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SPARE PARTS ON DEMAND USING ADDITIVE MANUFACTURING: A SIMULATION MODEL FOR COST EVALUATION

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ABSTRACT

SPARE PARTS ON DEMAND USING ADDITIVE MANUFACTURING:

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Little is known about the impact of additive manufacturing in the spare part supply chain. A few studies are available, but they focus on specific parts and their applications only. A general model, which can be adapted to different applications, is nonexistent. This dissertation proposes a decision making framework that enables an interested practitioner/manager to decide whether using additive manufacturing to make spare parts on demand is economical when compared to conventional warehousing strategy. The framework consists of two major components: a general discrete event simulation model and a process of designing a wide range of simulation scenarios. The goal of the dissertation is to help verify existing as well as gain new knowledge about operations of additive manufacturing and the cost implication in the spare parts supply chains. Particularly, the proposed model enables simulation based analysis with various strategies, setups, specific parts, machines and system operating parameters. Furthermore, the process related issues of interest are the influence of building speed, building space volume, material price, machine purchase price and cool down time. Strategy related issues are multi-machine and multi-material production strategies in several setups. Also simulation investigation of different spare part stock properties are executed and analyzed by using different part size distributions.

This dissertation establishes fundamental understanding of the characteristics of the additive manufacturing system for spare part supply strategies. This model could directly help the decision-making processes in whether to adopt additive manufacturing technology, and also helps the evaluation of different additive manufacturing strategies when the technology is adopted.

Both decisions (adoption and strategies) are made based on cost analysis for spare parts in a broader supply chain.

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1 INTRODUCTION

1.1 ADDITIVE MANUFACTURING FOR SPARE PART SUPPLY

Additive manufacturing is a relatively new discipline with a wide range of research opportunities. This thesis explores the application of Additive Manufacturing (AM) in the context of Rapid Manufacturing (RM). It is of special interest which potentials are provided by AM technologies to influence spare part stocks in an industrial environment. This thought can be taken further to isolated environments, meaning that the spare part supply is not possible by a supplier in an optimal way. Examples for application can reach from using AM for the spare part supply on an air craft carrier, space or arctic missions and in ordinary workshops which need to store simple parts due to a geographical, temporary or logistical isolation. A practical example can be an automotive supplier. Nowadays they need to store the spare parts, and/ or special tools, to react fast to an uncertain demand over an undefined period of time. This strongly affects the supply strategy and leads to economical drawbacks. Producing spare parts on demand by using AM is a good option to avoid high inventory and the related drawbacks. In comparison to ordinary part manufacturing, where relatively long lead times are common, spare part production on demand has strong restrictions with respect to delivery time of the parts. If a faulty part needs to be replaced and delivery or the replacement takes too long, this might lead to significant production losses and therefore high penalties. Due to this, "spare parts on demand" needs to be a well-considered concept, especially with respect to the application and performance of AM.

AM is a new form of manufacturing technology, which could have the potential to replace several manufacturing technologies and produce parts directly. When the requirements for a cost efficient manufacturing process can be met, AM technology can be a viable option for an improved supply of spare parts in industrial environments. According to Holmström et al (2010) "Further research is needed to develop conceptually the development of AM in the spare parts supply chain. However, the greatest challenge for research is empirical research. Field research and case research is needed to describe actual solution designs considered by different OEMs[1], as well as collecting empirical evidence on the effects and challenges of introducing AM in the spare parts supply chain" (Holmström, Partanen, Tuomi, & Walter, 2010)

To date, it is not common to integrate AM into the spare part supply chain. This is due to the unawareness of potential users, the ongoing development of the technology, and missing field experience of application. To contribute to the field of AM, this work will gain knowledge about the impact of AM to the spare part supply chain. In particular, we propose a cost evaluation framework that enables managers to decide is using AM to make spare parts is cost effective. The most instrumental to the proposed decision framework is a simulation model that helps to systematically evaluate and verify the performance of AM in the spare part supply chain. The simulation allows the change of parameters in a given set of conditions and foresees the effects on the performance. The goal is to execute fundamental research by simulating with the key parameters building space volume, building speed, machine purchase price, material cost and several production strategies in order to execute sensitivity analysis. Once validated, this model will allow to make predictions from a logistic and strategic perspective of including AM into the spare part supply, and therefore support decision making based on the understanding of spare part supply system characteristics.

[1] Original equipment manufacturers

1.2 PROBLEM STATEMENT

Today not much is known about the performance of AM machines in the spare part supply chain. Several authors worked on the development of strategies for spare part selection, maintenance and warehousing strategies. These studies are highly specific, depending on the particular parts being studied and the associated companies. In a more general setting, it is not yet clear how AM contributes to the spare part supply chain. This study intends to fill this gap.

The limited literature on simulation models for AM (for example Holmström et al (2010)) only address the economic effects of implementing AM for spare part supply. They do not allow for direct changes of performance parameters of the AM machines. In our view, it is essential to have the ability to change system parameters or technology to verify system behavior in several setups and gain fundamental knowledge. Given the fact that a variety of AM systems exist, practical testing is nearly impossible, especially in regards to their effects on the supply chain. Thus, it is necessary to develop a simulation model that enables simulation of realistic spare part scenarios, and to evaluate and verify the performance of AM for improvement of spare part supply.

1.3 RESEARCH OBJECTIVES

The objective of this work is to emphasize the establishment of understanding to the potential impact of additive manufacturing on the spare part supply strategy. Simulation is the selected tool that allows to compare different setups and strategies of using AM for spare part supply. The simulation model itself is meant as a framework, which will verify and gain fundamental knowledge. That is an important approach for the decision-making processes and supports evaluation of different AM strategies or setups. Strategies and setups will include specific spare part parameters such as geometric dimensions, material, or time to delivery[2] and machine specific parameters such as building speed, building volume or possible materials. These kind of parameters are used to evaluate changes in the supply strategy and/ or in the AM technology. Through this model the total cost generated by using AM spare part supply can be compared directly to other supply chain strategies such as classic warehousing strategies. The model is intended to be general and capable of being adapted to different applications.

The first step for reaching the defined goal is to execute a literature review on existing models and a summary of the findings. The second step is to develop a simulation model using Arena. The simulation model for spare parts on demand will be able to simulate the AM process for a given set of spare parts, taking into account technical and economic factors. One of the results will also be a comparison between classic warehousing and the abilities of AM. This could mean to compare warehousing cost to the total part cost when using AM. The third step calculates relevant scenarios with different parameters and machine setups. Scenarios reach from evaluation of upcoming trends in AM (for example increasing building space) to simple spare part strategy changes and the effect on the total AM cost. Lastly, results are compared, analyzed and documented.

[2] Time until the spare part must to be available to avoid further negative consequences.

1.4 RESEARCH CONTRIBUTIONS

Integrating new technologies into industrial environments bears certain technical and economic risks. Therefore AM requires careful evaluation before it can be applied. For this reason, it is important that realistic scenarios can be simulated to ensure that targets can be reached. In general, this work is an extension to the work by Pérès and Noyes (2006) or Holmström et al (2010). Pérès and Noyes focus on the strategies for spare part selection on a qualitative level and Holmström et al on the simulation issue, in regards to specific make-or-buy decisions.

As contribution to the body of knowledge, a simulation model is applied, representing a framework, which will verify and gain fundamental knowledge about the characteristics of the AM spare part on-demand supply strategies. A rigorous and quantitative approach is important for decision-making processes and to support evaluation of different AM strategies or setups on an economic and technical basis. The model can be applied for flexible spare part sets and it is variable-based to allow for a quick change in the parameter set according to the topic of interest. These changes can be done for warehousing strategies (for example lead times, EOQ), spare parts (for example material, built volume, priority) and AM (for example building speed, build volume). The ability to change parameter values enables optimization of process parameters and sensitivity analysis.

A similar model enabling such a level of detail was not found during literature review.

Application for the proposed work can be found in every area where spare parts or warehousing take part. As mentioned before, examples for application of the established model can range from using AM for the spare part supply on an air craft carrier, space missions to an ordinary workshop which needs to store simple parts due to geographic, temporary or logistical isolation, or other strategic reasons, for example form postponement. When the technology has matured to reach a wider group of interested users, the ability to simulate properly is a strong support for the decision process if it is an option to supply spare parts by AM.

1.5 OUTLINE

The dissertation gives an overview of the existing work and presents the proceeding and findings of this work. The following chapters are structured as follows:

Chapter 2 - is a literature review on existing works for simulating spare parts on demand by AM.

Chapter 3 - introduces the procedure of applying a simulation model and presents the developed simulation model in detail. Planned experiments and tasks are described.

Chapter 4 - describes the planned experiments.

Chapter 5, 6 & 7 – describe adjustments of the applied simulation models, proceeding, results and findings of the technical investigations and additive strategy investigations.

Chapter 8 – summarizes findings of chapter 5, 6, and 7, contains further conclusions and presents a process description for simulation of spare parts by AM, important factors for evaluation and an option to fit the spare part stock to AM.

Chapter 9 – presents an overview of the application of spare parts on demand by AM, taking the latest findings into consideration.

Appendix - introduces the reader to Arena by describing basic components of Arena and contains all results calculated during simulation.

2 LITERATURE REVIEW

Several publications focus on production by AM and point out that it can have benefits compared to other common manufacturing techniques, especially with small lot sizes. This literature review will not focus on that issue, except of the work by Brody and Pureswaran (2013) or Simkin and Wang (2014), which can be seen as the initiating reports for this work, and which can also be adjusted to the spare part issue. It is of interest which activities were done for the use of AM in the spare part supply chain.

Brody and Pureswaran (2013) published a report which describes the combined impact of 3D manufacturing, intelligent robotics and open source electronics. They analyzed the bills of materials down to the part, modeled the manufacturing and the distribution of manufacturing over the planet, and applied a software defined supply chain. The model allowed changes to the requirements, scale, location, cost, etc.

The result is the assumption that a "reconfigured global supply chain will emerge in the coming decade. It will radically change the nature of manufacturing in the electronic industry, shifting global trade flows and altering the competitive landscape for both enterprise and policy makers." (Brody & Pureswaran, 2013) They found that cost savings can reach an average of 23 %, the economies of scale are reduced by 90 % and the CO_2 "supply chain" footprint has the potential to be reduced.

This report was the most complete model found during the review. In fact, it is mind opening but does not allow a direct view on the spare part problem, since it focuses on the supply chain and the impact of new technologies on it. The further proceeding is adapted to the spare parts on demand issue described previously. The proceeding and results of this work can be used as input for further studies in this field.

In 2014 Simkin and Wang presented a cost-benefit analyses for final produced parts. In general they analyze if "just because a part can be produced using AM does not necessarily mean that it should be" (Simkin & Wang, 2014). They apply a cost-benefit analysis for a specific part and simulate the effects of changes in the AM parameter setup on this specific case on a cost basis, which is similar to what is presented in this work. But again the main focus is on regular production and the related cost. Specific issues related to spare parts are not taken into consideration.

Not many researchers did research on the application on AM in the spare part supply, but several articles were found by two researchers in cooperation with other scientists.

Pérès and Noyes (2006) present an interesting article "Making spare parts on demand in situ and on demand - State of the art and guidelines for further developments" (Pérès & Noyes, 2006). They focus on isolated systems and how AM can influence the spare part supply situation. They describe several isolated situations and present a comparison of time distribution for various strategies of spare part procurement. The comparison of the strategies is qualitative and compares classical maintenance (spare parts on stock), classical maintenance (no spare parts on stock), and rapid spare part manufacturing. Basically, it has demonstrated that order-, waiting time, and reception in a classic supply system can be significantly reduced by application of AM. Also examples of testing AM technology for use in space missions or the concept of the mobile part hospital, used by military in geographically isolated situations, is presented. Based on their experience they propose several fields where research is valuable. To sum these points up, research is required to check for the applicability of AM in the spare part supply chain.

The basic assumptions of Pérès and Noyes (2006) are comparable to industrial situations, since time and cost aspects are the same for industry.

Holmström et al (2010) work on the concept of including AM into the spare part supply chain. They compare distributed and centralized AM to replace inventory holding and conventional distribution. They present an example of deployment of distributed AM in the aircraft spare parts supply chain, where significant reductions in holding cost with an improved service level were achieved. They conclude that centralized AM by specialized service providers will show the biggest benefits at the current state. However, this will change to decentralized AM when the technology matures to a better state. This means a movement of the AM technology closer to the point of use. Also this article recommends further research to find possible applications of AM and the setup in the supply chain.

Other work by Hasan and Rennie or Peng et al (2013) strongly refer to the work of Holmström and extend the issue to the effects of AM to the supply chain for specific cases. Peng et al (2013) apply the Supply Chain Operations Reference Model (SCOR) for the aircraft spare part supply chain, and they conclude that AM is contributing to improvements.

General research for common industrial situations is missing, especially how AM centers perform in a decentralized setup.

2.1 OPPORTUNITY FOR ISOLATED SYSTEMS AND REMOTE PRODUCTION CONTROL

Next to applied maintenance, warehousing and supply strategies in industry such as spare part analysis, outsourcing, postponement and relocating the decoupling point, AM also gives the option to work in isolated systems and remote controlled.

The supply and warhousing issue is more complicated when the facility or any other system is isolated. To illustrate this issue, more information and definitions about isolated systems and supply strategies follow.

Pérès and Noyes (2006) describe the following isolated systems:

Geographically isolated - When accessibility is difficult because of lack of communication (polar regions, high mountains, thick forest, etc.), the nature of the environment (air, sea, space, ...) or possible on-site risks (for example battle fields, epidemiological areas).

Logistically isolated - Whenever external conditions govern the supply operations (Pérès F. , Grenouilleau, Housseini, & Martin, 2002).

Temporarily isolated - One example is the system that dependents on elements likely to disappear at the end of a given period of time (for example closure of production lines for profitability reasons).

Having an isolated system, with respect to spare parts, might result in having every part available as a spare part at any given time to maintain a continuous operation. For as long as the stock of spare parts allows such conditions this might be a solution. However, in practice this is not a realistic scenario, since it is an expensive solution. It gets even more difficult when the system becomes complex or big and consists of a large number of parts. It may also be impossible to provide such a stock, due to lack of room or economic reasons. Pérès et al (2002) question how to handle the problem of choosing the wrong spare parts or the wrong number of spare parts when having an isolated system, since both can lead to a serious impact on performance and budget. For example elements with a limited life time are easy to maintain (for example filters), but it gets more difficult when unexpected spares are needed.

In contribution to solve the problems of isolated systems a special option arose up during development of information technology and machines using CAD data for processing. Holmström et al (2010) comments that "the introduction of information technology has a potentially revolutionizing effect on the provision of spare parts" (Kennedy, Patterson, & Fredendall, 2002). Tay et al (2001) underline that AM-technologies can be used in a remote controlled way. Remote controled part preparation becomes possible because CAD or machine specific information like maximum use of building space, can be transfered through adapted networks. Also monitoring the process itself is possible, by installation of for example a camera. Merely the pre- and post-processing dependends on skilled operators until a specific technology is developed to cover these tasks as well. According to Tay et al (2001) especially the use of the internet can bypass logistical problems if the user/ initiator and the physical hardware are separated. One of the aspects is the use for AM, where service providers can benefit in their low volume manufacturing by utilizing their AM-machines by pooling jobs. As a consequence, a remote access to manufacturing in geographically isolated areas becomes possible. In general, this principle is applicable for all AM-technologies. The link to temporary isolated systems is simple too, since CAD data is easy to store and can last as long as the data-storage is available. To mention another point, Holmström et al (2010) state that using information technology in combination with AM is a strong argument for using 3D design tools to produce seldom used spare parts to order with various manufacturing technologies such as CNC or AM. Also the logistical isolation is improved as long as the material for manufacturing is available, since new designs can be transferred "online".

2.2 MANUFACTURING USING AM TECHNOLOGIES

As stated previously, AM experienced new developments regarding new technologies and applications. Rapid Manufacturing is based on the same technology basis and has therefore also been developed further (Gebhardt, 2007). To use the AM technology in operative applications, a certain quality, which is equivalent to requirements for the specific element, is necessary at a competitive cost level. Smith P.G. (1999) discussed that product development projects typically balance four objectives to achieve the biggest benefit with applicable technologies. These can also be applied for the spare part issue:

1. Performance objective - The product should satisfy the features and performance levels of the product specification.
2. Cost objective - Meet the cost target for the resulting production.
3. Expense objective - Run the development project in a certain budget.
4. Schedule objective - Run the project in a given time frame.

Pérès and Noyes (2006) take the thought of spare parts on demand even further, which means thinking about spare part manufacturing on request in a short time. Usually companies keep many required spare parts on stock to reach a maximum of availability of spares. As discussed before, the drawback of this strategy is the related cost and that it may not be possible to meet the required targets with this stock. The situation becomes more difficult at the point when a complex system can be defined as a geographically or temporarily isolated system. This combination of isolated and complex system can lead to a high stock volume, which will result in higher cost and, depending on the case, a lack of room or increased warehousing cost.

Zäh (2006) and several other authors state that AM can have a great impact on the spare part stocks. The simplicity is given by manufacturing highly complex geometries by pushing a button at the moment the item is available as a 3D-CAD model. Depending on the specific part and used technology, it is possible to work cost efficiently with a lot size of one. Having the opportunity to manufacture complex parts with small lot sizes opens up the chance to reduce stock size to a minimum and replace several steps in the supply chain of spare parts (Pérès & Noyes, 2006). It might be sufficient to store a 3D-CAD file and reproducing the needed part on demand, which will change the storage of parts to a storage of data, which is more economic than storing parts physically over many years.

Pérès and Noyes (2006) show a good theoretical illustration using RM technologies to improve the maintenance level in temporary isolated situations. Figure 2-1 shows the comparison between "classical maintenance strategies with and without spare parts in stock and the strategy based on the rapid spare parts manufacturing concept", which can be an advantage in specific cases. Smith and Reinertsen (1998) addresses the topic of time compression and time saving opportunities.

