layout. This is an interesting outcome, since the product-process matrix, as shown in *Figure 7*, highlights that a cell layout might be more convenient for this type of business given the high variances and low volume. This might be explained by the fact that there are many factors that make processing the VCs somehow completely non-standard, where the continuous variation in the cycle time is affected by every car's condition and brand as well as the demand on its VPs. Consequently, managing such a system in a job shop layout might seem better, which almost makes processing every VC unique. Also, this outcome proposes a methodology that was not touched upon frequently in the literature, since very few papers investigated having the tasks of testing, depollution and dismantling within one station, such as the 70 ELVs case study, see Section 3.4.2.

Similar to scenario A, *Figure 19* also shows that Q_PreTAD keeps on rising, but at a slower pace than that of scenario A. The main trade-off in this situation is that the company has the chance to shut down the VC TAD building, where all VCs and NVCs can now be processed in the other big building.

Doubts however are raised if that can cover for the associated investment costs. Thus, structuring the layout in this manner was based on the idea that every station has its own depolluting equipment. Currently, there are six depolluting equipment, four of which are in the VC TAD building, and two of which are in the other building. And since it is not possible for every two stations to share these equipment, as they are not compatible with this functionality, the company must invest in two new depolluting equipment, whose purchasing cost is about SEK 100,000 each. Second, there are reinstallation costs of the old equipment after being moved and installation costs of the new depolluting equipment, which leads to the total investment costs rising up to SEK 300,000.

Although this scenario showed promising results, the current situation of having a rising Q_PreTAD stays the same, which means that other scenarios ought to be tested.

4.3.3 Scenario AC results

The idea of scenario AC is to have two operators working on the same dismantling station. Since there are only three dedicated dismantling operators, this scenario has two of these operators at one station, while the remaining dismantling stations function the same way as scenario A.

The findings of the lean team indicated that it is possible to cut the cycle time of a dismantling station by half approximately if two operators work on it simultaneously (Bergqvist & Islam, 2017). Given these outcomes, the processing time was set to be cut by half on that station in the simulation model. The KPI summary results for scenario AC can be seen in the table below.

Table 14. KPI summary results for scenario AC.

Simulation Object	Performance Measure	Run Result	% Difference from	
			Model Zero	Scenario A
Q_Warehouse	Items Entered	54,614	1.82	-3.28
Q_PreTAD	Average Queue Size	65.93	-42.56	45.86

4.3.3.1 Scenario AC analysis

By having only two operators working on the same dismantling station, scenario AC yielded a final output of 54,614 parts. This represents a decrease by 3.28% when compared to scenario A.

Although it was hypothesized that having such a setting will decrease the lead time to have faster throughput, the simulation results indicate a drawback in productivity. Thus, given the variation of the dismantling times of different VCs, this might prompt continuous unsteadiness in the system, even if two operators work on the same station. Consequently, the efficiency of one station would be high; however, that does not necessarily have to improve the system as a whole, see Section 3.3 on flow efficiency vs. resource efficiency. In addition, the possibility of having other stations conduct the same setting may not be possible, since there is one dedicated operator left for dismantling. This means that whoever might be helping him out, they will need to leave as soon as they are being requested by another process. Such a way of working eliminates the robustness from the system and creates more variation. Therefore, it was considered unworthy to continue investigating in this scenario.

4.3.4 Scenario AD results

Scenario AD was modelled by testing the influence of the wheel loader, its driver and the forklifts on the system's performance. To do that, these resources were deleted. The KPI summary results for scenario AD are displayed in the following table.

Table 15. KPI summary results for scenario AD.

Simulation Object	Performance Measure	Run Result	% Difference from	
			Model Zero	Scenario A
Q_Warehouse	Items Entered	57,085	6.42	1.1
Q_PreTAD	Average Queue Size	38.51	-66.45	-14.8

4.3.4.1 Scenario AD analysis

Since scenario AB tackled one way of eliminating unnecessary transport within one section in the system (i.e. between depollution and dismantling), whereas scenario AD was designed to tackle the criticality of the transportation issue that is highlighted in the literature but in a different way.

By eliminating all transportation resources in the system, the result is an increase by 1.1% in the final output compared to scenario A. Hence, the impact on productivity after eliminating the forklifts, the wheel loader and its driver can be considered minimal.

This might be because of the fact that there is so much variation in the processes' cycle times, that it becomes rare for more than one process to claim the same transportation resource simultaneously. Furthermore, the amount of time to conduct transportation using these machines takes relatively a little amount of time (about 5 min on average), and may not be that frequent per dismantling operator, which explains the low utilization of the forklifts and the wheel loader, see *Table 11*.

4.3.5 Scenario AE results

In scenario AE, the operator R_Barc_Eng_Dism will focus on just doing dismantling, instead of continuously helping out in engine treatment and barcoding. A newly employed operator (R_BC_ET) will be responsible for performing barcoding mainly and helping out in engine treatment if the buffer preceding that station, Q_PreEng_Trtmnt, exceeds an amount of 15. The KPI summary results for scenario AE can be seen in the following table.

Table 16. KPI summary results for scenario AE.

Simulation Object	Performance Measure	Run Result	% Difference from	
			Model Zero	Scenario A
Q_Warehouse	Items Entered	58,211	8.52	3.09
Q_PreTAD	Average Queue Size	8.41	-92.67	-81.39

Given the attractiveness of these results regarding the output and work-in-progress, it was interesting to plot the time after which it takes for scenario AE to diminish Q_PreTAD significantly given the current real situation. *Figure 20* illustrates the development of the average queue size of Q_PreTAD in scenario AE for 3 years starting with 256 cars to mimic the exact current situation of the real system. The figure shows that after 53 weeks (16 months), Q_PreTAD will vanish.

4.3.5.1 Scenario AE analysis

The reason for allocating the new and old operators in this arrangement is because of the fact that it takes less time to learn barcoding and engine treatment than dismantling. The results show an increase in the output by 3.09% compared to scenario A and 8.52% compared to Model Zero. Moreover, as shown in *Figure 20*, Q_PreTAD vanishes after 16 months, and stays on that manner afterwards.