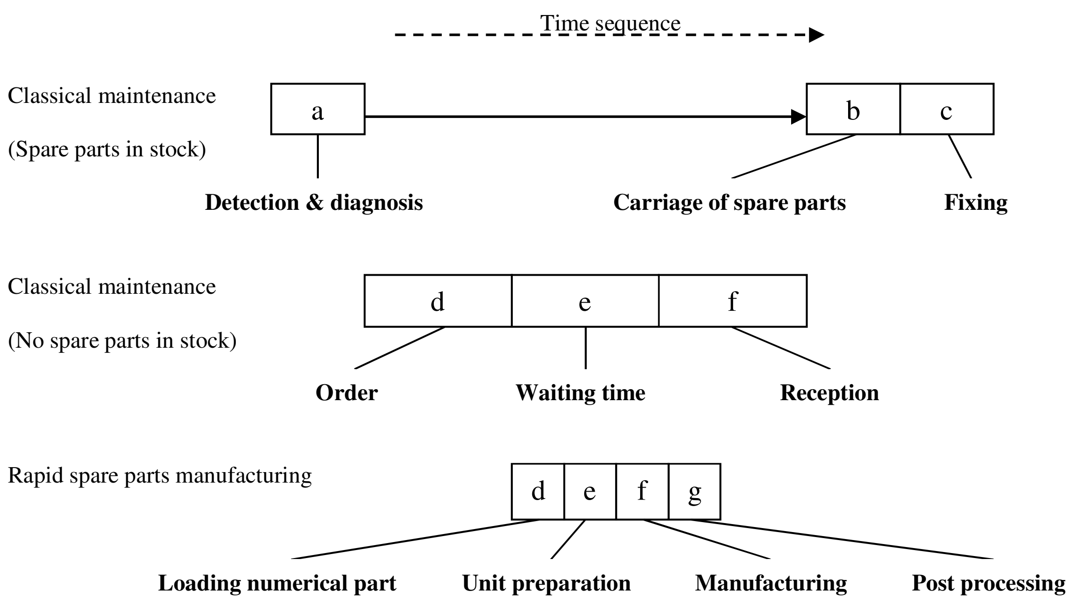

Figure 2-1: Comparison of time distribution for various strategies of spare parts procurement (Pérès & Noyes, 2006)

As can be seen, Figure 2-1 does not include time information. It is only a qualitative overview about the idea of the supply concepts, but it is important since it shows the lack of research at this point to show potentials. Pérès and Durand (2002) filled in that lack of information by calculating the required time to maintain a space station sub-system, but this is not valid for a typical industrial environment on earth. To reach more information on this topic, research is necessary in this area.

It must be stated that other manufacturing technologies exist. However, basically traditional manufacturing technologies such as CNC are a standard in manufacturing and will not be further discussed here, since information is widely available. The use of AM technologies is new because "Producing functional parts is the evolution of layer manufacturing." (Atzeni, Iuliano, Minetola, & Salmi, 2010). When AM machines are able to deliver sufficient part properties, "product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies" (Gibson, Rosen, & Stucker, 2010) can be maximized.

2.2.1 ADVANTAGES AND POSSIBILITIES

When AM technology matures to the point that it can be easily used for manufacturing it will have advantages to traditional manufacturing. Especially with respect to isolated systems Pérès and Noyes (2006) list several strong reasons for the use of AM technologies in supply issues:

- "Due to their nature, these technologies are fast and can be adapted to the reactivity need inherent in the resumption of the operation of the system by replacing a faulty component.
- They are also self-sufficient in so far nearly no intermediary operation takes place between the digital file making and the part making.
- Once the manufacture is launched, no operator has to supervise the work in progress.
- They make it possible to achieve excellent identical parts because of the automated process.[3]
- In some cases they can be multi-purpose and can be used to work out parts made of various materials (plastics, metal, ceramics, ...)
- Most of them need only raw materials from which several articles will be made irrespectively of their functionality.
- Implementation of these technologies does usually not require bulky machines for which large floor room is necessary, but portable ones." (Pérès & Noyes, 2006)

Also Holmström et al (2010) contribute by mentioning that AM is an alternative to classical concepts to "reduce supply chain cost while at the same time improving service". They add the following arguments:

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[3] Precisely duplicating means having a reusable CAD-dataset to be used for manufacturing. (Gibson, Rosen, & Stucker, 2010)

- "No tooling is needed significantly reducing production ramp-up time and expense.
- Small production batches are feasible and economical.
- Possibility to quickly change design.[4]
- Allows products to be optimized for function (for example optimized cooling channels).
- Allows economical customized products (batch of one).
- Possibility to reduce waste.
- Potential for simpler supply chains, shorter lead times, lower inventories.
- Design customization." (Holmström, Partanen, Tuomi, & Walter, 2010)

Another advantage is that non-identical parts can be produced in one production run, as long as building space allows it (Hopkinson & Dickens, 2001), which further supports the ability of mass customization (Atzeni, Iuliano, Minetola, & Salmi, 2010). Dimitrov et al (2007) add that AM has the unique ability to produce highly complex parts quickly. Gibson et al (2010) state that CNC mainly differs in that it is primarily a subtractive rather than additive process, requiring a block of material that must be at least as big as the part which is to be made. This is a clear advantage of AM, since every shape can be formed out of a bag of powder.

Another interesting option for AM is the possibility of reverse engineering, which can also be used for remanufacturing. This is mentioned by Xing et al (2011), where used components are rebuild to a like-new condition. This addresses the field of reverse engineering, where used parts are acquired and available on demand to meet the needs of remanufacturing.

[4] This becomes possible due to the use of CAD-datasets, and can support in-situ optimization or remote control. (Pérès & Noyes, 2006) It can be understood as electronic "spare parts". (Gibson, Rosen, & Stucker, 2010)

Reverse engineering is the term for the generation of 3D-data based on an existing part. To catch the geometry of the parts calipers and coordinate measurement devices are traditional methods for generating 3D-data, which can be substituted by modern technologies today. For example laser scanning based technology does not even require direct contact to the part. This can be important for fragile or sensitive parts[5] (Zhang, Tsou, & Rosenberger, 2000). In general reverse engineering might be a solution in specific situations. Christensen and Bandyopadhyay (2000) present a general overview about the mainstream reverse systems.

Postponement is another important key-word for AM with future potential. The work of Yuen (2003) presents a framework to assist developers in choosing a good postponement strategy. The term postponement stands for a system where common platforms, components or modules are used, but the final assembly or customization does not occur until the final customer requirements are known. Van Hoek et al (1998) state that improvements in the area of postponement strategies have potential to improve distribution service quality and make companies more responsive to customers (and therefore the availability of spare parts). The point of postponement strategies is that risk and uncertainty costs can be reduced by the differentiation of goods.

2.2.2 LIMITATIONS AND CHALLENGES

During literature review it became obvious that several general challenges exist in regards to the implimentation of RM in an industrial environment. Pérès and Noyes (2006) found that previous analysis, performed by Alström, did not include the use of AM techniques. This means that there

[5] An example for a traditional method: "The traditional method for object reconstruction in paleontology is two-step process beginning with forming latex molds from fossils or specimens, and followed by creating epoxy cast of the object." (Zhang, Tsou, & Rosenberger, 2000)

is a lack of knowledge about the performance of AM in an industrialized environment, especially when it comes to spare parts.

According to Holmström et al (2010) another challenge is the limited part range, allowing an application only in specific situations.

Based on Neef et al (2005) the weaknesses can be categorized in seven bullet-points:

Speed - Even the fastest RM-machines cannot meet the speed of traditional machines. The success of AM is strongly dependent on a reduction of manufacturing time. Only when the total production cycle is taken into consideration, AM can show its potential (from design to the delivered product).

Quality - Quality is not at the same level as the quality produced by traditional machines. Post-processing might be required to reach the acceptable quality level. But AM is continuously improving this issue and results equal to traditional products will be reached.

Object size - The current state of the art allows only a limited object size for common AM machines. As a rule of thumb, an increased size of an object increases the manufacturing time, which affects the use of AM significantly and may lead to ineffectiveness. The effect inverts when the size decreases, which may lead to an advantage of AM. But this advantage can be limited by a minimal wall thickness, dependent on the used process. Dimitrov et al (2007) contribute that it is possible to manufacture parts that are bigger than the space available in the AM-machine, by splitting the part into several parts that are to be assembled later on. This may affect the assembly time and therefore enlarges the manufacturing time.

Cost - To buy and maintain an AM machine is often not economic for a company. But it is expected that an increasing market will decrease the overall cost.

Material drawbacks - The scope of materials used for AM has not yet reached the scope of traditional manufacturing, so there are no equivalents for every case (mechanical, thermal or electrical properties). However, AM offers also new possibilities such as mixing different materials in one piece, variable properties of photopolymers or upcoming possibilities in Nano-technology. Material research and development is a continuous process.

Legal issues - Main issue in the context of legal issues or intellectual property is the copy potential of parts that are available. This might lead to discussions about protecting the rights of the supplier of a specific technology, since the economic impact can be significant. At the moment, only weak protection systems are in use.

Internal difficulties and general skepticism - In addition to the mentioned points, no company will reorganize its manufacturing until noticeable benefits are certain to be the result. Established technologies complicate the implementation of AM as well. A good chance for AM is expected where highly customized products in very low quantities are required (for example customized ear plugs).

Pérès and Noyes (2006) identify other interesting issues. It is stated that today even the strongest AM technology is not ready to fulfill all the requirements of spare parts manufacturing, but good progress was made in the past years. This fact raises the question about what technology improvements are required to make AM technology a realistic option for making spare parts on demand in an industrialized environment.

Wohlers (1995) reports the biggest upcoming changes and improvements in the ratio price/ performance, material property, accuracy, software ("interface and process") and "technology enhancements (different technologies)". He further states that the properties most desired by industry are a reduced time for manufacturing functioning objects, a reduced process chain from initial design to the finished product and based on that a speed-up development process. This might be true for classical production companies, but it is not clarified whether it is also valid for spare parts.

Ruffo et al (2007) see that "there is a lack of work on the implementation of AM as a mainstream manufacturing process" (Ruffo, Tuck, & Hague, 2007). Hull et al (1995) tell about the "bad experience" of possible users. These users experienced an insufficient quality of their products with an earlier state of the art technology. They recommend a regular update about the technology to keep possible users informed, since AM is in a continuous improvement process. Atzeni et al (2010) see a challenge in the redesign for AM applications, since traditional manufacturing processes can be different compared to AM processes.

To sum up, following drawbacks exist for the implementation of AM in an industrial environment:

AM process performance - Process properties and possible object size are limited.

Limited scope of materials - The scope of materials, constant part quality and the material price are an ongoing issue.

Design - Parts need to be designed or redesigned for AM.

Management, organization and implementation - It is still difficult to get over general skepticism in industry.

Cost - It is expensive to buy and maintain an AM machine which is able to hold an industrial standard.

2.3 FURTHER PROCEEDING

As mentioned several times during review, further research is required. Unfortunately, not many practical applications are known. For this reason simulation seems to be an appropriate tool to estimate the behavior of AM machines when they are placed in a decentralized supply chain. The software which will be used to execute the simulation is Arena. This software is fully hierarchical and allows the user to setup simulations by use of a simple graphical interface. A short introduction into Arena can be found in the appendix, which gives readers who are not familiar with the software an overview about its concept and functionality.

It should be stated here that simulation is strongly dependent on available data, which requires an intense data collection to have a representative model. Due to the fact of unavailable practical data the input data will have to be estimated. Selection of the right interfaces of the model can allow for reduced required input, focusing on performance data. Regardless, simulation seems an appropriate tool, since it allows to measure system performance, effects of various inputs, or improved system setups as well as detailed analysis of a system. All of this can be done without the physical system, and allows to run experiments without inflicting harm on an actual system.

3 SIMULATION OF SPARE PARTS ON DEMAND

In order to define the problem an extended literature review was executed to define an appropriate problem which would be able to contribute to ongoing research activities. Over the course of several discussions it became clear that a simulation model, showing the performance of an AM machine, would be of biggest interest. This is in accordance with other manufacturing simulation approaches, where a variety of cases is simulated to evaluate performance of manufacturing. Often the goal of these simulations is "to develop a simulated workshop for designers to conceptual design work while taking into account manufacturing process information" (Xu, Zhao, & Baines, 2000). Other problems were decided to be of minor interest for the scope of this work, so it was possible to set clear boundaries for the research problem. The system and concept of the simulation will be discussed in the following chapters.

Kelton et. al (2010) present several aspects which are typical and important for a simulation study. They sum things up as a multi-step procedure to support the development of simulation studies. The steps of the procedure are to (1) understand the system, (2) be clear about goals, (3) formulate the model representation, (4) translate into modeling software, (5) verify the simulation model, (6) validate the model, (7) design the experiments, (8) run the experiments, (9) analyze the results, (10) get inside the results, (11) document what is done.

The proceeding is applied for the development of the simulation model.

3.1 UNDERSTANDING THE SYSTEM

Two points of interest were found in regards to spare parts on demand. One is to select the correct spare parts and the other is to test if the system will work in an acceptable range. Since the main interest of this work is to evaluate the performance of an AM machine, simulation was found promising in gaining results without having a real system to perform tests. To do so, the AM process with all of its parameters was analyzed to get a full picture of what happens when the AM machine is set in a spare part supply chain. It is important to mention that the model aims to be on a generic level and based on this allows to make predictions of future development. The further work will assume that the process of spare part selection was executed previously to deliver input for the simulation model.

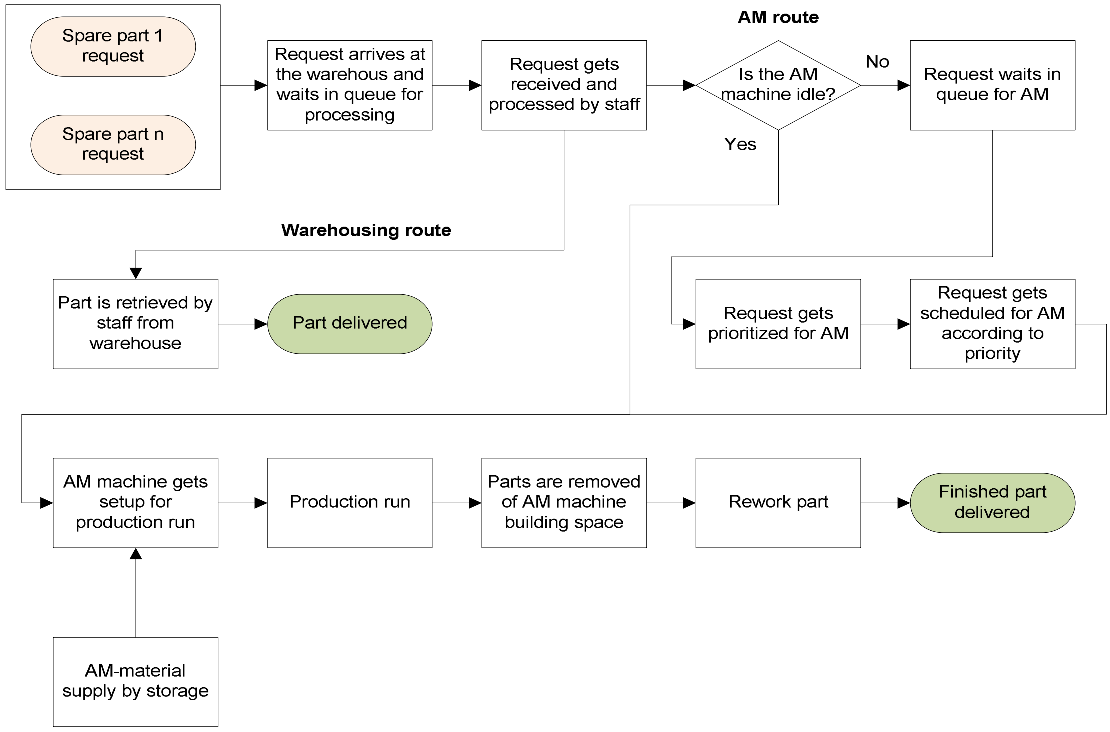


Figure 3-1: Process of AM vs. warehousing

In the following paragraphs the simulation model will be mapped out and explained in detail to help the understanding of the process. This will also define the scope of the simulation, which ranges from the arrival of a spare part request all the way to the final delivery of the requested item. Since the simulation model aims to compare the AM results with classical warehousing, so both will be included in the simulation. Accurate details will be included when the model is translated to Arena.

Spare part request - The process starts when a spare part is requested, which can be understood as order of a spare part. The request for the part can be based on various reasons. It can be based on a maintenance strategy or a random request for a part. For this work it will be assumed that it is possible for every requested part to be manufactured by AM. Furthermore it is assumed that all pre-work to allow AM has already been done. This means that engineering was done and the CAD data is available to run the AM process. In consequence all part information like material, geometric parameters, time to manufacture, priority or cost of unavailability are available.

Request waits in queue for processing - The request will arrive and has to wait until a member of staff can receive it. This time is based on the availability of the staff, following opening times or shifts. This is an important factor when spare parts must be available in a relatively narrow time window.

Request gets received and processed - When the staff is ready to receive the request it will be processed further, which contains a processing time for the request. At this point the process is split up. One route follows the warehousing route, the other one will follow the AM route. To enable the comparison between AM and warehousing parts both processes run in parallel. The warehouse route will be explained first.

Part retrieved by staff from warehouse - The staff picks the part from the warehouse and delivers the part directly. This often results in a relatively short processing time. The related cost and warehouse data are updated and available immediately when the part is delivered and leaves the system. A blink on Figure 3-1 allows to see that the process of warehousing follows a simpler process than AM. Since a wider scope of the model is assumed not to be beneficial for the results, the model is not more detailed for the warehousing route.

Check if AM machine is idle - The first step in the AM route is to check if the AM machine is idle. When the AM machine is idle the production can start immediately. If the machine is not idle the part has to wait in queue until the AM machine is idle.

Request waits in queue - When direct spare part supply by AM is the target, the AM process has longer processing times than warehousing, therefore queuing of the requests becomes a relevant issue and prioritization is necessary to have the right part available on time. The required lead time of parts can reach from several weeks, having to be available as soon as possible, or somewhere in-between. The time in queue is an important factor for the overall system performance.

Request gets prioritized for AM - The basic prioritization should already be predefined in the priority of the part when it enters the system. Prioritization in this case is a loop process, updating the priorities before each production run. It may happen that parts have to wait for several production runs due to their lower priority or that parts need to be produced immediately. This means that the prioritization needs to follow a logic that always updates the priority, setting up the most important parts for the next production run.

Request gets scheduled for production - Based on the latest priorities the production run is planned. This means that the building space is planned to be filled with parts until the volume is filled up. The batch is then ready for production.

AM machine setup for production run - Before a production run starts, the AM machine needs to be prepared by staff who will take the necessary actions such as for example preheating and assuring conditioning of the machine to fulfill the production run without failure.

AM material supply - The AM material is a consumable for the AM process. Material must be available during the whole process, in order to have a successful production run. Therefore storage of the material is important to keep the process running.

Production run - The production runs automatically and no further activities are needed during production. The production itself is dependent on the performance parameters of the AM machine. The best example for a performance parameter is the building speed, which has a strong influence on the production time. The production will run until the batched parts are finished.

Removal of parts from building space - The parts are removed by staff from the building space. Depending on the setup of the machine that might influence the proceeding. for example fixed building space compared to exchangeable building space. The removal of parts also includes maintenance actions such as cleaning the machine.

Rework of part - After production of the part it is possible that a part may need rework in order to reach the final quality. Parts which need rework will need some extra time before they are delivered, while parts that do not need rework, only cleaning, can be delivered directly. Cleaning is assumed to be a standard rework activity.

Both the AM and the warehousing solution, have benefits and draw backs. While AM is promising in reducing warehousing cost, problems might occur when spare parts are not available on time due to the AM process time. On the other hand warehousing generates higher cost for parts which are used seldom, but parts are available immediately up on request. The simulation model is able to compare both, and makes it possible to compare both solutions on an economical basis and to find boundaries for a useful application of AM in the spare part supply chain, and to evaluate the impact of parameter changes.

3.2 ESTABLISHING CLEAR GOALS

Having defined the targets for the simulation model, we now discuss which method will produce realistic results to meet the targets.

1. A simulation model is to be developed, representing reality as close as possible. The model should be verified to have trust in the results and variations in the performance parameter. However, a validation will not be possible, due to a missing real system.
2. A realistic base case is to be set up. This means integrating a spare part request, staff and AM performance parameters, warehousing cost, and other assumptions on a realistic level. If real information is available, it is used. Examples for assumptions are spare part requests or warehousing costs. Defined parameters are available for the AM machines or materials.
3. Communicate the base case and set up alternative scenarios for further evaluation and execute experiments manipulating the parameters of interest. At the current state the machine parameters building space, building speed and material cost are of major interest, such as several production strategies.

A variety of actions have been considered in achieving the above scope. The overall goal is to make the effect of changes in the performance parameter set visible. Simulation will support decisions in the development of AM machines, especially focusing on the application of AM in the spare part supply chain.

3.3 FORMULATION OF MODEL REPRESENTATION

The model follows the described process. It seems most effective to follow the requests through the process and see what the effect is on the system and how fast parts can be delivered, which is important for spare parts.

The request generation can be assumed to be an easy task, since it follows probabilistic distributions which can be formulated easily. The arrival in the system and waiting for processing also does not need a lot of attention.

The process gets more complicated when parts are already in production and queuing occurs. The parts in the queue will need special attention with respect to prioritization. The model allows to bring the parts in an appropriate order for the next production run. The rules for prioritization will be described in detail in Chapter 3.4. Prioritization is essential for having the parts in time as often as possible. The prioritization should include the allowed time for manufacturing, processing time, time in queue, priority of the part, and the resulting place in the queue for the next production run. When the prioritization is clarified the rest of the process is a straight forward calculation of the results of interest.

For the calculation of the results and processing times the model needs a carful setup so that all important factors can be taken into account. A detailed description of this will be included in Section 3.4.

It is of major interest to have a flexible model that allows manipulating the arriving part requests and to exchange the AM machine type.

Since the model should result in a comparison of AM and warehousing in the spare part supply, the warehouse should be represented on a level of detail which allows an acceptable insight. It is decided that the stock values of a stock represent the basis to calculate the warehousing cost. It must be assured that changes in the stock are tracked. It is further assumed that the generated warehousing costs are directly related to the individual part and no further calculations are required. Also, the relevant warehouse data will be explained in Section 3.4.

The time frame for the model cannot be set without a given set of requested spare parts. Spare parts can be stocked for many years without being used once. Depending on the case, a spare part type can also have a daily turnover. Predictions of usage are not possible for every case. A practical solution to solve this issue is to stress the system with a spare part set and focus on the volume of the parts. To illustrate, the AM machine is able to supply spare parts with an average of 24 hours when the average requested build volume is 7000 cm^3. With respect to the building cycles which can easily extent to over 8 hours, and bearing in mind that staff may work according in shifts or on fixed opening times, it is proposed to simulate over the course of one year. In this year planned and unplanned requests should occur with different states of priority. When real data is available, the request simulation and the time frame can be adjusted accordingly.

When real data becomes available, several information is of interest. It starts with the basic spare part information. For each part a description, unique ID, number on stock, material, value per part, usage statistics, associated storage cost, priority, geometric information, EOQ and the accepted time to delivery should be known. To gather this data it is likely that different sources will be used. The warehousing data is probably accessible in form of historical in-house data, observations, or other kinds of log books or lists. What will most likely not be included in the warehouse data is the priority and accepted time to delivery of each part. When warehousing, parts are typically available immediately and it is not necessary to define these attributes. The assignment of priorities and accepted time to deliver each part should be done as a group between the model developer and representatives of the organization interested in the topic. It might require an extensive work load and discussions to define the attributes for each part properly.

Schedules for staff can be collected and included in the simulation model.

AM machine data is provided by suppliers of AM machines and is available. Websites or direct communication with the supplier is sufficient to find proper information.

Further details and proceedings were setup during the work and are described in the further text.

3.4 TRANSLATION TO MODELING SOFTWARE

After describing the model it needs to be translated to the modeling software. The used software is Arena, what allows a good graphical display of the model. This chapter describes in detail the setup and abilities of the model. Figure 3-2 shows the finished base model after a simulation run.

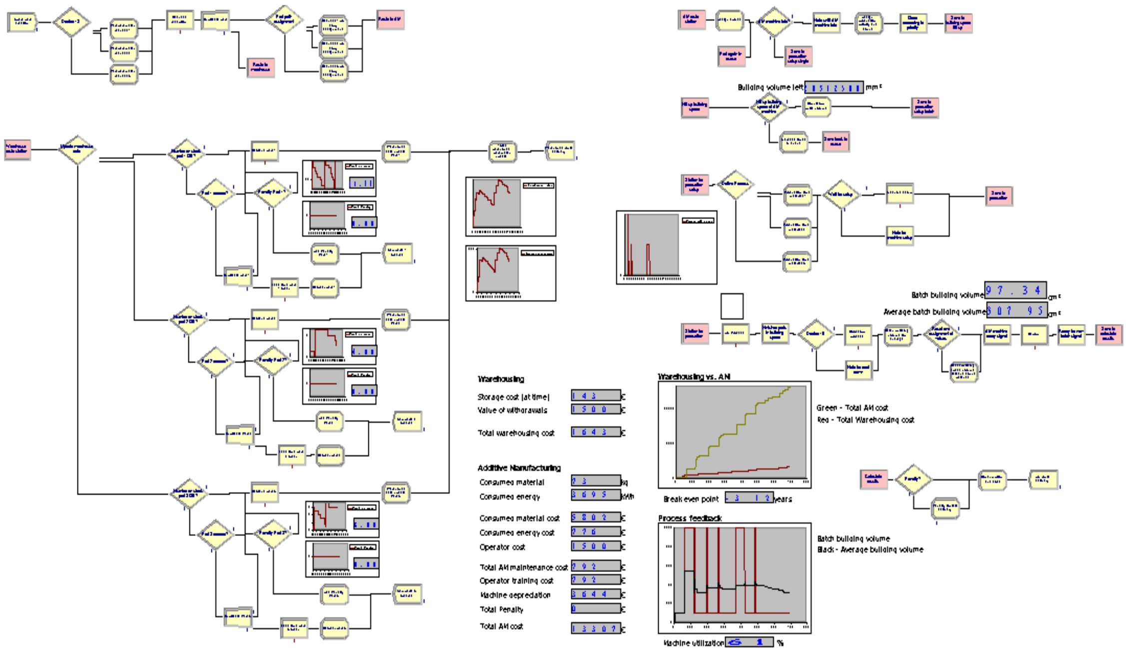


Figure 3-2: Full view of the simulation model

At this point the setup of the base model is explained in detail to keep a better overview about the different modules and sections of the model. After the general description of the simulation model the extensions to the full model will be described in later chapters.

This will include the issues selected spare part set, run times, replications of simulation runs and further model adjustments to meet the specific scenarios. During experiments several parameters or settings might be changed due to required adjustments. Changes of are documented when they are executed.

The model begins with at the run setup where initial model parameters are set. Figure 3-3 shows the used parameters in the run setup dialogue box. To reduce the standard deviation of the results, the model will run 150 times for each scenario. The model will have a warm up period of 720 hours (one month). This allows to start observing the system when it is in a steady state. The total run time for each replication will be 1440 hours (simulation over 2 month). Based on this, the replication length represents one month. The basic model assumes a 24/7 schedule, since the machine must produce whenever it is needed to meet the spare part requirements. The used base time unit is in hours through the whole model.

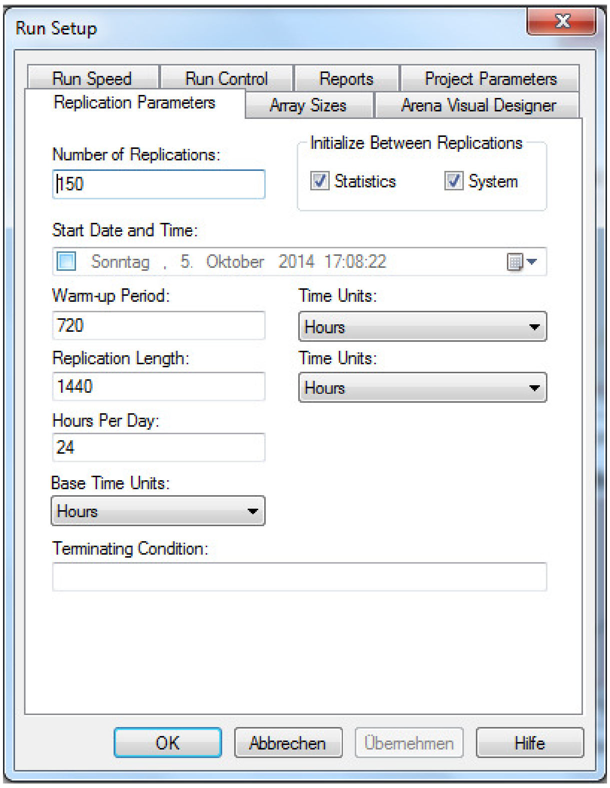


Figure 3-3: Run setup

3.4.1 CREATION OF PARTS AND ROUTING

Figure 3-4 shows the first section of the model where spare part requests are created, parameters assigned, parts are duplicated, routed to the warehouse and the AM machine for further processing.

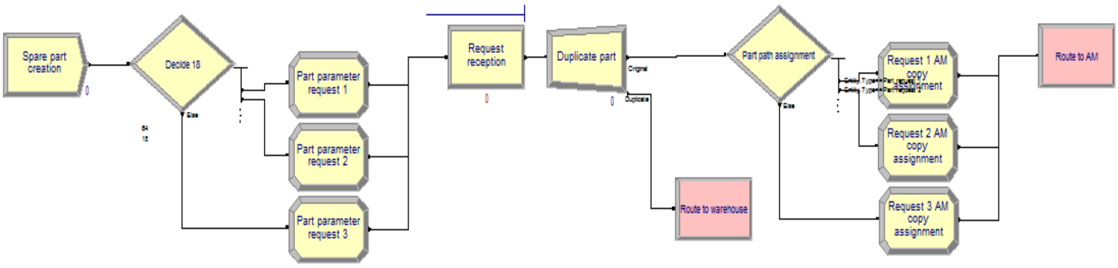


Figure 3-4: Creation of parts and routing

The model starts with a create module which generates all spare part requests. The time between arrivals is set to a uniform distribution with a minimum of 0.25 hrs and a maximum of 45 hrs. According to Kelton et al (2010) a uniform distribution should be used when only little is known about the present situation and provides a “worst case” setting. If more information should become available, it is possible to change this setting accordingly. The number of generated entities per arrival is one.

After an entity is created, it enters a decide module. The decide module is set to N-way by chance, which routes the arriving entities to the following assign modules, based on a percentage chance. The assign module assigns part specific attributes to each part request. The appendix holds an overview about all attributes and variables used in the model. Specifically, the following attributes are assigned in the “Part parameter request” module:

Table 3-1: Assignment of attributes to part at "Part parameter request 1" assignment module

Name	Description	Unit
Building volume	Product of building height, width and length of the part.	mm^3
Building depth	Describes the building depth of the part.	mm
Building width	Describes the building width of the part.	mm
Bulding height	Describes the building height of the part.	mm
EOQ Part 1	Economic order quantity of part 1.	pcs
Material type	Material type assignment by use of integer number.	---
Operator cost	Estimated cost of required operator for this part.	€/ pcs
Part value Part 1	Purchase price of part 1.	€/ pcs
Penalty	Receives the penalty value of each part for further calculation.	€/ pcs
Penalty Part 1	Penalty when part 1 is not delivered in time.	€/ pcs
Priority	Pre-assigned priority of part as production order basis.	---
Reorder point part 1	Reorder point of part 1.	pcs

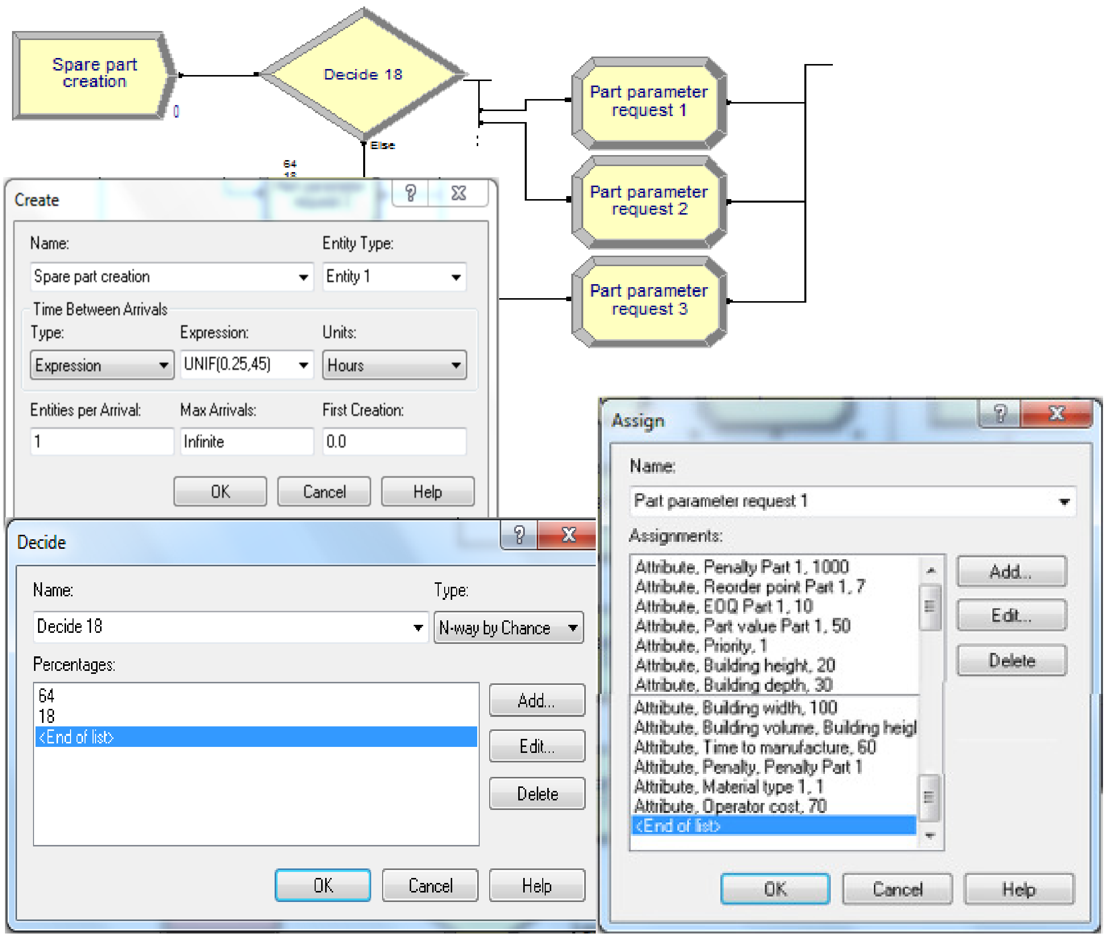


Figure 3-5: Creation of spare part request and attribute assignment

Attributes marked with a number (for example "Part 1") are valid for the specific part only and are used to allow a precise routing and treatment of the part throughout the model. Attributes which do not have the numbering are general and assigned to each spare part request regardless of the type of spare part. For example, in the second (and further) assign module "Part parameter request 2" "Penalty Part 1" is called "Penalty Part 2", while Priority is again named priority.

A process module in the setting "Seize Delay Release" is the next step for each entity. The process module is called "Request reception" and simulates what its name states. The reception seizes a Reception Staff who will need an average of 0.1 hours to process the request. For this model it is assumed that one receptionist is available 24 hours each day. It could be an option to use more receptionists or to use a shift plan by applying a schedule. Also, the time for processing can be changed and adjusted to the individual case.