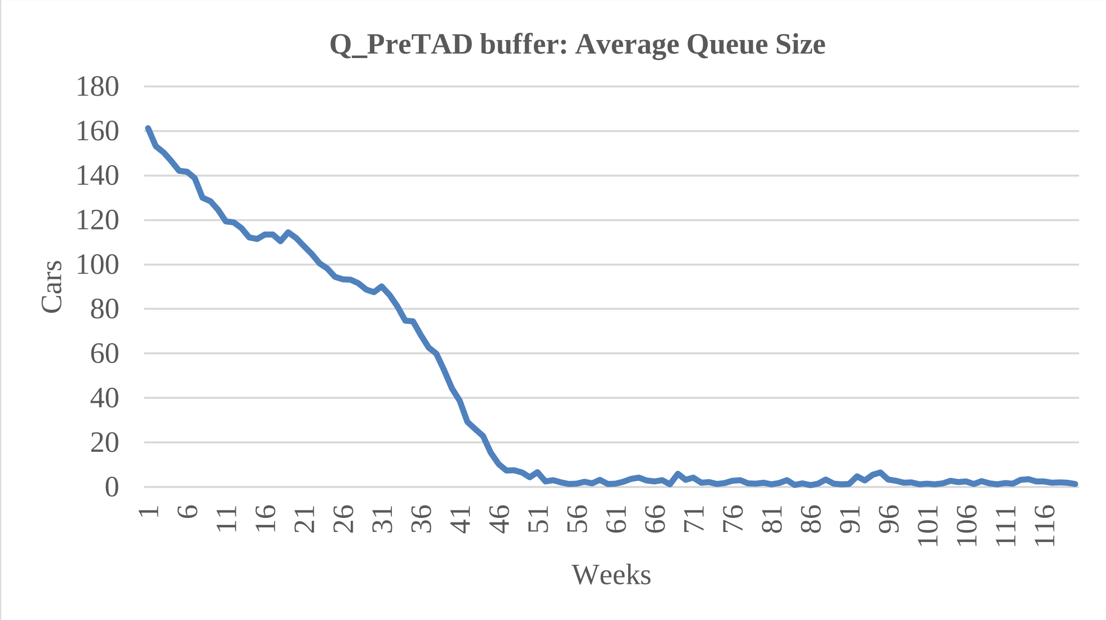


Figure 20. Effect of scenario AE on the average queue size of Q_PreTAD for 3 years.

Having the system's main buffer at an empty level, and given the scenario of adding one more operator (R_BC_ET), indicates that the system will reach a state with overcapacity as shown in the table below, where R_BC_ET has no data in Model Zero given that the operator is newly hired in scenario AE.

Table 17. Comparing resource utilization ratees (in %) between scenario AE and Model Zero (positive difference in bold and negative difference in italics).

Resource	Scenario AE Utilization Rate (%)	Model Zero Utilization Rate (%)	% Difference
R_Dism	98.40	99.44	*-1.04*
R_NVC	91.44	40.75	**50.69**
R_NVC_Dism	91.37	99.23	*-7.86*
R_Eng_Trtmnt	88.82	85.53	**3.29**
R_Barc	88.68	99.27	*-10.59*
R_BC_ET	88.35	----	----
R_MS_Trtmnt	80.08	75.67	**4.41**
R_TAD_Dism	74.26	99.62	*-25.36*

Although R_NVC has a significant increase in utilization, along with a slight rise of that of R_Eng_Trtmnt and R_MS_Trtment, the overcapacity can be clearly seen with the utilization rates of the dismantling operators and the two barcoding operators being lower than that of the base model. Also, given that these rates are not close to 100% in scenario AE, this indicates that further improvements should be made to make this operator hiring a temporary process. It would be required therefore that the system should continue afterwards with relatively close productivity, reasonable buffer sizes and high utilization rates.

4.3.6 Scenario AF results

Scenario AF is based on the idea that the company provides support, training and process improvements to decrease the dismantling cycle time by 5%. The following table shows the KPI summary results for scenario AF.

Table 18. KPI summary results for Scenario AF.

Simulation Object	Performance Measure	Run Result	% Difference from	
			Model Zero	**Scenario A**
Q_Warehouse	Items Entered	57,293	6.81	1.47
Q_PreTAD	Average Queue Size	14.54	-87.33	-67.83

Given that Q_PreTAD decreased, it was interesting to plot its change over time as presented in *Figure 21*.

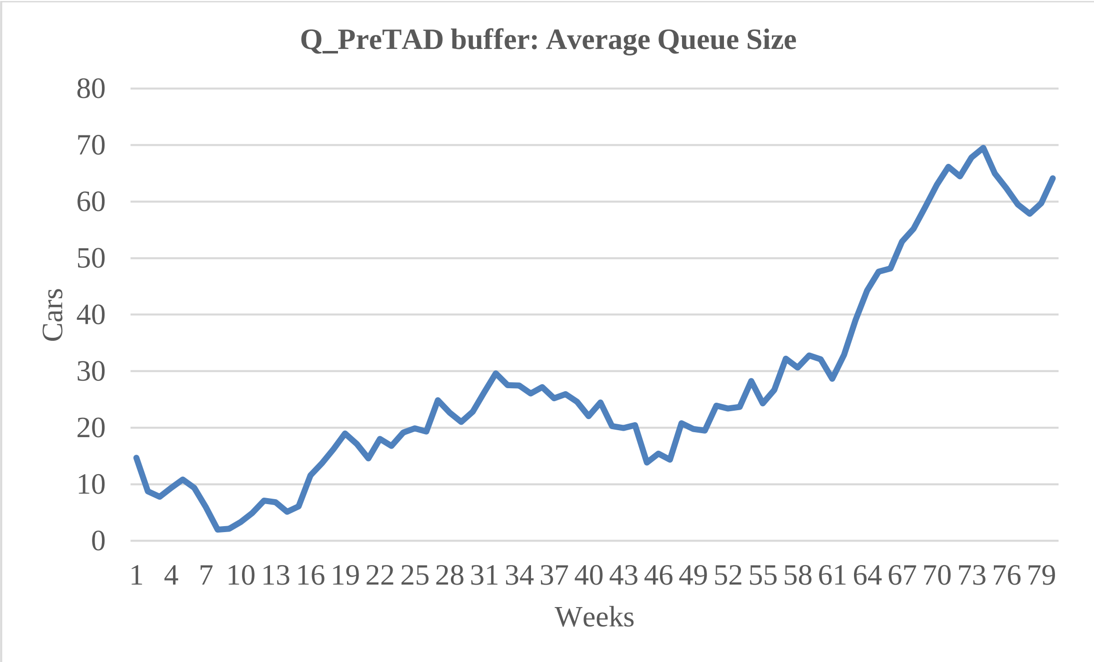


Figure 21. Effect of scenario AF on the average size of Q_PreTAD for 2 years.