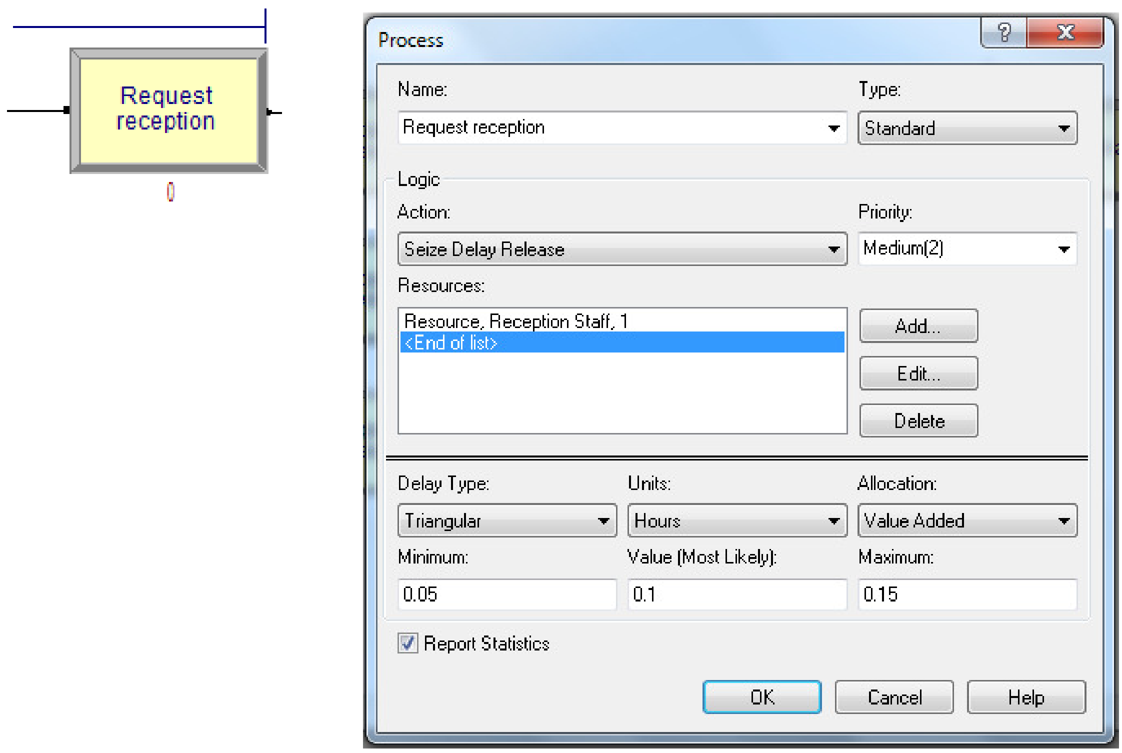


Figure 3-6: Request receptionist

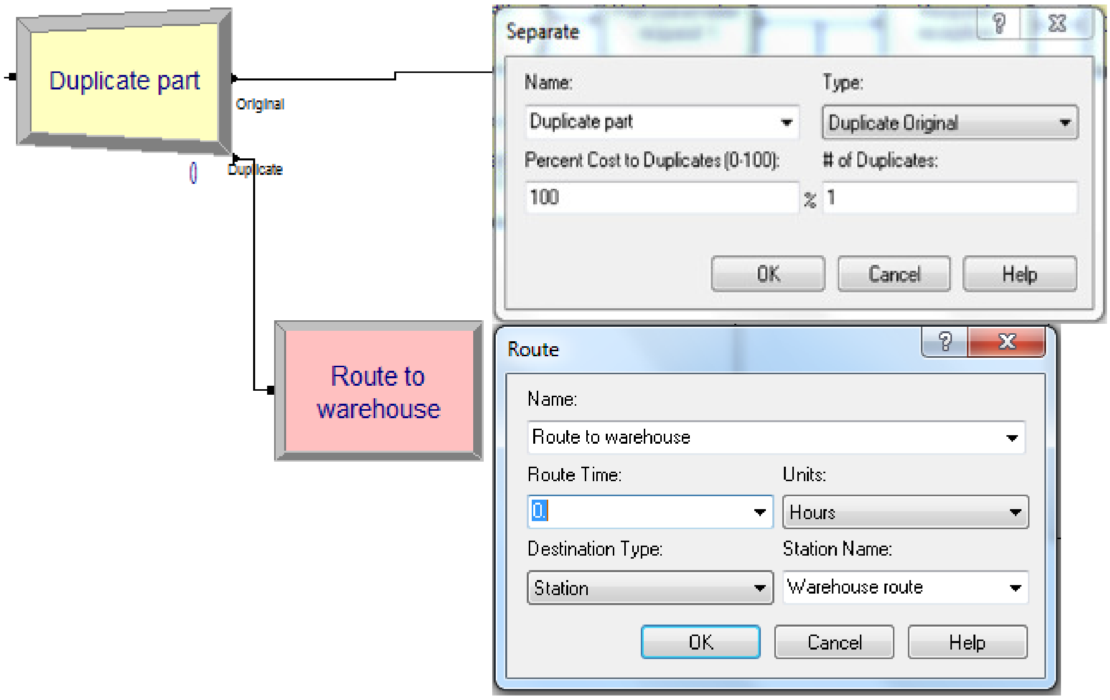


Figure 3-7: Duplicate part requests and route to warehouse route

When the entity is registered at the reception, it continues its way through the model and is duplicated. The duplicate is directly send to the warehouse route where it is processed, while the original part is routed in the direction of the AM process.

Before the part is allowed to enter the AM route another assignment must be done. To do this, a decide module is used in combination with assign modules to make the correct assignments.

The decide module splits the arriving entities based on the entity type. "Part request 1" follows path one, "Part request 2" follows path two and so on. This way, each entity is directed to the correct assign module. Each entity type is now renamed in the assign module with addition "AM". Example: "Part request 1" is renamed "Part request 1 AM". The entities can then be routed to the AM path by use of a route module.

To duplicate the original part is important to have the original named parts and the renamed parts separately in the model, which is essential to treat both independently and reach full flexibility of the model. It is also essential to analyze both independently in the results later on. It is possible to look into for example processing times or other statistics in detail of “Part request 1” and “Part request 1 AM” in detail which allows to compare both directly.

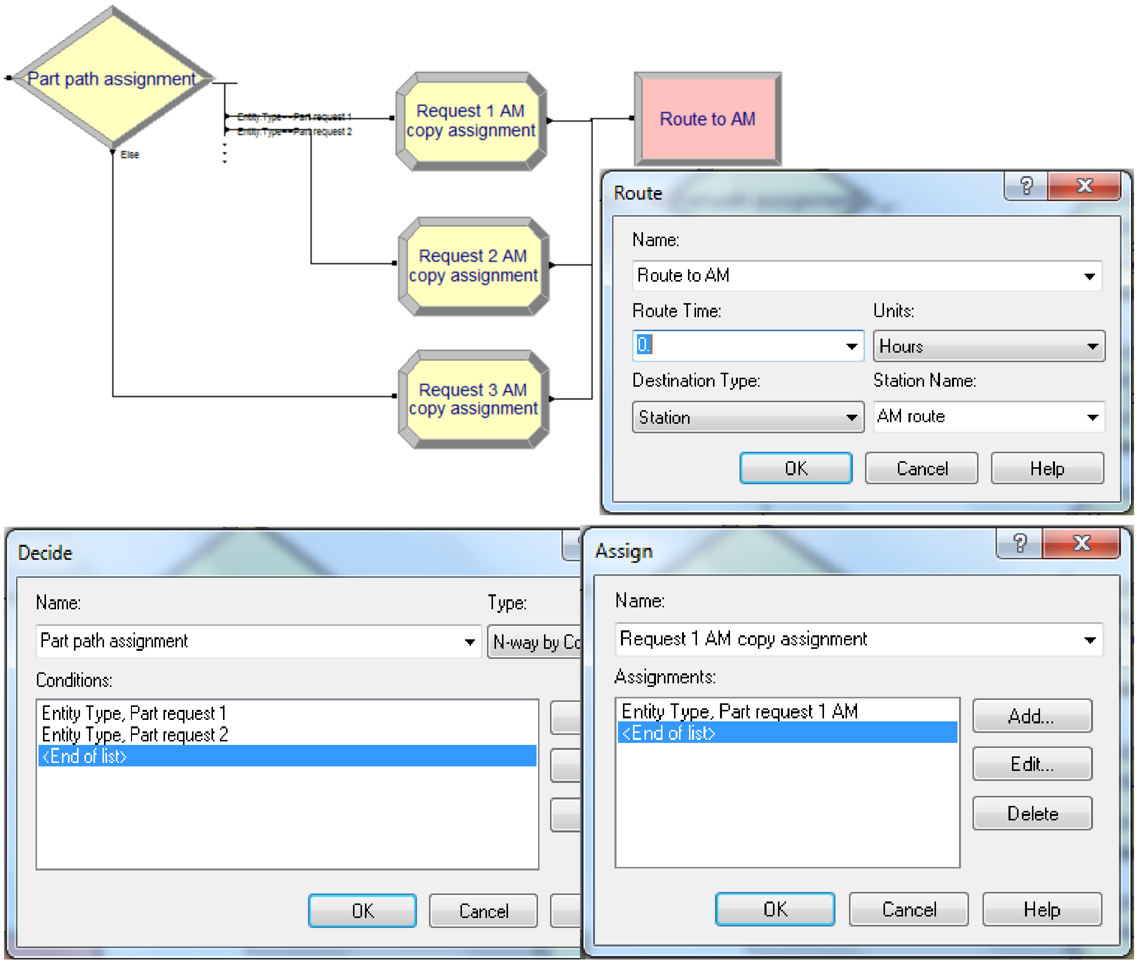
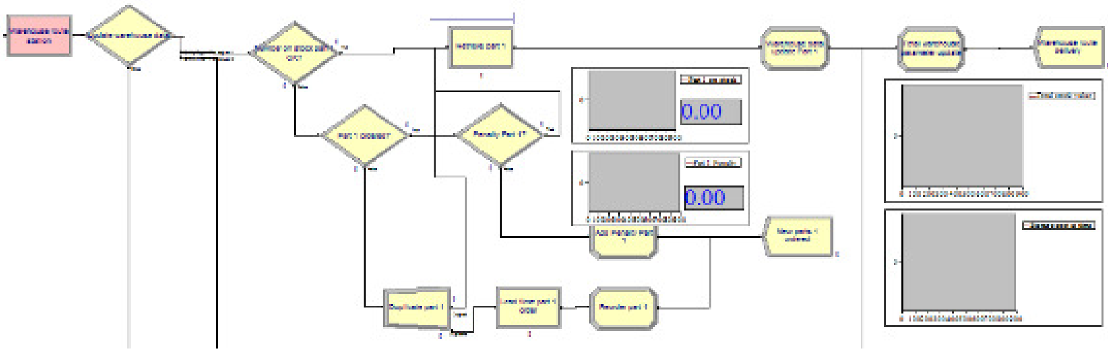


Figure 3-8: Rename entities

3.4.2 WAREHOUSE ROUTE



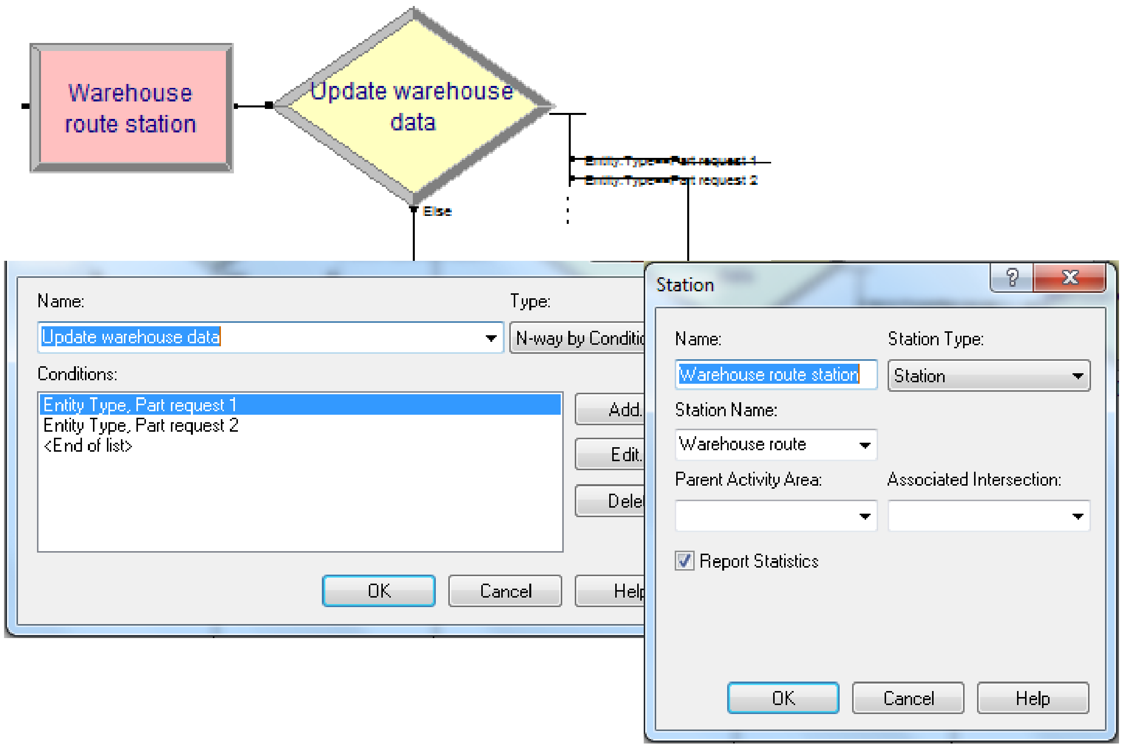


Figure 3-9: Warehouse route station, split up and path for Part request 1

First the warehouse route is described. The entities are sent from the route module and arrive at the "Warehouse route station", which is called "Warehouse route". The spare part requests are now in the ware house simulation part of the model. After the station module the spare part requests are split up according to their entity type in a decide module called "Update warehouse data" to update the warehouse data on an individual basis. Part request 1 follows path one, Part request 2 follows path two and so on. This way of dividing the paths allows to keep track of every spare part and stock individually.

In this description only the path of Part request 1 is followed. All other paths are equal in the setup, except that they are set up as an independent path for another part request. A decide module occurs first on the individual path. It is checked if the Number on stock of Part 1 is bigger than the reorder point. If this is true the part request can continue on its way, otherwise new parts must be ordered.

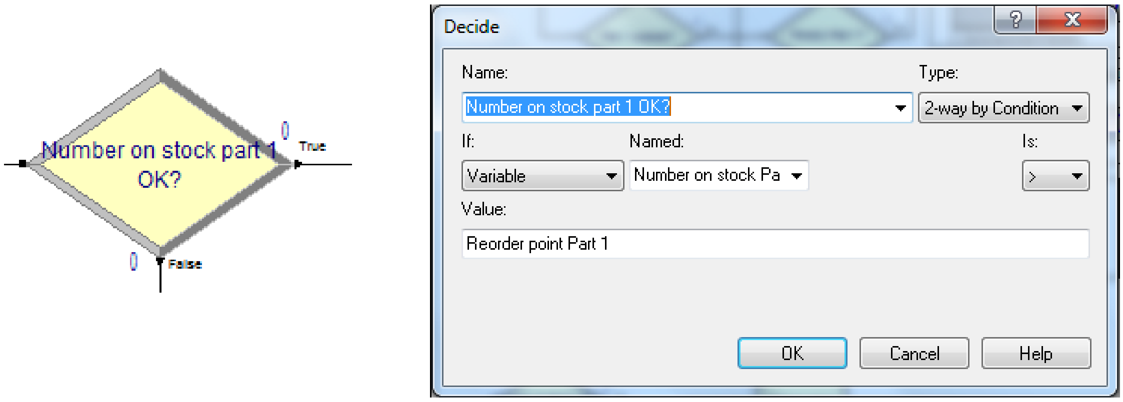


Figure 3-10: Check if number of parts on stock is ok

Next it must be checked if an order is already placed. Therefore the process module "Lead time part 1 order" is used in combination with a decide module. The process module uses the logic action Delay applying a uniform distribution with a minimum of 7.5 hours and a maximum of 36 hours. This time represents the reorder lead time of a specific part type. The type of distribution and values can be adjusted in every intended way to fit the purpose. When there is no entity in the process the WIP is set equal to 0, while it is 1 when the process is active. The WIP is used to control the way of the part requests.

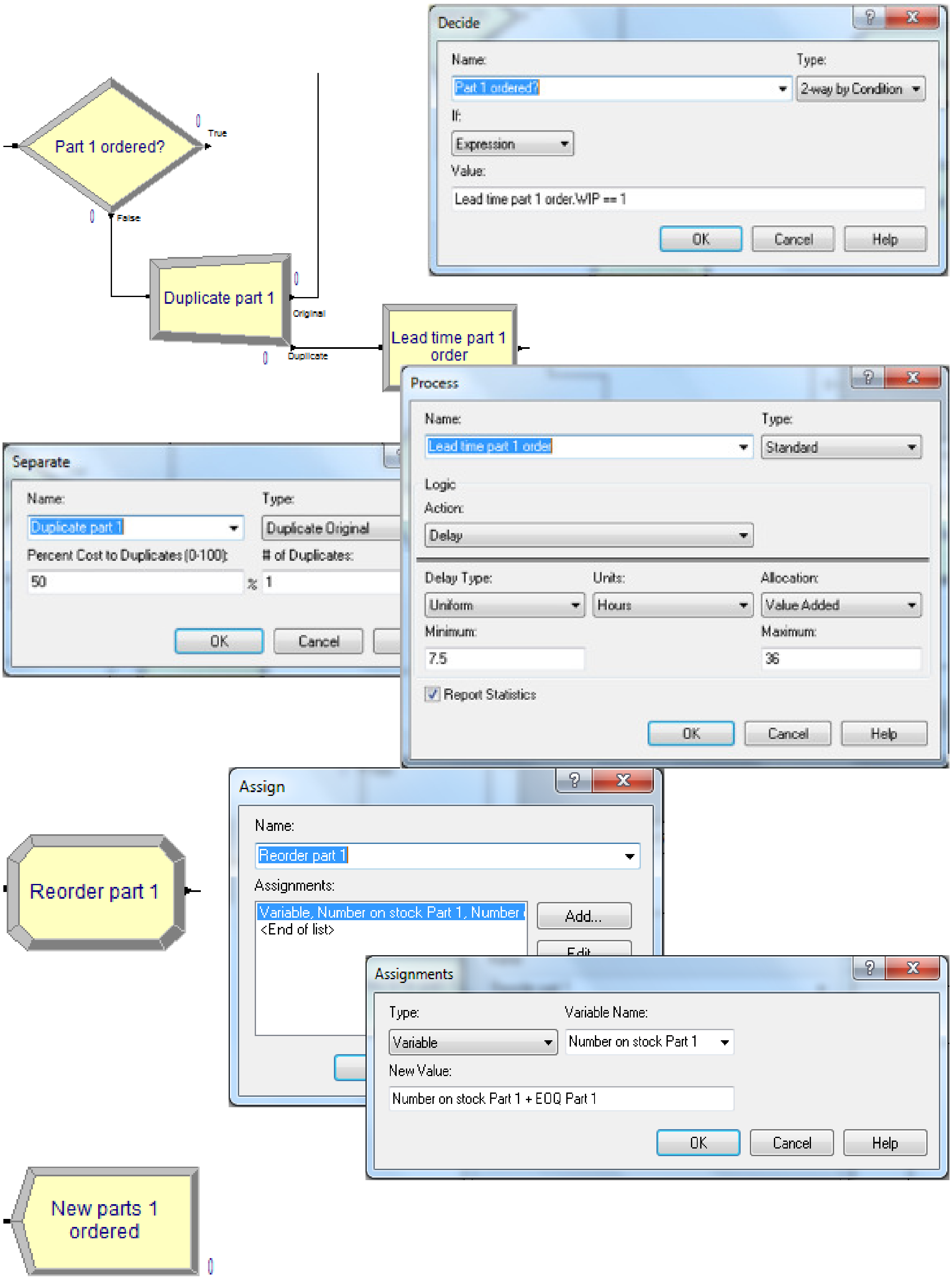


Figure 3-11: Ordering new batch of parts

The decide module "Part 1 ordered" checks if the process of "Lead time part 1 order" is active or not. When it is active the part request is seen as true and follows this path. Otherwise the part request follows the false path and enters the process module, where it simulates the lead time until the new batch arrives. After the lead time is over, the part request enters an assign module, where the number of parts on stock is updated. The updated number on stock adds up the current number on stock and the EOQ. (Both, reorder lead time and EOQ can later be used to optimize the spare part stock.) After the assignment, the request is disposed in the dispose module "New parts 1 ordered". In order to keep the running request active, a separate module is used to make a copy of the part request. The original part request returns to the normal path, while the copy enters the process module to delay the part order. This means the duplicate is just used to initiate the order. The original part is then treated as every other part following this path and enters the process module "Retrieve part 1". The retrieve process module will be described later.

The true path of the decide module "Part 1 ordered" leads to a decide module called "Penalty Part 1". The decide module checks if the number of part 1 on stock is bigger than 0. If the number on stock is bigger than 0 the part request is send to the process module "Retrieve part 1". If the number on stock is equal to 0, it is not possible to deliver the part and a penalty is charged. To charge the penalty an assign module is used. The new variable "Part 1 Penalty" is defined at this position. If a penalty is charged, related to part one, it is added to "Part 1 Penalty", which represents the total penalty of part one during the simulation run. When the new value of "Part 1 Penalty" is assigned the part request is disposed at the dispose module "New parts 1 ordered", which was also used for the reorder logic.

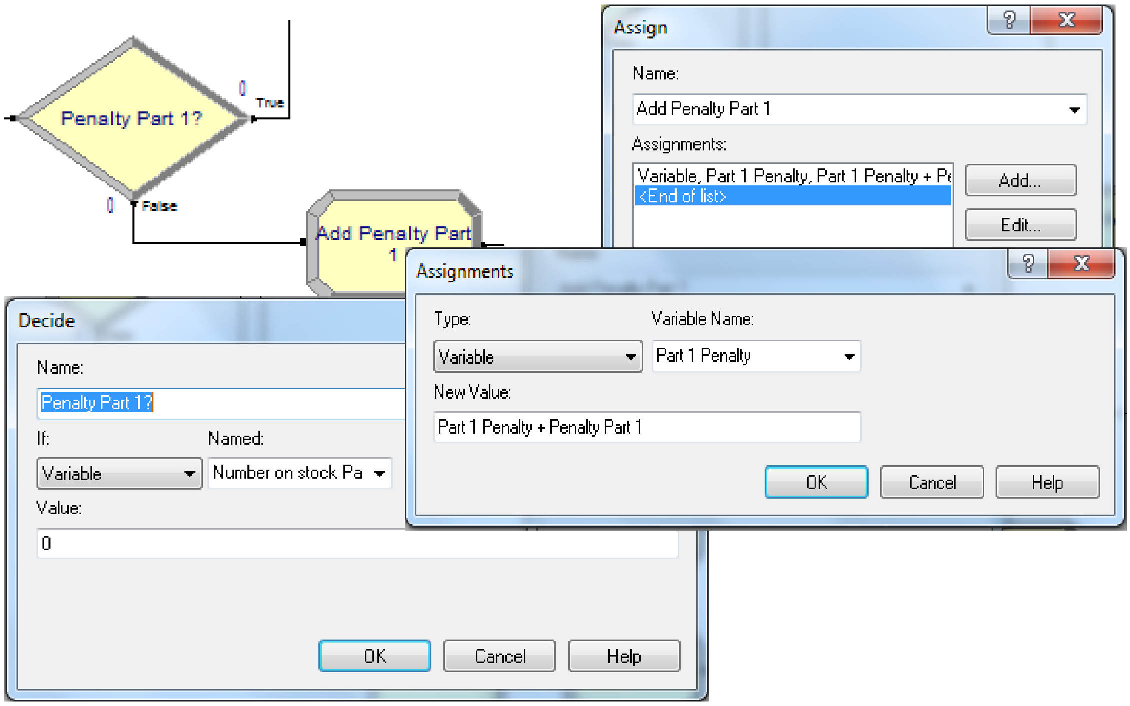


Figure 3-12: Check for penalty and adding it

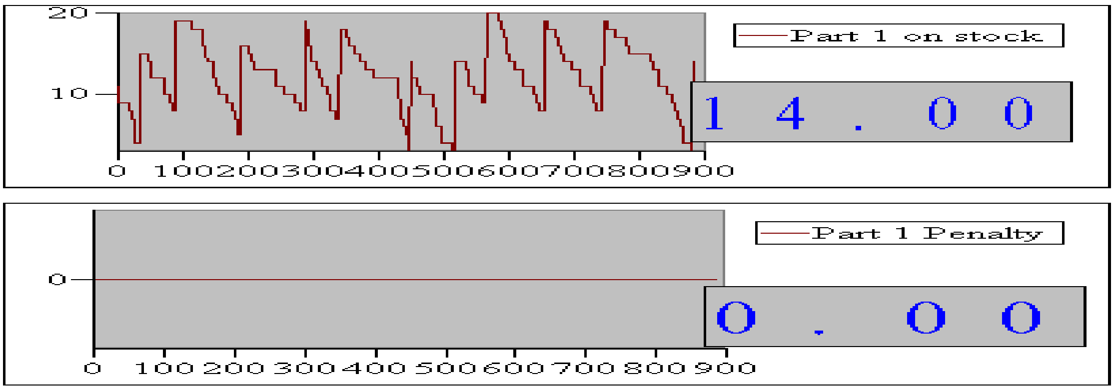
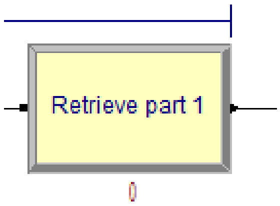


Figure 3-13: Graphical display of Part 1 on stock and Part 1 Penalty (after simulation run)

At this point it might be interesting to introduce to the two graphs in Figure 3-13. One tracks the variable "Number on stock Part 1", the other one "Part 1 Penalty". The displays are mainly used for debugging and an overview of the stock behavior. Both graphs are used to minimize the parts on stock in the later proceeding, for each spare part type individually. A general policy for the stock will be one of each part type will be on stock, EOQ is set to zero and the reorder lead time follows the previously mentioned distribution. A penalty will not be accepted for any part type. If a penalty occurs during simulation, the number of stored parts and EOQ are increased for the specific item until no penalty is created. No changes on the reorder lead time are intended.

The process module "Retrieve part 1" simulates the picking of the parts from the warehouse. A resource called Picker Staff is used to execute this action. In this model 1 picker is used to get all requested parts from the warehouse (Part 1, 2, and 3). The number of pickers might be extended and/ or schedule based. Also the processing time can be adjusted.



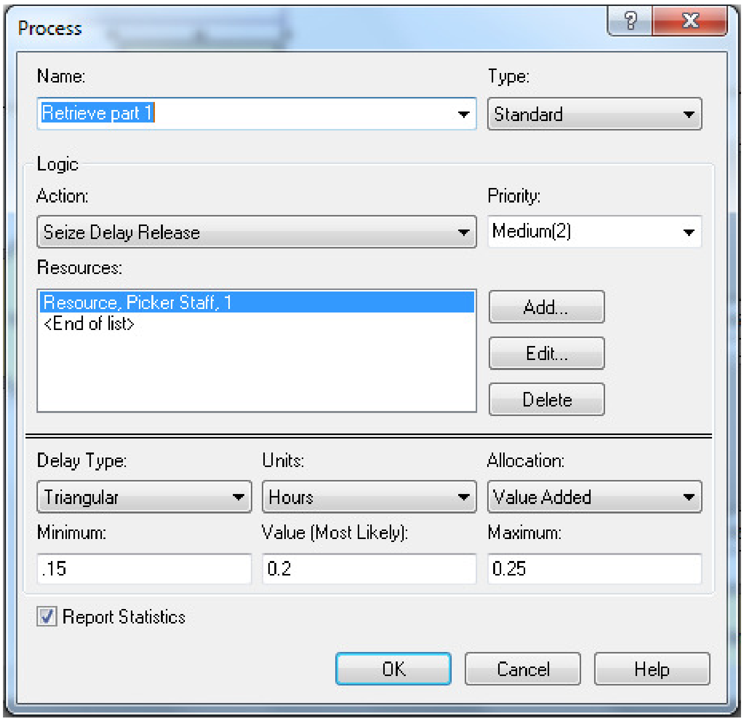


Figure 3-14: Process module - Retrieve part 1

After retrieving part 1 from the warehouse and serving the spare part request the warehouse data must be updated. An assign module is used to do so. Three new variables are defined. "Value withdrawals Part 1consumed parts", "Stock value of Part 1" and "Number on stock part 1". The related calculations can be seen in Figure 3-15. What should be noted is that the initial values of each defined variable is 0 as an internal standard setting of Arena. This is important because the initial value of "Number on stock part 1" is intended to be set to a specific value. This is done in the variable module of the basic process panel. For part 1 it is set to 11 to have a start value (could also be 0 and every other integer number).

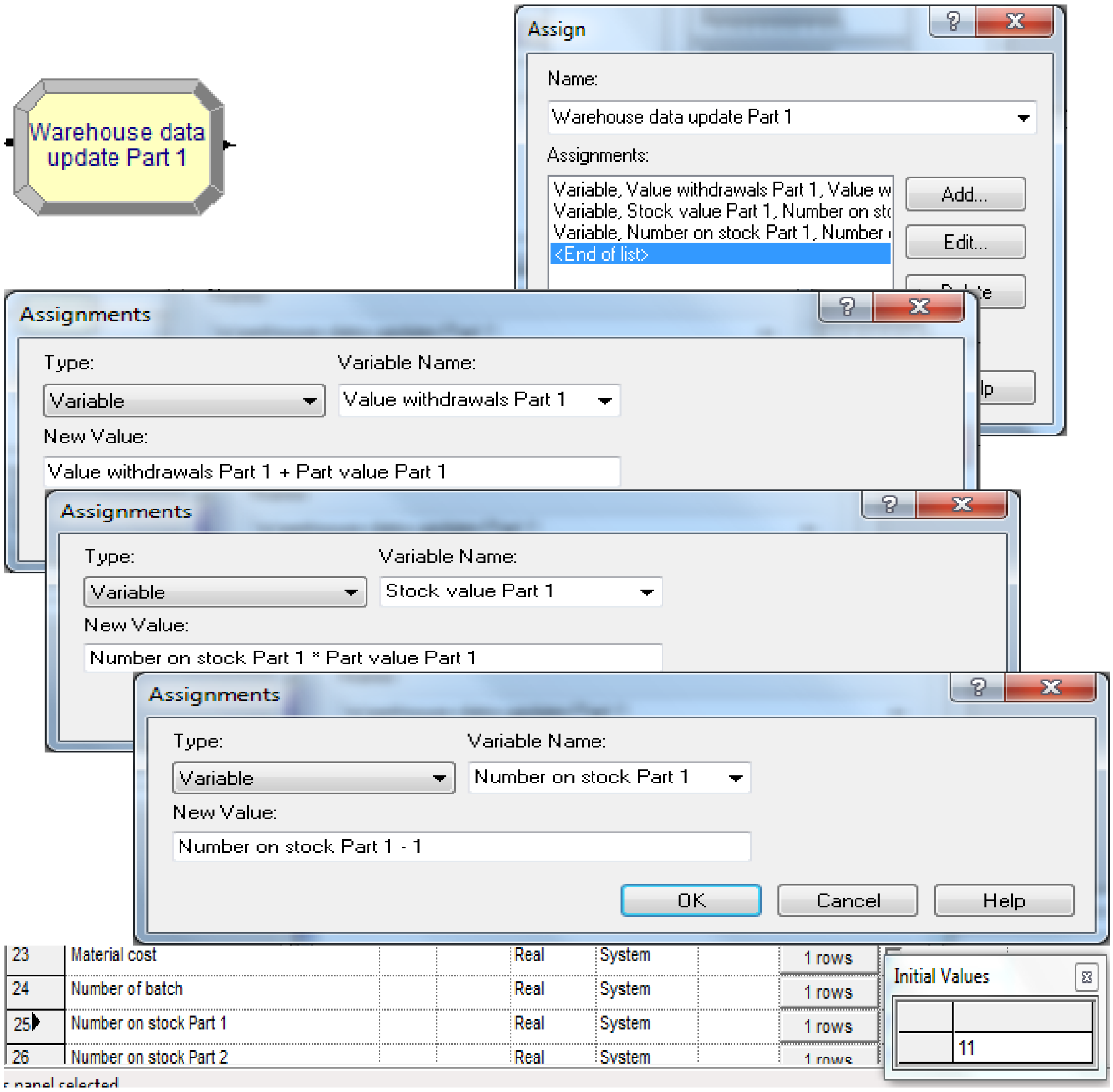


Figure 3-15: Warehouse data update

After the warehouse data update of each individual part, the total warehouse parameters are updated. This happens in the assign module "Total warehouse parameter update". Four new variables are defined: "Total stock value" - adds up the total stock value of each spare part type.

"Part value consumed" - Adds up the total value of parts taken from stock

"Storage cost at time" - Takes the total stock value and calculates the storage cost by multiplying the total stock value with the storage cost. "Storage cost" is also a new defined variable. The storage cost are set as a fixed percentage value which assumes that for every part on stock the same percentage of cost is generated based on the part value (set to 13 % in this example), covering all cost.

"Total warehousing cost" - Is the sum of the total withdrawal value and the storage cost at time.

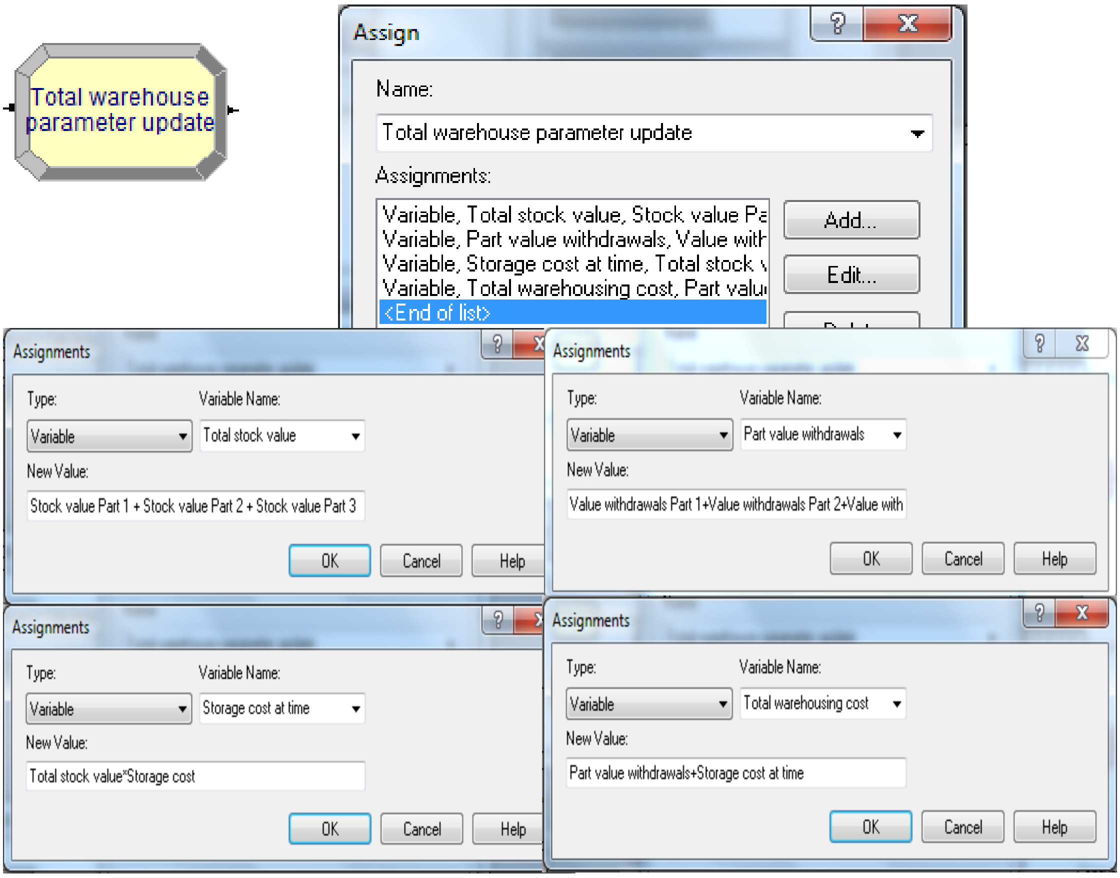


Figure 3-16: Updating total warehouse parameter

After that the spare part request is disposed in a dispose module called "Warehouse route delivery".

To have an overview of the results of the warehousing route, graphical displays and output fields help. Therefore the relevant displays with sample results are shown in Figure 3-17.

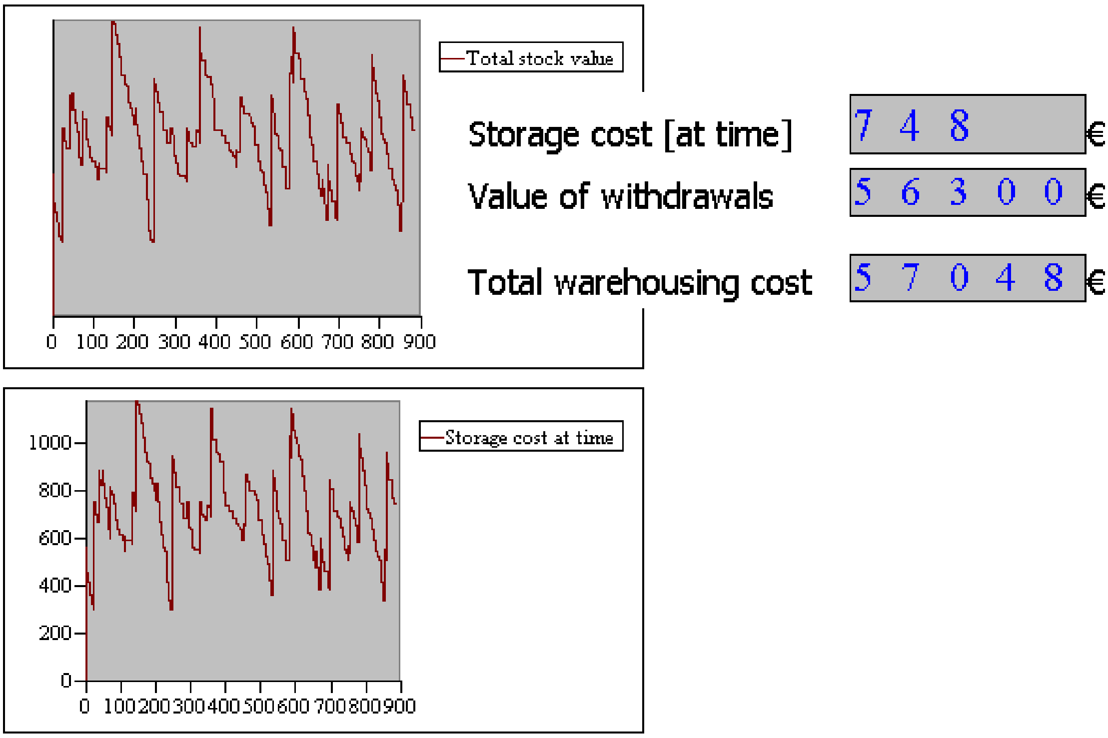


Figure 3-17: Results of the warehousing route

3.4.3 AM ROUTE ARRIVAL AND QUEUEING

As stated earlier the original spare part requests are routed to an AM route, which models the whole AM process from preparation, over the process itself and rework activities.