4.3.6.1 Scenario AF analysis

Increasing the efficiency by 5% caused a slight increase by 1.47% from scenario A. Although *Figure 21* reveals that Q_PreTAD keeps on rising, the behaviour shows a significant reduction in its growth rate as shown in *Figure 22*.

Still having 100 cars in Q_PreTAD – as shown on the right-hand side of the figure for scenario AF– occupies significant space, which might be used for something else, such as putting PP cars. Also, although it might take more than three years for the buffer to reach the current capacity of 256 cars, it would be more beneficial to steer the improvements in a way to guarantee stability of that buffer with a much lower number of cars.

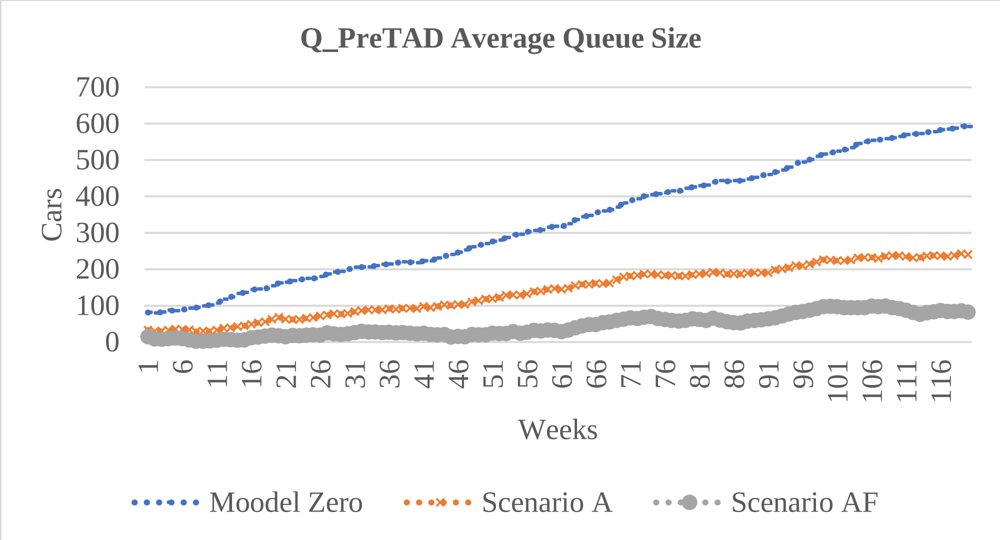


Figure 22. Comparing Model Zero with scenario A and scenario AF regarding the average queue size of Q_PreTAD for three years.

4.3.7 Scenario AFG results

Built on the conditions set for scenario AF, scenario AFG adds the condition to the model of not having VPs taken from the red cars type (the NVCs), in an attempt to help more in VC dismantling; and hence, decrease the average Q_PreTAD size faster. *Table 19* shows the KPI summary results for scenario AFG.

Table 19. KPI summary results for Scenario AFG.

Simulation Object	Performance Measure	Run Result	% Difference from	
			Model Zero	**Scenario A**
Q_Warehouse	Items Entered	57,048	6.35	1.03
Q_PreTAD	Average Queue Size	14.97	-86.95	-66.88

Figure 23 plots the change of the average queue size of Q_PreTAD in scenario AFG for 3 years starting with an initial buffer start-up of 0 cars.

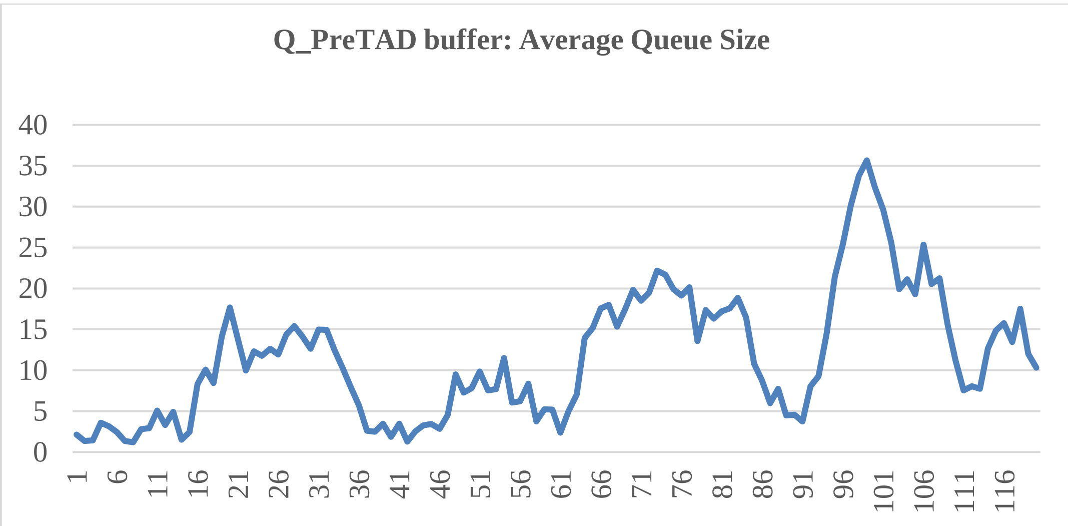


Figure 23. Average queue size of Q_PreTAD in scenario AFG for 3 years starting with an initial quantity of 0 cars.

4.3.7.1 Scenario AFG analysis

Including scenario AF and adding the idea of eliminating the 20 min dismantling process for red cars led to a 6.35% increase from Model Zero, but very slight increase by 1.03% from scenario A. The result is an increase and not a decrease since the NVC depolluting operators are using these 20 min intervals to work more on VCs and clearing Q_PreTAD. Also, it appeared that Q_PreTAD was stabilized in a range of about ± 40 cars; hence, ranging consistently between 80 cars and 120 cars.

Given this finding, it was interesting to investigate how the system would behave if the buffer would start empty. The chart below highlights how scenario AFG not only stabilizes Q_PreTAD, but also sets it at a maximum peak of only 35 cars, which is a decrease by 82.69% from Model Zero.