The AM route starts with a station, "AM route station", followed by an assign module, "Assign arrival". The AM route station follows its function and receives the spare part request. Route and station modules are used often in the following, so they will not be explained in detail, since functionality should be clear.

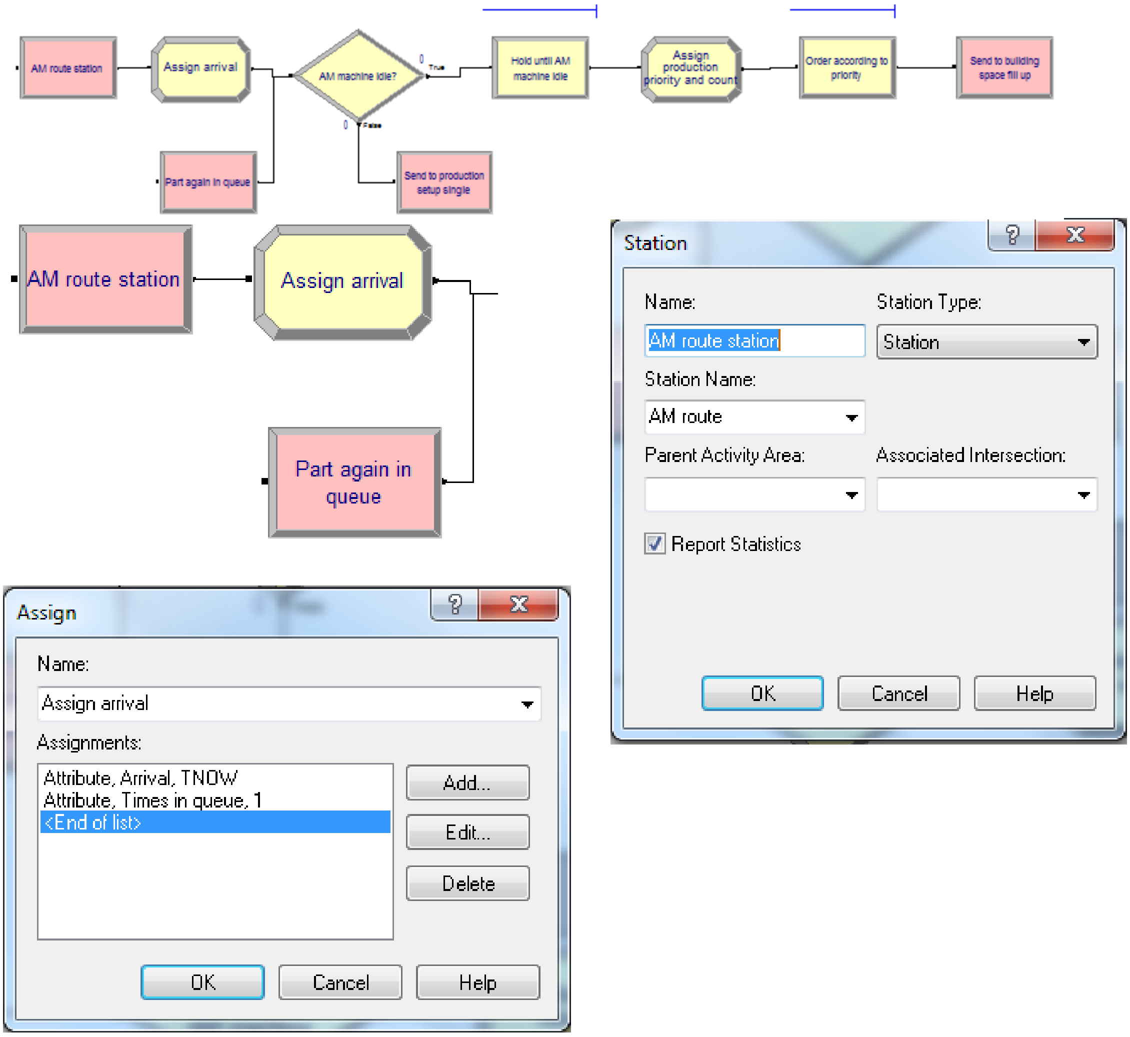


Figure 3-18: Queuing logic and arrival in AM route

Next the part request enters an assign module, which assigns the arrival time and how often the part entered the queue of the AM processing. "Times in queue" is set to 1 initially because the part request arrives for the first time in the queue. This value will be used and updated through further simulation. Another station module is added to the arrival section. Parts which were not allowed to enter the production process for a production run will arrive at "Part again in queue" and enter the queue for the next production run again.

"AM machine idle?" is a decide module which is used to check if the AM machine is idle and can be used for processing. If the machine is idle the part request will be routed to "Station for production setup" directly and production will be initiated for one part only. Details about production setup will follow later. When the AM machine is not idle, further steps are required due to the fact that queuing will occur, which can have significant impact on the delivery time of the finished parts.

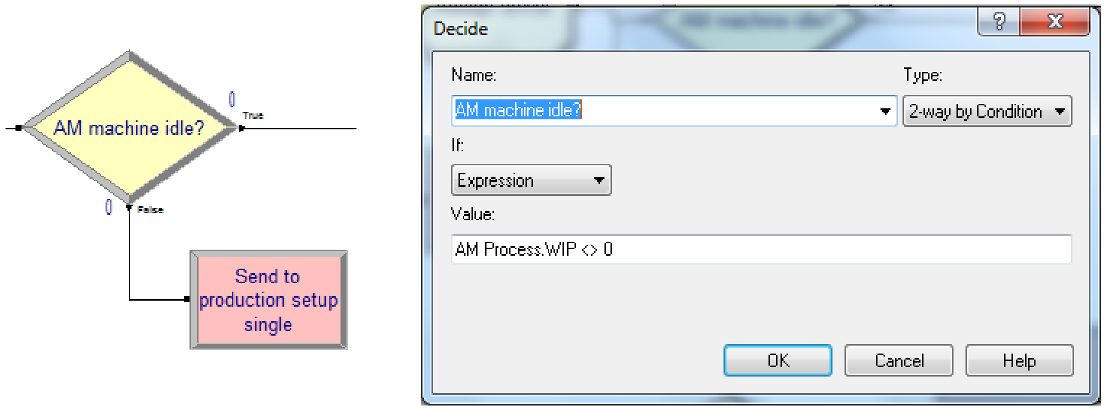


Figure 3-19: Check if AM machine is idle

Modeling the queue follows a specific logic. Arrived part requests need to be prioritized. This is done with a hold module, an assign module and another hold module. The logic uses the fact that logical operations in Arena can happen without that simulation time passes. Details will follow when the production section of the model is explained. After the AM process has finished, parts leave the AM machine and enter a first signal module which sends the signal "1" to the entire model. This will be explained in depth at a later point. To get back to the hold module, when the signal "1" is generated the hold module will release all parts in queue and forward them to the next module. The same idea is used for the second hold module, which uses the second signal 2, which is generated a process later than the first hold module.

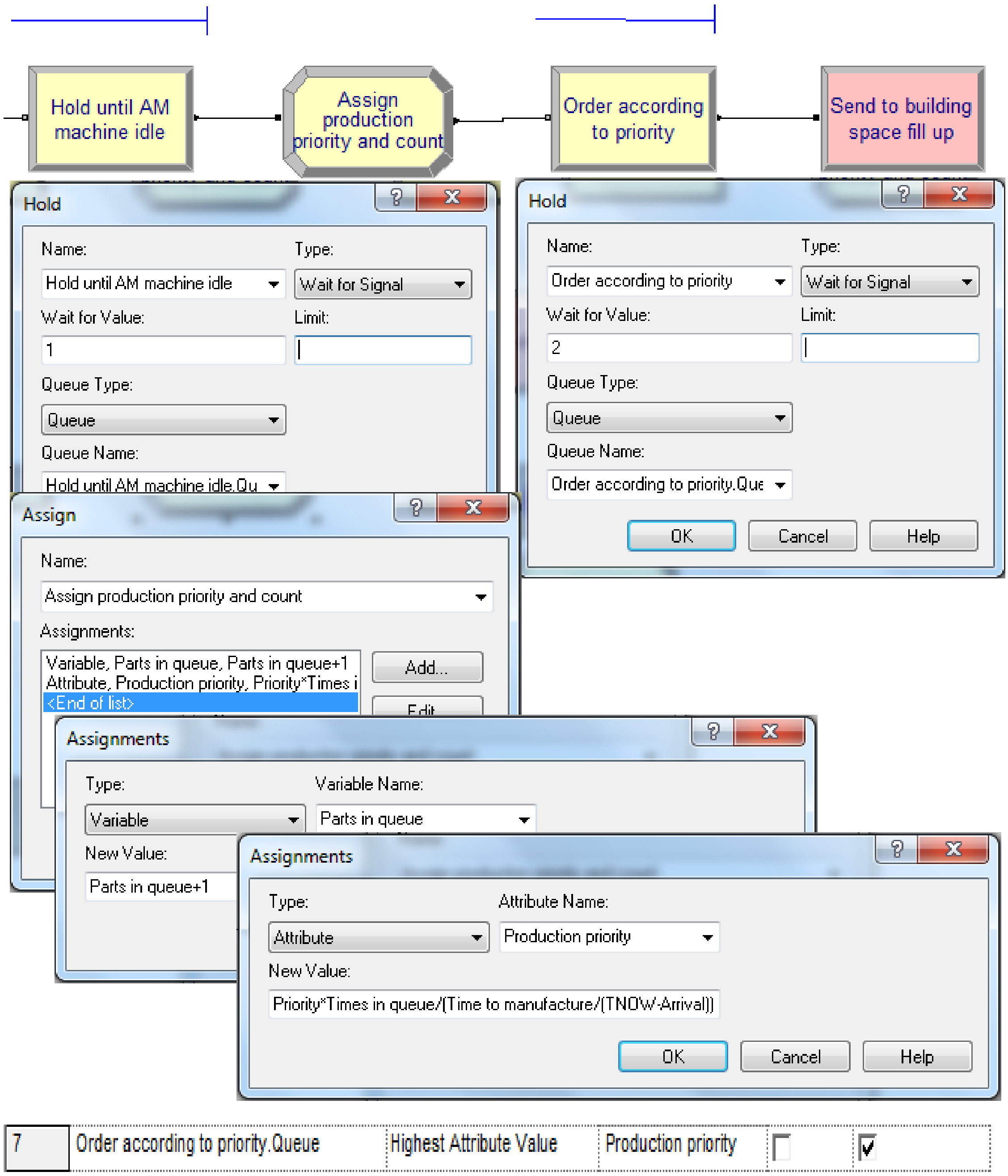


Figure 3-20: Queuing logic

With this in mind the queue logic should be coherent. The hold module "Hold until AM machine idle" holds all parts in queue until the signal 1 appears. Then all parts enter the assign module "Assign production priority and count". Two things happen in the assign module. "Parts in queue" are counted and the priority for the individual part is defined. "Parts in queue" is used to draw a graph so it is possible to study parts in queue at a specific time. Every queue is followed by Arena automatically, so further queuing statistics are available in the result section.

The priority setting follows a specific rule, which is defined as:

$$Production\ priority = \frac{Piroity * Times\ in\ queue * Time\ in\ system}{Time\ to\ manufacture} \qquad (1)$$

Def.:

Priority	---	Can be every number. In this model 1 (low), 2 (medium) and 3 (high) is used.
Times in queue	---	Counts how often the part entered the queue.
Time in system	hr	Describes how much time the part spent in the system.
Time to manufacture	hr	Describes the time the part will need for processing.

The formula assigns a production priority to each part request every time before it enters the "Order according to priority" queue. Each time the part request enters the "Hold until AM machine idle" queue, "Times in queue" and "Time in system" will be increased, which results in a higher production priority for the next production batch.

When the part requests leave the assign module they enter the "Order according to priority" hold module with the according queue. The queue is set to "Highest attribute value first" and uses the attribute "Production priority". As result the part request with the highest production priority will be first in queue and therefore first for processing. The hold module releases the parts from the queue when the signal 2 is sent by the signal module "Ready for new batch signal" which is also located in the production section of the model. All parts are then sent to a logic which fills up the production space.

3.4.4 BUILDING VOLUME COUNTER

Filling up the building volume is modeled by use of a counter. The part requests arrives at a decide module which checks the free volume of the building space. The variable "building volume left" is used for this check. If the building volume left is bigger than the required building volume, the part request is sent the true path for further processing. If the building space left is not enough, the part request will be redirected to the queue logic and the "Times in queue" variable is increased by 1.

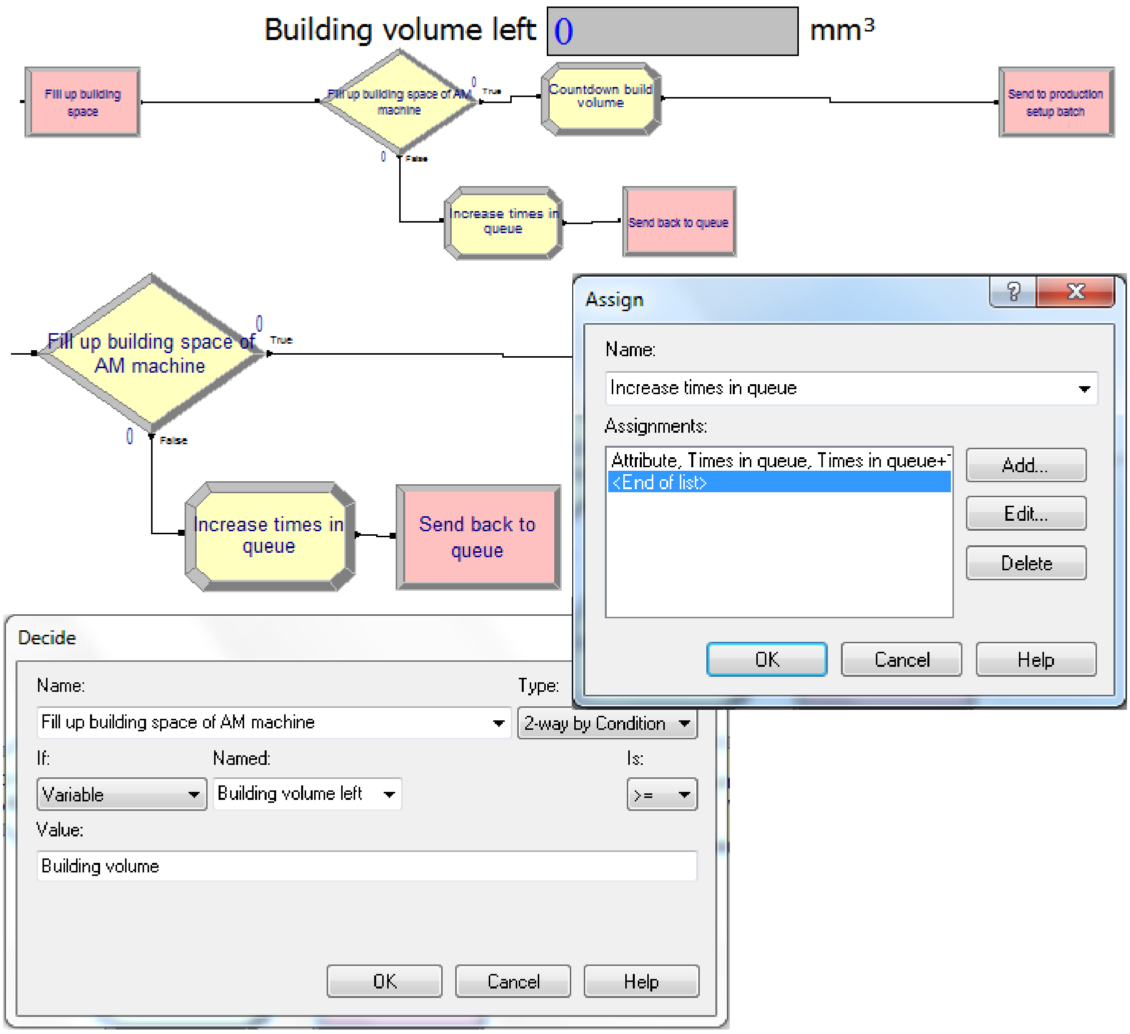


Figure 3-21: Logic for filling the building space

Following the further processing leads again to an assign module. "Countdown build volume" subtracts the "Building volume" of each part passing the module from the "Building volume left", whose initial value equals the available building volume of the building space. The variable “Part Counter” counts the current number of parts in the build volume. Both, “Building volume left” and “Part counter” are reset to the after each production run.

Then the part request is sent to the production planning logic.

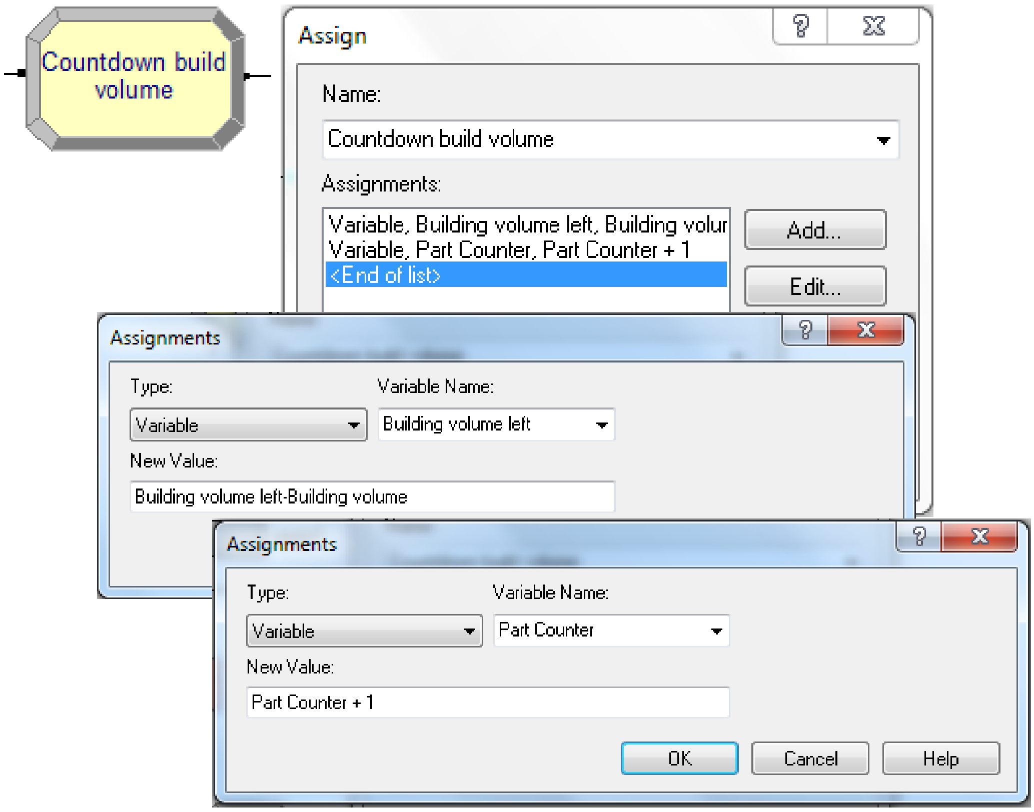


Figure 3-22: Countdown build volume

3.4.5 PRODUCTION SETUP

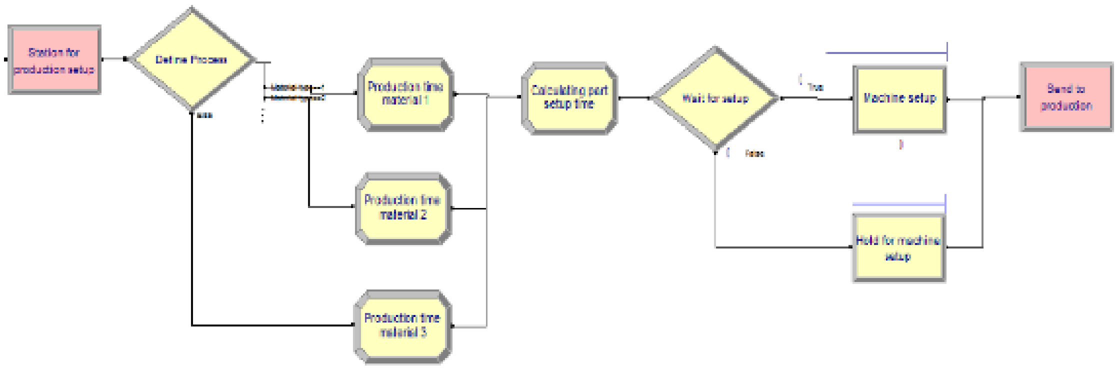


Figure 3-23: Production setup logic

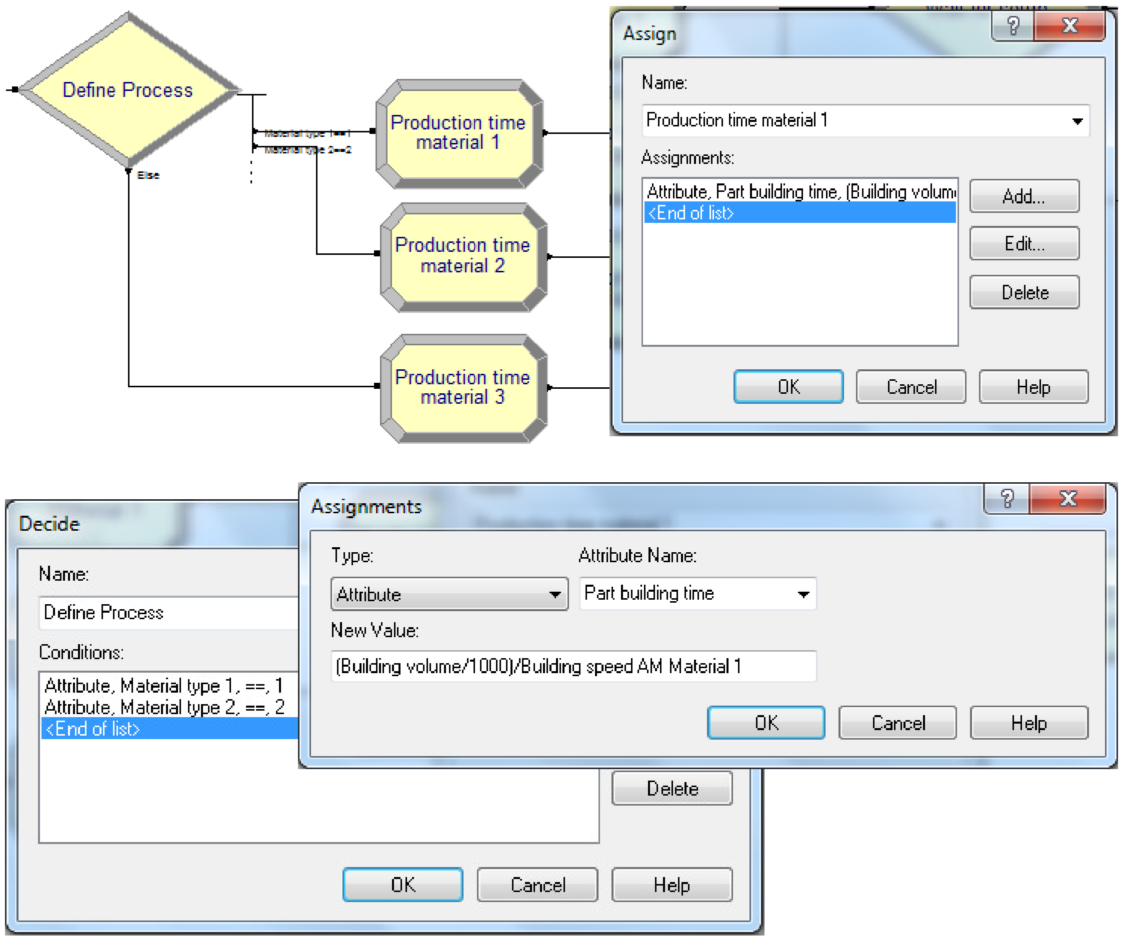


Figure 3-24: Production time assignment

The production setup logic calculates the production time of based on the material type, the specific setup time of a part and the general machine setup time.

"Define Process" is a decide module which splits the part requests according to the material required for the part. When the part requests are split up, they enter assign modules which are used to assign the production time of the part according to the material. After the assignment all parts follow the same path again and enter the machine setup logic.

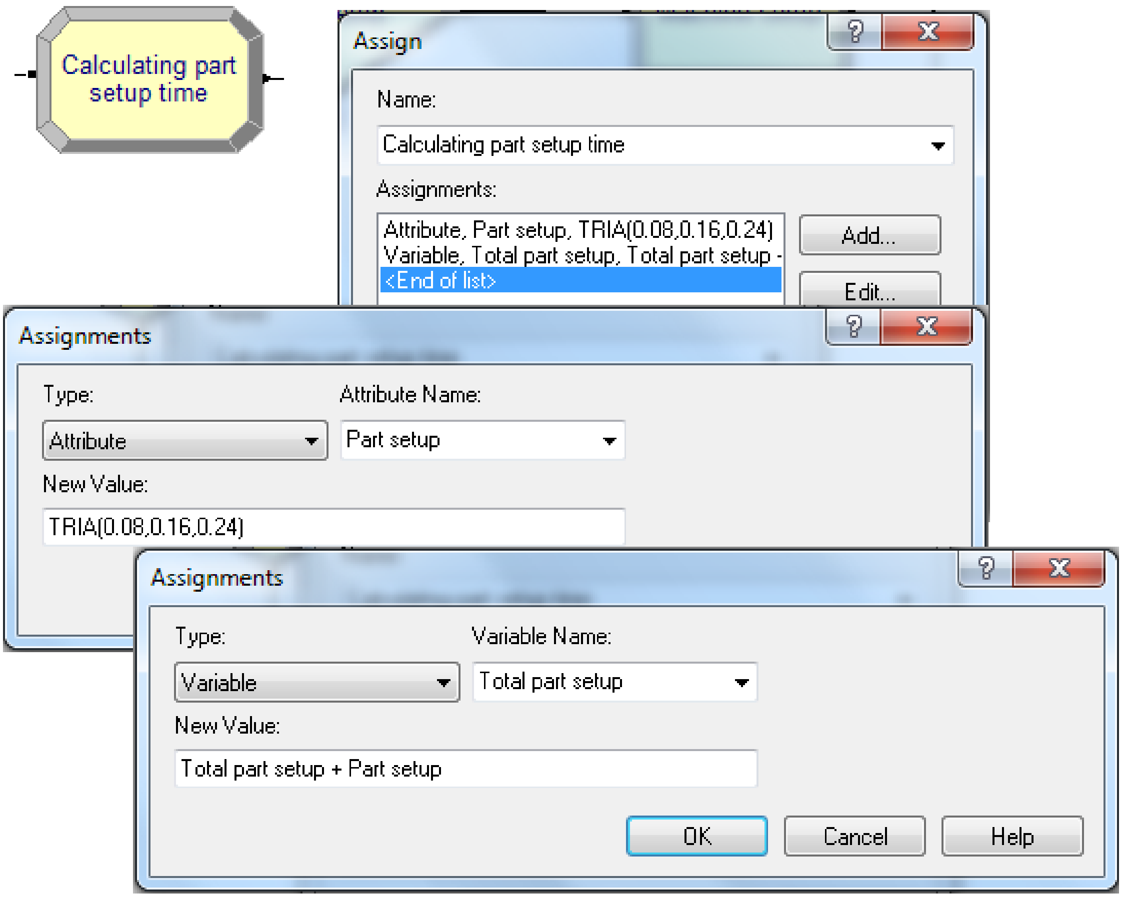


Figure 3-25: Part setup time

The machine setup logic starts with an assign module which assigns the setup time for the individual part to the individual part. The attribute is called “Part setup” and represents activities like importing the model and setting up the production parameters for the specific part. The basic setup follows a triangular distribution with min. 5, mean 10 and max. 15 minutes setup time per part. “Total part setup” sums up the setup time for all parts in one production run and will be reset to zero when the production run is finished.

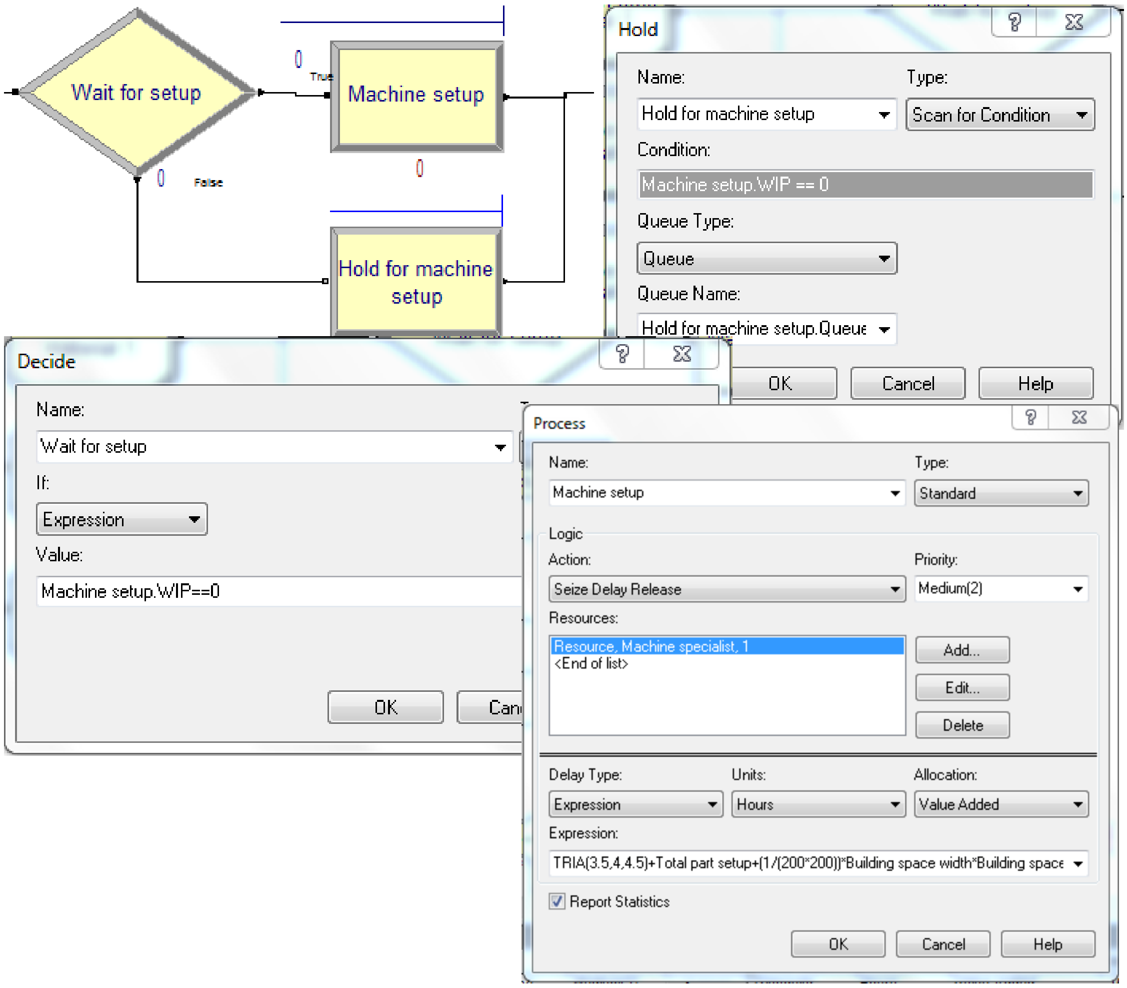


Figure 3-26: AM machine setup

Next a decide module checks if machine setup is already in progress or not. If the machine setup is not active, the first part request will enter the setup module and activate it. For processing, the resource "Machine specialist" is seized, which can be changed in number and/or according to a schedule. The standard “Machine setup” setting is according to Figure 3-26. Activities like powder bed setup or calibration are assumed to be standard activities which follow a triangular distribution using min. 3.5, mean 4 and max. 4.5 minutes. The total part setup time is added to represent the full setup time. Additionally preheat and atmosphere preparation time is added. The preheat time is set as a linear function of the total substrate area (width and depth of the building space volume). It is assumed that it takes 1 hour to heat up a 200 x 200 mm area. The actual preheat time is then scaled up or down depending on the actual build substrate area. Time for atmosphere preparation is added in the same way. It is assumed that it takes 1 hour to prepare a building space atmosphere of 200 x 200 x 200 mm. Based on this input the actual time is scaled up or down depending on the actual building space volume. For example a 300 x 300 x 300 mm building space volume will need 2.25 hr for preheat and 3.375 hr to create the building space atmosphere.

Each following part request in the batch will be sent to a hold module, "Hold for machine setup". "Hold for machine setup" is used to queue the spare part requests and to pretend a batch. When the machine setup becomes inactive, the AM process can start and the hold module releases all parts in queue to be processed by AM. Then the requests are sent simultaneously to the production logic. (This can also be done by a module, but by using this module specific part information gets lost.)

3.4.6 AM PROCESS SIMULATION

The production logic simulates the production of the parts, post processing as well as calculates specific results and resets specific variables.

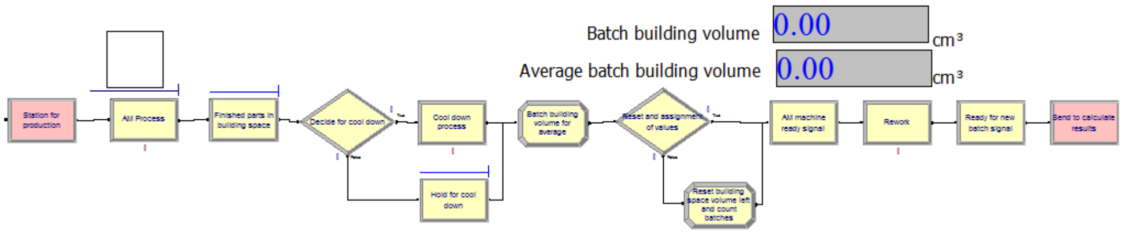
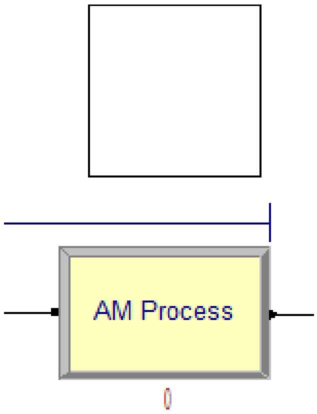


Figure 3-27: Production logic

First the part request enters the AM Process module. Here the actual simulation of the AM process is processed. The resource "AM Machine" is used for doing this. Like every resource the number of the machines can be changed or it can work according to a schedule. As delay time "Part building time" is used, which was calculated in the production setup logic. Each part is simulated to be produced individually, which needs to be corrected, since a production run is executed batch wise. (For simulation of multi material cases a special sorting logic will be integrated to the model in the setup section to arrange arriving part request according to their materials.)

To correct the model for a batch production, the hold module "Finished parts in building space" is applied. The module queues the produced parts until there are no parts in queue in the AM Process queue and the process is not active. All parts are released simultaneously when this condition is true and no part related information is lost.