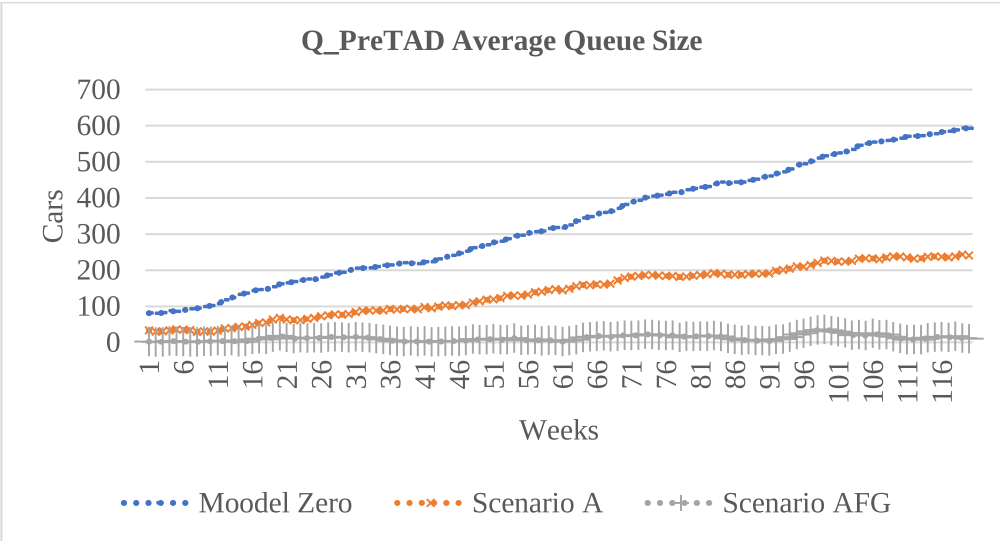


Figure 24. Comparing Model Zero with scenario A and scenario AFG regarding the average queue size of Q_PreTAD for three years.

Not only does this scenario control Q_PreTAD within acceptable limits and maintain productivity, but also it assures maintaining high resource utilization rates in comparison with Model Zero as shown below.

Table 20. Comparing resource utilization ratees (in %) between scenario AFG and Model Zero (positive difference in bold and negative difference in italics).

Resource	Scenario AFG Utilization Rate (%)	Model Zero Utilization Rate (%)	% Difference
R_Dism	99.27	99.44	*-0.17*
R_NVC	92.38	40.75	**51.63**
R_NVC_Dism	91.90	99.23	*-7.33*
R_Eng_Trtmnt	91.35	85.53	**5.83**
R_Barc	99.44	99.27	**0.16**
R_MS_Trtmnt	82.05	75.67	**6.39**
R_TAD_Dism	98.18	99.62	*-1.44*

Consequently, this scenario makes the best out of the operators working at every station, where almost all utilization rates are above 90%.

4.3.8 Scenario ABFG results

Given that scenario AF shows a stable range of Q_PreTAD's performance, and since this was the key issue of scenario AB, both scenarios were combined. The following table summarizes the key findings of this scenario.

Table 21. KPI summary results for Scenario ABFG.

Simulation Object	Performance Measure	Run Result	% Difference from	
			Model Zero	Scenario A
Q_Warehouse	Items Entered	57,056	6.37	1.05
Q_PreTAD buffer	Average Queue Size	11.74	89.77	-74.03

As it was observed that the size of Q_PreTAD diminishes drastically, it was interesting to plot the time after which it takes for the buffer to vanish by taking into account the current real situation. *Figure 25* therefore highlights the development of the average size of Q_PreTAD for four years starting with 256 cars, where the buffer disappears after 155 weeks (45 months).

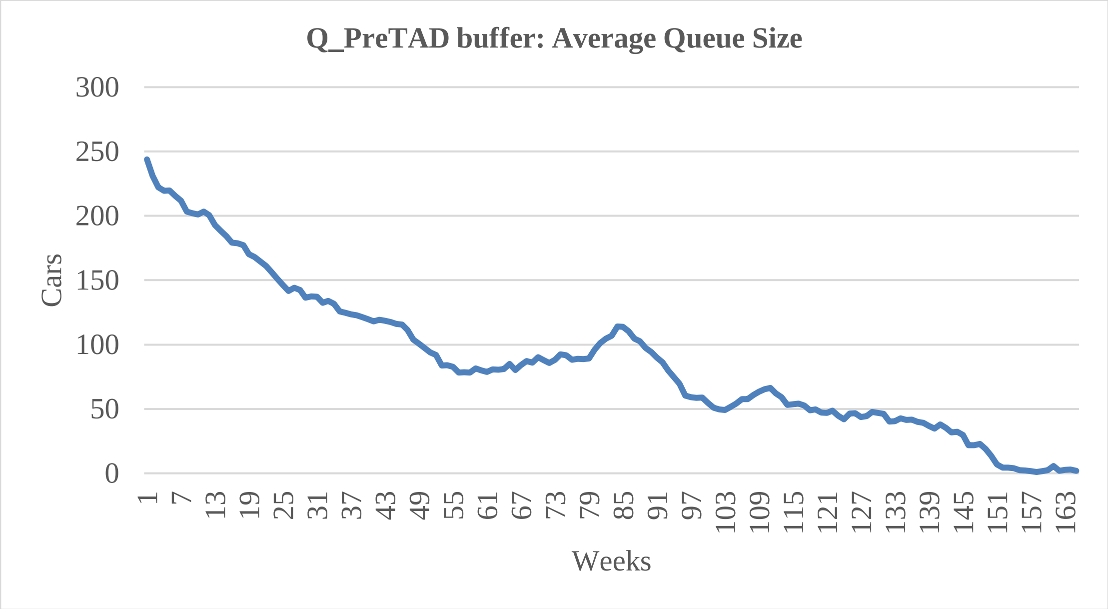


Figure 25. Average queue size of Q_PreTAD in scenario ABFG for four years starting with an initial quantity of 256 cars.

4.3.8.1 Scenario ABFG analysis

Combining scenario AB (by having testing, depollution and dismantling in eight stations) with scenario AF led to a 6.37% increase from Model Zero, but a very slight increase by 1.05% from scenario A, which is pretty close to scenario AFG. The trade-off however would be waiting longer than scenario AFG to vanish Q_PreTAD, where *Figure 25* shows that it takes 45 months for the buffer to disappear, after which it performs with a maximum size of 14 cars. Furthermore, the resource utilization rates appear to be high as shown below, which means that the system almost always performs at the most suitable capacity.

Table 22. Comparing resource utilization ratees (in %) between Scenario ABFG with scenario AFG (positive difference in bold and negative difference in italics).

Resource	Scenario ABFG	Scenario AFG	% Difference
R_Dism	95.87	99.27	*-3.40*
R_NVC	88.81	92.38	*-3.57*
R_NVC_Dism	90.17	91.90	*-1.72*
R_Eng_Trtmnt	92.78	91.35	**1.43**
R_Barc	99.48	99.44	**0.05**
R_MS_Trtmnt	83.78	82.05	**1.72**
R_TAD_Dism	95.73	98.18	*-2.45*

The same pros and cons of Scenario AB still apply, such as shutting down one building and investing in depolluting equipment respectively. However, this time, scenario ABFG will yield a permanent increase in the output and a permanent decrease in the buffer sizes, which would make investing in this scenario worthwhile.

This result opposes most of the literature that the optimal layout should be more cell or line-oriented; however, this scenario proves that combining all necessary tasks within one station also works really well.

4.3.9 Results summary

The following table summarizes the results of the different scenarios in comparison to the base model and scenario A regarding the percentage difference and the values associated with the total items entering the warehouse annually and the average size of Q_PreTAD.

Table 23. Benchmarking all scenarios against Model Zero and scenario A.

	Q_Warehouse			**Q_PreTAD**		
	Items Entered			Average Queue Size		
Scenario	Value	% Difference from Model Zero	% Difference from scenario A	Value	% Difference from Model Zero	% Difference from scenario A
Scenario A	56,464	5.26	----	45.20	-60.62	----
Scenario AB	57,293	6.81	1.47	43.96	-61.70	-2.73
Scenario AC	54,614	1.82	-3.28	65.93	-42.56	45.86
Scenario AD	57,085	6.42	1.10	38.51	-66.45	-14.80
Scenario AE	58,211	8.52	3.09	8.41	-92.67	-81.39
Scenario AF	57,293	6.81	1.47	14.54	-87.33	-67.83
Scenario AFG	57,048	6.35	1.03	14.97	-86.96	-66.88
Scenario ABFG	57,056	6.37	1.05	11.74	-89.77	-74.03

5 Discussion

Although the base model and the tested scenarios were preliminary discussed one at a time in the previous section, the following subsections describe in detail how to combine these models to provide adequate recommendations for the company with a suitable implementation plan. Moreover, general recommendations will be provided for the ELV dismantling along with a reflection on some sustainability aspects related to this topic in particular.

5.1 Improvement suggestions

In summary, the scenarios that make the most significant impact on the system's behaviour can be broken down into five, which are scenarios AB, AE, AF, AFG and ABFG.

Implementing scenario AB has its ups and downs. On one side, Q_PreTAD keeps on increasing, and the company must install and transfer the depolluting equipment from the VC TAD building to the dismantling building as well as purchase two new depolluting equipment. On the other hand, the output increases significantly, Q_PreTAD's growth rate is slower, and the company has the chance to allocate other investment opportunities to the empty building.

Implementing scenario AE is not sustainable in itself, since the role of the new operator might become unnecessary after clearing Q_PreTAD within 16 months. The output however would increase within this period by 5,676 parts or 8.15% which might help in paying the operator off, given that these parts are sold.

On the other hand, scenario AF presented promising results; however, this was not enough to stop Q_PreTAD from rising. Consequently, scenario AFG can still be applied to stabilize the system. This would represent a good base for scenario AB, leading to scenario ABFG. Hence, although scenario AB showed promising productivity results, it would still have a rising work-in-progress, which is an issue that can be solved through scenario AFG.

5.2 Recommendations for the company

Given these findings, two main recommendations can be provided to the company.

5.2.1.1 Recommendation one: apply scenario AE then AFG

If the company wishes to have high productivity, quick decrease in the work-in-progress and direct feasibility of implementation while being tolerant with relatively high investment costs, then a two-phase implementation plan is preferred to be adopted as shown below.

Phase 1: apply scenario AE by implementing the capacity shift when Q_NVC_Depol exceeds 47 cars, and hiring one operator for barcoding for a period of 16 months. The output therefore would increase by 5,676 parts, which is enough to pay for the operator's investment cost of about SEK 500,000, where Q_PreTAD will also vanish. Therefore, a payback period of one year is expected, see Appendix IV for payback period calculation. This phase is simple to apply since it will be relatively fast to train the operator on barcoding and engine treatment; hence, no equipment need to be installed or moved.

During this time, the company can aim to become 5% more efficient by further training its employees and applying process improvements, like eliminating unnecessary walking and providing the tools at a closer reach. Moreover, the customer base can be adjusted meanwhile so that the company's customer list can become independent of selling VPs from red cars. Therefore, within these 16 months, the company can work on expanding to other clients and negotiating its contracts with those who get affected by this strategy.

Phase 2: apply scenario AFG, which is about adopting the 5% efficiency increase and adjusting the customer base, while still maintaining the same plan for shifting capacity. This will yield a permanent decrease by 82.69% in the maximum peak size of Q_PreTAD (the system's most critical buffer), and will increase the output by 6.35%; i.e. 3,408 parts annually.

The benefits from following this two-phase recommendation include:

- Higher output, which will increase permanently by 6.35%.
- Shorter lead time, since the size of the buffer preceding VC TAD will drop by 82.69%. Hence, the lead time will be cut from 5 weeks to one week. The company therefore can secure the requests fast without the need to shuffle capacity in an unorganized way. Moreover, this can be associated with the fact that the VCs will not suffer from erosion, since they will be put for a less time duration in the open-air field, which would increase the VPs' dismantling rate.
- Since the main buffer will be diminished significantly, more empty space will be present, which the company can cater for other revenue streams, such as PP cars.
- In case one of the operators leave the company or gets sick in the upcoming period, the ex-hired operator can serve as a qualified substitute, since they already developed the required experience at the facility.
- Almost all operators will have utilization rates above 90%, which indicates a proper utilization of capacity, and that no free time would be wasted.

5.2.1.2 Recommendation two: apply scenario AB then AFG

If the company wishes to have high productivity and slow decrease in the work-in-progress with lower investment costs, then a two-phase implementation plan is preferred to be adopted as shown below.

Phase 1: scenario AB can be applied by shutting down the VC TAD building to use it for other errands, such as warehousing, where processing of all ELVs would be done in the second building. That way, the productivity increases by 6.81% leading to a payback period of one year, see Appendix IV, which covers the SEK 300,000 investment costs of purchasing and installing two new depolluting equipment as well as the moving and reinstallation costs from the VC TAD building to the other one. Although the maximum size of Q_PreTAD would decrease by 66.36%, the buffer will still be rising but at a slow rate.

Phase 2: this phase will be catered to eliminate the rise of Q_PreTAD, where the company should work on combining scenario AB with scenario AFG simultaneously, similar to phase 2 of the previous recommendation. That way, productivity can increase permanently by 6.37%; however, it would take 45 months for Q_PreTAD to vanish, which is 2.8 times the duration of the first recommendation, after which the maximum size of the buffer gets to 14 cars. Furthermore, the resource utilization rates appear to be high and pretty close to that of scenario AFG, see *Table 22*.

To sum up, the benefits from following this two-phase recommendation include:

- Increase in the productivity permanently by 6.37%.
- Work-in-progress vanishes slowly after 45 months, leading to the same associated benefits as that of the first recommendation.
- All main operations will be in one building. This means that the VC TAD building can be used for other revenue streams. Also, this would make it easier for the shop floor manager to visualize how everything is connected, which would assist him better in shifting capacities if contingencies arise.
- Almost all operators will have utilization rates above 90%, which highlights that no capacity will be lost.

Nevertheless, this recommendation would require more time to move and reinstall the current depolluting equipment into the new building, as well as purchasing and installing two new depolluting equipment.

5.2.1.3 Recommendation summary

Given the above findings, the two recommendations can be summarized in the table below.

Table 24. A summary of the two main recommendations for the company.

Parameter	Recommendation One	Recommendation Two
Investment costs	SEK 500,000 by hiring one operator	SEK 300,000 including: • Buying and installing two new depolluting equipment • Reinstalling equipment from the VC TAD building to the other building
Payback period	~ 1 year	~ 1 year
Productivity	6.35% increase annually	6.37% increase annually
Q_PreTAD	Vanishes after 16 months, after which maximum of 35 cars stay in the buffer	Vanishes after 45 months, after which maximum of 14 cars stay in the buffer
Resource utilization	Almost all operators above 90%	Almost all operators above 90%
Time required to start	About a couple of weeks, since this requires training the new operator	About a couple of months requiring purchasing, installing and moving equipment
Other benefits	A new operator that might serve as a substitute in case of sick leaves and absentees	• Shutting the VC TAD building down, which can be used for warehousing or other errands • Visualizing the dismantling system would be clearer, which makes it easier for the shop floor manager to make better decisions in cases of contingencies

The company must assess its investment capabilities in detail given that both recommendations above yield somehow close and satisfactory results. Finally, the company should look in how critical its need is when it comes to the urgency of eliminating Q_PreTAD. Perhaps waiting for 45 weeks would be too long, and therefore abiding by the first recommendation might be more applicable in this context.

5.3 Recommendations for the ELV dismantling business

As discussed in Section 1.3, the project also aims to provide general guidelines for the dismantling business as a whole. Based on what was analysed and improved at the company, three key takeaways for improving any dismantling system are concluded as follows:

1. Prioritize VCs over NVCs when shifting capacity. This is because NVCs take less time to process and have no (sometimes less) VPs to be dismantled from. Whereas, VCs take more time and have more VPs that are worthy of dismantling, which would contribute more to the business.
2. Eliminate dismantling of VPs from NVCs, especially given low volumes of such ELVs in the system as well as the small number of extracted VPs. Trade-offs must be made between the type of customers the company wishes to satisfy and the type of VPs to be dismantled, especially from NVCs. Consequently, spending time on such process must be critically analysed to weigh its benefits not only against the number of customers the company deals with, but also against its effect on dismantling of VCs, which is a more crucial process.
3. Combining the main functions in a job shop layout might be worthy if a company would like to start its dismantling business from scratch. That way, moving and reinstallation costs can be avoided, and maintaining relatively fast lead times and high productivity would still be feasible.

Unfortunately, the available literature does not touch upon shifting capacity based on classifying ELVs as VCs and NVCs; rather, it sheds light on the overall system efficiency and effectiveness in processing any ELV arriving into the dismantling system. Consequently, the first two takeaways might be specific to businesses that deal with both ELV types. As for the last recommendation, it came as a surprise that having a robust dismantling system would require a job shop layout, and this is because of two reasons. First, there are only few papers that investigated facilities having testing, depollution and dismantling within one station, such as the 70 ELVs cast study (Berzi et al., 2013). Second, this contradicts most of the literature about having a cell layout (Park & Sohn, 2004) or line-oriented dismantling systems (Sim et al., 2005) as the most efficient. This can be attributed to the fact that the facility under study categorized the ELVs under six different subcategories, where – when associated with the variable cycle times coupled with the car's brand, condition and demand on its spare parts – the variation in the system would be difficult to control; hence, having a job shop layout would be more suitable. The relevant literature might have studied facilities that classified the ELVs differently, or might have had space and economic restrictions, which might have made it easier, and perhaps efficient in their own perspective, to process in a line or cell-shaped manner.

5.4 Reflection on the project’s sustainability aspects

Sustainability is a wide theme, but is mostly constituted of three main components, which are environmental, economic and social (Epstein & Rejc, 2014). Touching on the environmental aspect, this thesis tackles dismantling ELVs and reselling their used parts. This would decrease the demand on manufacturing new parts and contribute more to circular economy. Furthermore, with more optimized dismantling systems, more parts can be extracted, which means that compressed cars would have less material to be shredded and buried in landfills.

On the other hand, the company’s economic benefits from both recommendations are sustainable, and do not require pretty much high capital or marginal costs. Hence, the most important investment is changing the way of working, which is more sustainable in the long run. Moreover, simulation was used, which is a low-cost tool, to test scenarios that could have cost way more if implemented directly in real life; thus, saving the company time and money.

Finally, the social aspect includes providing general recommendations for the business as a whole, so that similar companies around the globe can make optimized dismantling systems. As a result, competence and knowledge of dismantling optimization techniques can be shared for a better well-being of the planet and the stakeholders affected by this business. In addition, the authors developed key skills in learning the software, which might leverage their stance in serving as consultants in the dismantling sector or other similar businesses. Therefore, what was learnt during this thesis project will still be used and hopefully transferred to other stakeholders.

6 Project Reliability

The authors strongly believe in the quality of the results due to the iterative verification and validation efforts, the continuous guidance from the project coordinator, the supervisor and examiner as well as the benchmarking compiled against the literature and interview findings. In addition, both authors have previous experience in creating DES models for production systems via the software AutoMod. This knowhow in programming paved the way for a faster learning of Simul8, which led to the successful completion of this project.

Nonetheless, there are certain tasks that could have been done, given more time, to secure more reliable and profound results. This includes:

- Working more on collecting the data by conducting time studies to gather as many data points as possible. First, this could have helped in having the data independent of any other individual, which provides the simulation models with more credibility and representativeness of the real system. Second, this could have saved time for validating the simulation model by focusing more on testing improvement scenarios. Third, the uncertainty in the data collected drew some scepticism about its validity. Therefore, ensuring that enough data points have been gathered to mimic the real system might have strengthened the belief of the company's management in the simulation model and its capabilities. Finally, this could have helped in segmenting the processes further down into their key components. For example, by knowing how much time it takes to dismantle the lamps. tires, the seats and all the other parts, a line layout could have been modelled and tested as presented in Section 3.4.1. Consequently, this could have added more interesting scenarios to experiment with.
- Investigating other car dismantling companies to further develop different approaches about how to improve the dismantling systems. Studying different case studies at the same time may trigger testing different scenarios that were not thought off.
- Working on more cases touching on scenario AC, where most VPs would come from blue and yellow cars instead of the white ones. This would have been interesting, since the significance in variation of cycle times between the two categories and the unproportionate distribution of their quantity – the blue and yellow cars on one side and the white cars on the other – might have been the reason of why scenario AC was inapplicable. Therefore, investigating the possibility of having two operators working on one station might apply only in certain settings.
- Other optimization tools provided by Simul8 could have been used, such as OptQuest and the sensitivity analysis. That way, more optimal numbers could have been derived.
- Looking into other software packages used in industry, such as Arena or WITNESS. Although Simul8 was user-friendly via its drag-and-drop functionalities, there were some other issues touching on online support, excel compatibility and operator availability. For example, posting questions on online blogs and receiving answers takes more than two to three weeks. Also, the data compiled is not fully compatible with excel, which forced the authors to design their own interface for data organizing and filtering. Finally, one of the reasons the system was modelled with 14 operators and not 17 operators with 3 randomly absent, is that this feature is not embedded in Simul8. Rather,

the software provides tools to decide on every operator's availability every once in a while, but this excludes random selection of several operators' unavailability for an entire day.

- It would have been interesting to apply the recommendations provided and observe their applicability on spot. Hence, even if the company decides to apply them, it will take the warmup period of three months to start witnessing the first tangible results.

7 Conclusion

To sum up, this project presented the improvement of a dismantling facility by focusing on its layout via DES. Bottleneck improvement techniques and tools were used, such as TOC and the scenario manager provided by Simul8. The following concluding points summarize the main thesis outcomes for the company:

1. A VSM of the company was verified and validated.
2. A simulation model was compiled mimicking the input, output and behaviour of the dismantling system.
3. The main outcomes of the simulation model were improvement recommendations for the company. The dismantling process appeared to be the main system's bottleneck, which is compatible with the literature, and prioritizing VC dismantling over NVC depollution was a crucial turning point. Moreover, this should be supported by increasing the dismantling efficiency by 5% and eliminating the process of dismantling VPs from red cars, which would require the company to assess its situation with some of the clients. Along with these propositions, two approaches are proposed. The first approach would be hiring an operator temporarily, while the second would be combining testing, depollution and dismantling tasks within every station. Deciding on which suggestion to follow depends on the company's investment capabilities and its sense of urgency in eliminating the system's most crucial buffer. Nevertheless, applying either solution should be based on two phases, where this will yield a better and more sustainable outcome on the facility as a whole, which includes higher productivity (minimum increase by 6%), drastically decreasing the main work-in-progress (minimum by 80%) and possible expansion to other revenue streams.
4. Applying the recommendations at the company requires time that the authors lack. If the company wishes to apply them, then it will take the warmup period of three months to observe tangible results.

Finally, key takeaways for any dismantling business include:

1. Prioritize VCs over NVCs when shifting capacity.
2. Eliminate dismantling of VPs from NVCs, especially given low volumes of such ELVs in the system as well as the small number of extracted VPs.
3. Apply a job shop layout combining testing, depollution and dismantling in every station would be more suitable if building the dismantling system from scratch. If the system is already in place, then assessing the feasibility of buying, installing and reinstalling equipment should be further investigated.

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Appendix I: Typical ELV Treatment Processes

After investigating the literature covering common flows in dismantling facilities, the following layout featuring how the processes are interconnected with each other was presented (Berzi et al., 2013).

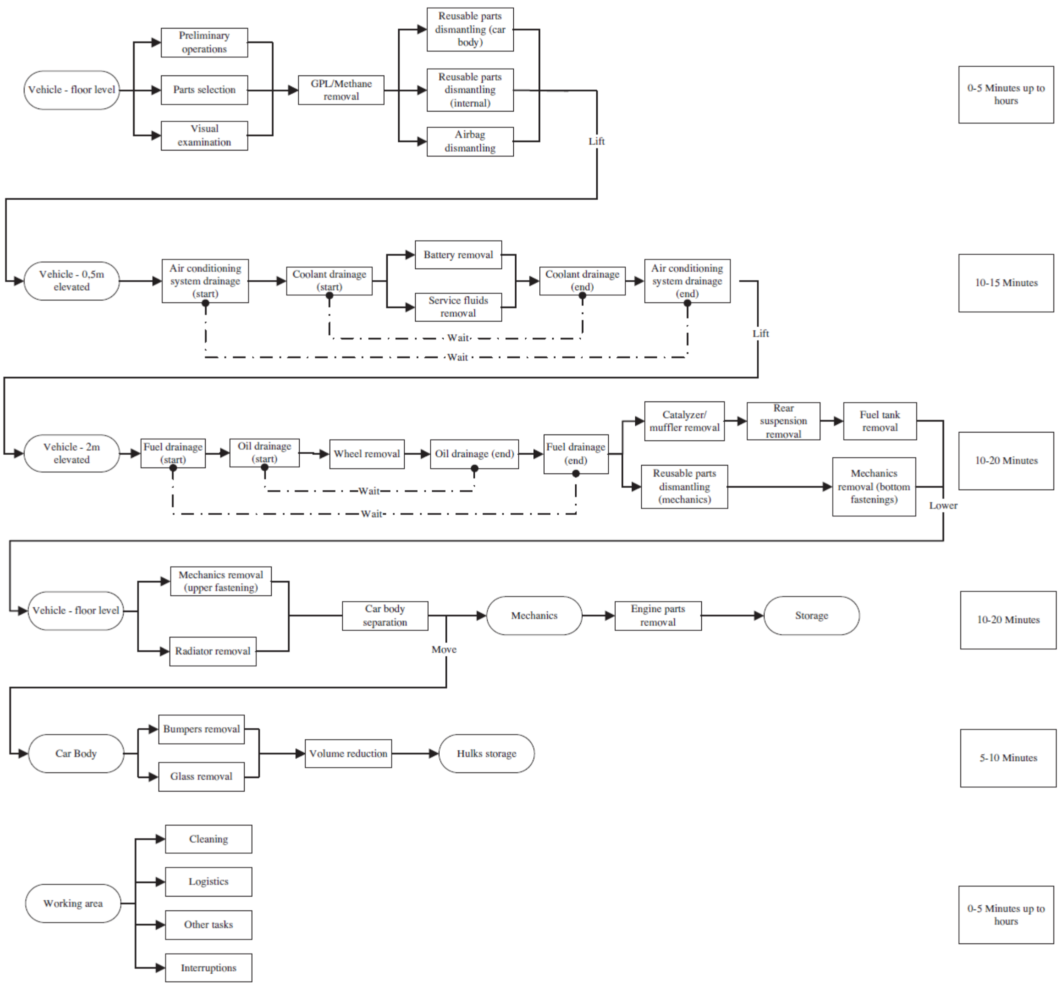

Figure 26. Typical ELV treatment processes (Berzi et al., 2013).

Appendix II: Changes in Simulation Objects' Abbreviations

There were some object abbreviations that were changed from the simulation model to this report. Changes in abbreviations regarding resources, queues and variables can be shown in *Table 25*, *Table 26* and *Table 27* respectively.

Table 25. Resource abbreviations in the simulation model and the report.

Resource abbreviations in the simulation model	Resource abbreviations in the report
R_TruckDriver (W1)	R_TruckDriver
R_ShpFlrMngr (W3)	R_ShpFlrMngr
R_DriverWL (W2)	R_WL_Driver
R_W1,W2,W3	R_pool
R_TADs1_DSMs5	R_TAD_Dism
R_DSMs4	R_Dism
R_BC_ET_DSMs1	R_Barc_Eng_Dism
R_NVCs2_DSMs7	R_NVC_Dism
R_ET	R_Eng_Trtmnt
R_BC1	R_Barc
R_MS	R_MS_Trtmnt
R_WS	R_Warehouse
R_Forklift 2	R_Forklift2
R_NVCs1	R_NVC

Table 26. Queue abbreviations in the simulation model and the report.

Queue abbreviations in the simulation model	Queue abbreviations in the report
Q_Receiving storage	Q_Receiving
Q_NVC DP buffer	Q_NVC_Depol
Q_PreTAD buffer	Q_PreTAD
Q_PreDSM buffer	Q_PreDism
Q_PreYard buffer	Q_PreYard
Q_PP yard	Q_PP_Yard
Q_PreBarcoding parts buffer	Q_PreBarcParts
Q_PreTreatment engine buffer	Q_PreEng_Trtmnt
Q_Engine parts from Engine	Q_EngParts
Q_PreTreatment metal sheets buffer	Q_PreMS_Trtmnt
Q_Door parts from MS	Q_MS_Doors
Q_PostParts buffer	Q_PostBarcParts
Q_PreSorting buffer	Q_PreSorting

Table 27. Variable abbreviations in the simulation model and the report.

Variable abbreviations in the simulation model	Variable abbreviations in the report
VarFixed_Q_NVC DP buffer	Var_NVC_Depol
VarFixed_Q_PreDSM buffer	Var_PreDism
VaFixed_Q_PreBarcoding parts buffer	Var_ PreBarcParts

Appendix III: Additionally Tested Scenarios

Besides the eight main scenarios discussed previously, other scenarios were also tested, such as:

- While starting from the base model, the operator responsible for one of the dismantling stations as well as helping out in barcoding and engine treatment had his conditions changed. The current situation is that this operator helps out in barcoding when there are 800 parts waiting to be barcoded. The new scenario changes this condition to determine the optimal value upon which the operator should help out. It appeared that having a buffer size of 800 was the best situation given the productivity and space required to handle the waiting parts.
- Similarly, the condition of the two operators in VC TAD had their condition changed when helping out the dismantling operators. The current situation was that they should wait to have 24 cars in Q_PreDism to help out in dismantling. It appeared that the value of 24 cars gave the best satisfactory result.
- Building on scenario AC, and adding another operator to join the left out dedicated operator. The results were less than that of scenario AE and were not worthy of further exploration.
- Building on scenario AF, the dismantling time for taking out parts from red cars as well as the number of parts extracted were cut in half. This yielded only 1% increase from scenario A.

Appendix IV: Payback Period Calculations

The authors received some approximations from team lean, who compiled profit analysis on the company's sold parts (Bergqvist & Islam, 2017).

It appears that the average profit margin – accounting for only processing and dismantling costs – is 83%, which features only the most sold parts. Nevertheless, given the lack of time to dig deeper of whether the parts that were extracted by the extra operator can be sold or not, and given that the parts' type differs from one item to another, a reasonable estimation of a 20% profit margin was taken. Therefore, for every part the company sells, the price is SEK 737 and the profit is SEK 147.4.

Payback period calculations for recommendation 1: it is common in Sweden that an operator's yearly cost is about SEK 500,000. Therefore, the required number of parts to break even is by dividing the investment cost by the profit per part, which yields about 3,393 parts. Given that the scrap rate is 10%, therefore, 3,733 parts should be dismantled more than the base model. Within the first 40.95 weeks (12 months) of adding the extra operator (phase 1), slightly more than that output is produced. Therefore, 1 year should be enough to pay back the operator's investment.

Payback period calculations for recommendation 2: the shop floor manager highlighted that one depolluting equipment costs about SEK 100,000. It is estimated therefore that buying and installing two new depolluting equipment as well as reinstalling the equipment from the VC TAD building into the other building would cost about SEK 300,000 in total. Similarly, the required number of parts to break even would be 2,036 parts. Given that the scrap rate is 10%, therefore, 2,239 parts should be dismantled more than the base model. During the first phase of this recommendation (Scenario AB), the period required to produce these parts appeared to be 40.95 weeks (12 months). Therefore, 1 year should be enough to pay back the associated investments.