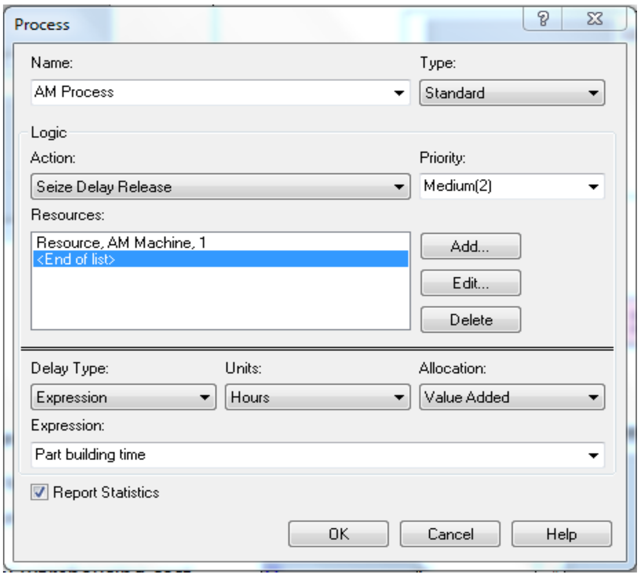


Figure 3-28: AM Process

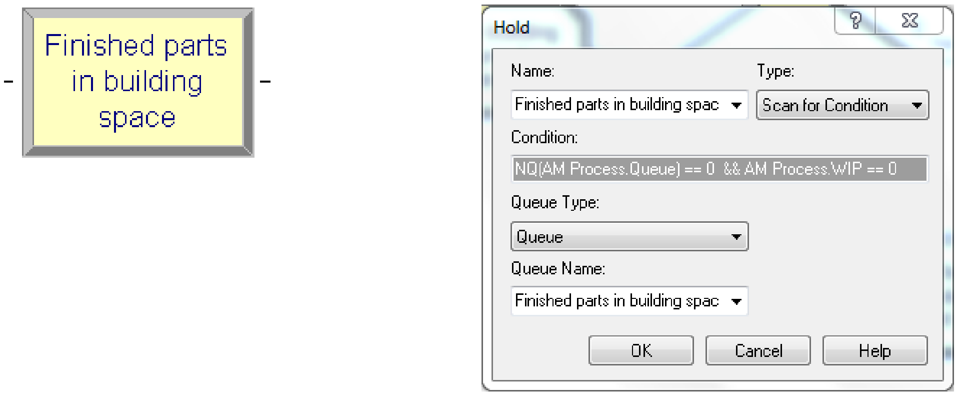


Figure 3-29: Hold for finished parts in building space

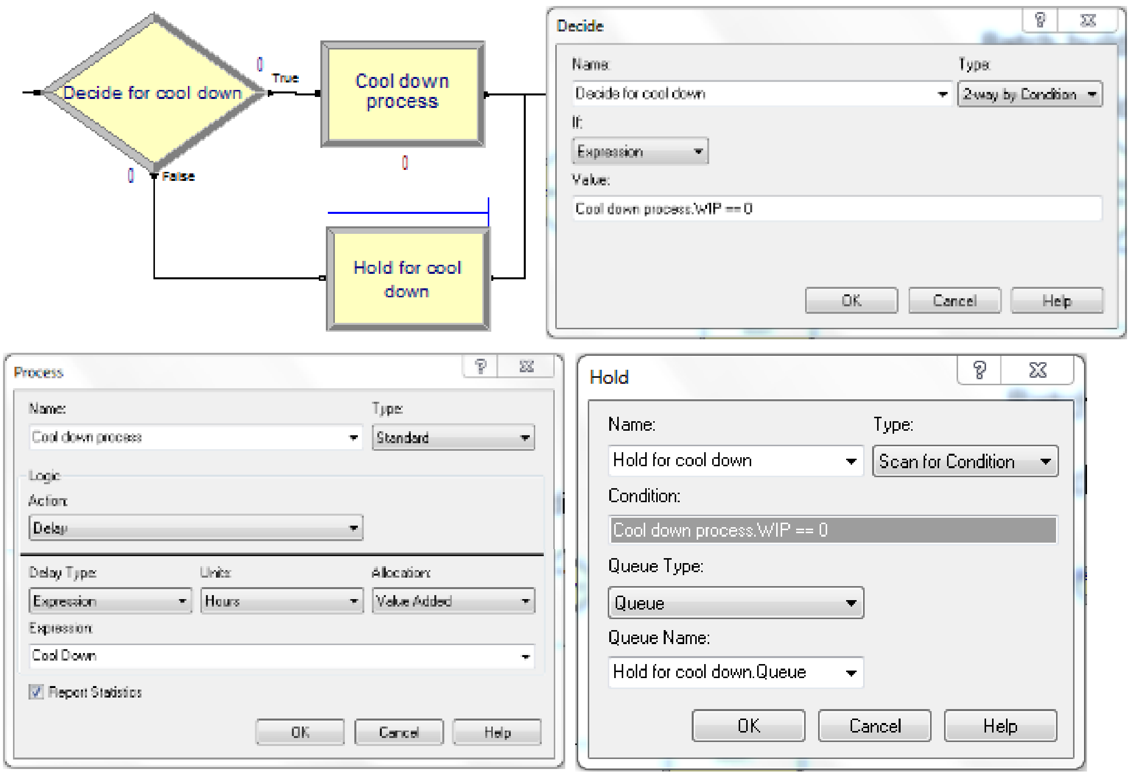


Figure 3-30: Cool down process

The cool down time after a production run needs to be considered as well. It is simulated by use of a decide module, process and hold module. The decide module scans for the condition of the cool down process. If the cool down process is idle, the entity will follow the process path, otherwise the entities will enter the queue of the hold module until the cool down process has ended. The time of cooling down is defined in the variable "Cool down". When the cool down process ends the hold module releases all parts in queue and processing continues.

For the model, the average building volume per batch is of interest. Therefore the variable "Batch building volume" is used. It sums up the building volumes of all parts of a batch. This is used later to calculate the average building volume.

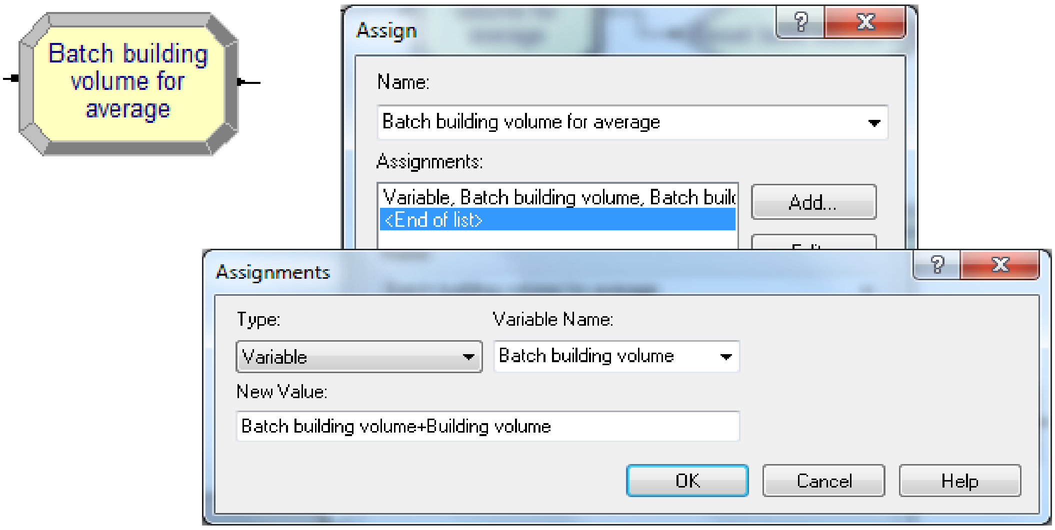
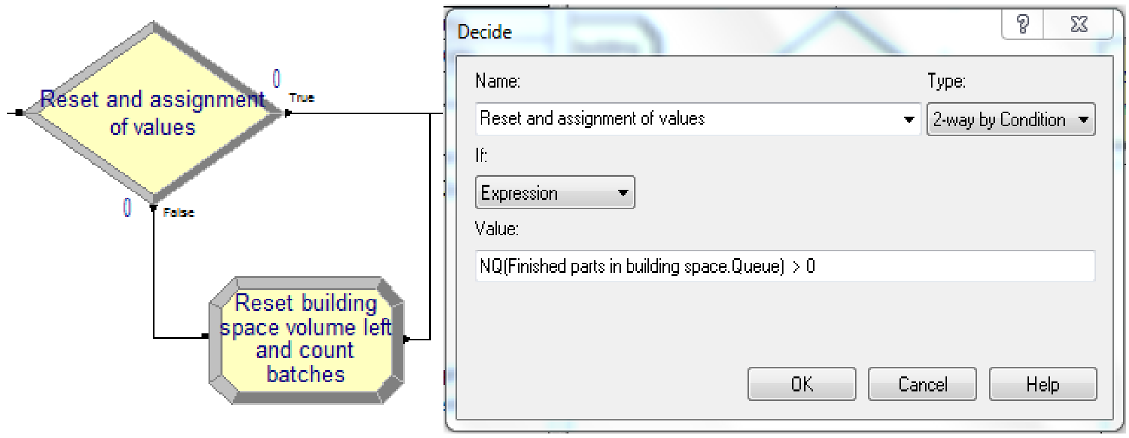


Figure 3-31: Average batch building volume

Next is a decide module, "Reset and assignment of values". The module forwards each part to the next module until the number of "Finished parts in building space.Queue" is 0. This means that only the last part is send to the assign module "Reset building space volume left and count batches".



Module type	Assign
Name	Request building space volume left and count batches
Type	Variable
Variable name	Building volume left
New value	Building space depth*Building space height*Building space width
Type	Variable
Variable name	Number of batch
New value	Number of batch + 1
Type	Attribute
Variable name	Assigned batch building volume
New value	Batch building volume
Type	Variable
Variable name	Batch building volume
New value	0
Type	Variable
Variable name	Building volume per batch
New value	Assigned batch building volume
Type	Variable
Variable name	Average building volume
New value	Average building volume*(Number of batch -1)/ Number of batch + Building volume per batch/ Number of batch
Type	Variable
Variable name	Part counter
New value	0
Type	Variable
Variable name	Total part setup
New value	0

Figure 3-32: Reset of variables and attributes

The assign module fulfills several functions. First, it resets the variable building volume left back to the initial value before the next parts are allowed to enter the process. This is essential for filling up the building space again.

All other attributes and variables in this assign module are used to calculate the average batch volume. The number of batches is updated by adding 1 each time a part passes the assign module. "Assigned batch building volume" is an attribute, directly assigned to the part. By doing this the "Batch building volume" is stored in an independent variable and is not lost when the "Batch building volume" is set back to its initial value of 0, which happens in the next assignment. Since "Assigned batch building volume" is an attribute and directly related to a part, it needs to be transformed back to an independent variable which is available in the whole model. This is done by the variable "Building volume per batch" which takes the value of "Assigned batch building volume". Next, the "Average building volume" is calculated.

After the reset and the calculation of the average building volume, the part meets a combination of signal modules and a process module. The first signal module "AM machine ready signal" sends the signal 1. As described earlier in this text the signal allows the waiting part requests on the module "Hold until AM machine idle" (queue logic) to move further along in the model, meaning that the parts get sorted in the following queue according to their priority when the signal 1 is set.

The process module "Rework" simulates the rework activities, by seizing a resource for these activities. The time for processing follows specific values in this example, but this can be adjusted to each individual case. In the base setup a triangular distribution is selected with min. 5, mean 60 and max. 120 minutes.

When the first part leaves the "Rework" process module it enters the signal module "Ready for new batch signal". This module sends the signal 2 into the model. This signal causes the hold module "Order according to priority" (see queuing logic) to release all parts for further processing.

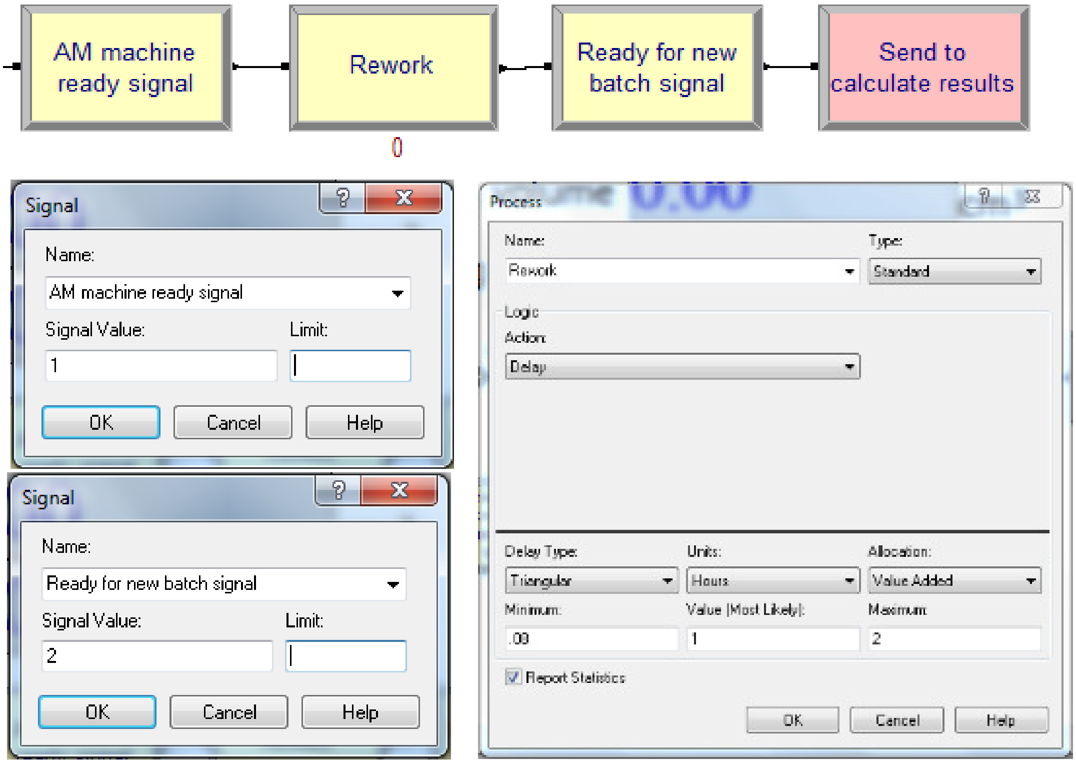


Figure 3-33: Signals for new production run and rework

3.4.7 OVERVIEW OF RESULTS

After the production logic final calculations are executed according to the points of interest.

For final calculations it is checked if the parts meet the delivery requirements. This is done by the decide module "Penalty?", which calculates the time from the initial spare part request until the finished part leaves the system and checks if the allowed "Time to manufacture" is exceeded. If the allowed time to manufacture is exceeded a penalty must be paid. The assign module sums up all penalties in the variable "Total penalty".

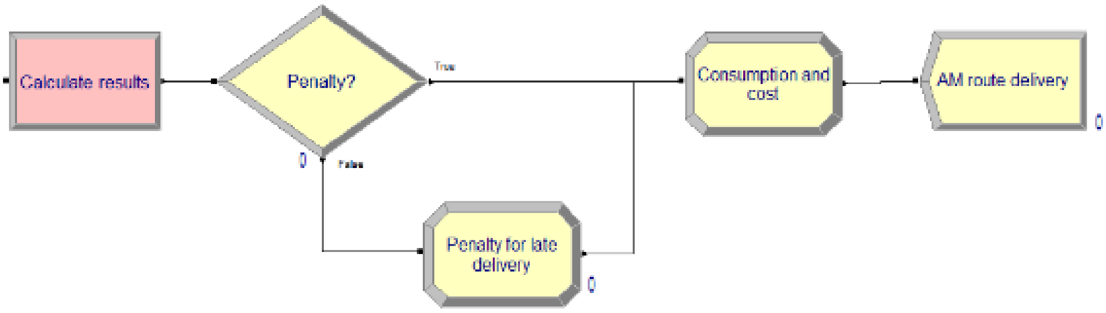


Figure 3-34: Final calculations

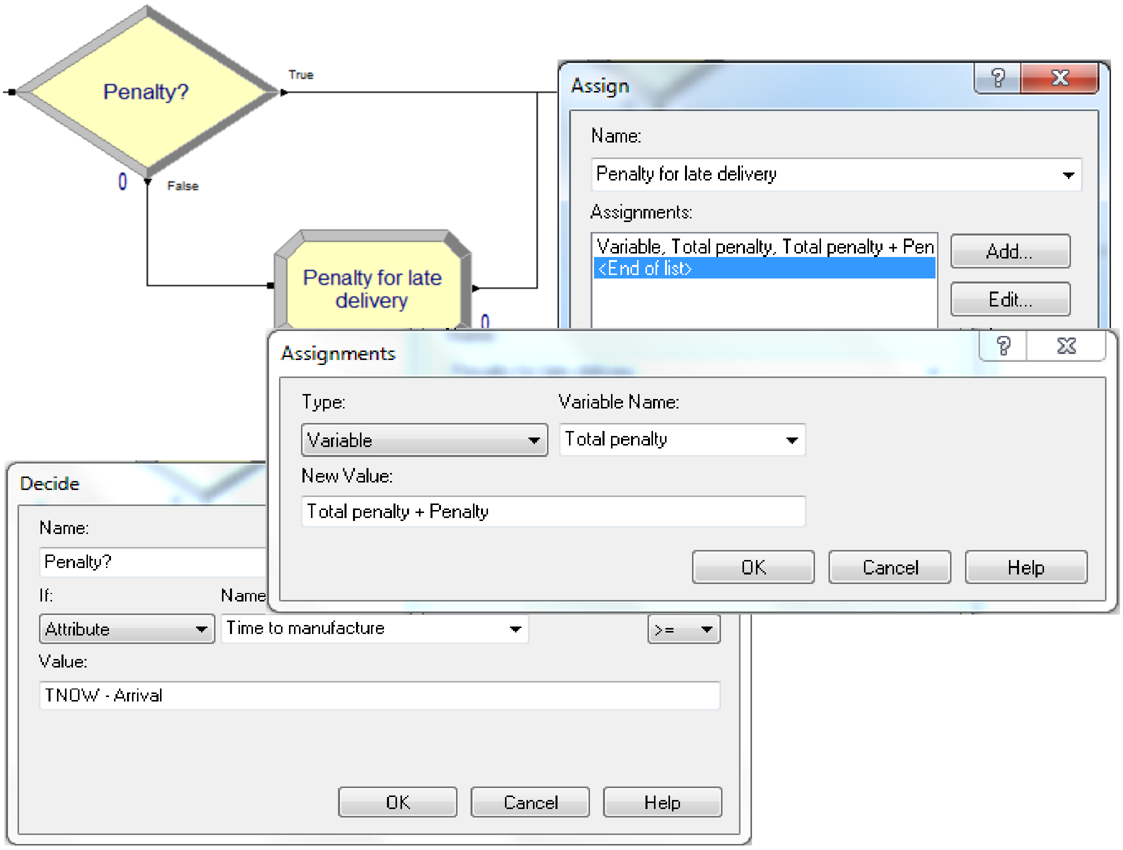


Figure 3-35: Check for penalty

The last module of the model is the assign module "Consumption and cost". Final calculations are executed in this assign module. The calculations are listed in Figure 3-36. After this assign module the spare part leaves the model by the use of a dispose module.

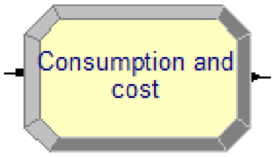


Figure 3-36: Calculation of consumption and cost

Table 3-2: Calculation of consumption and cost

Module type	Assign
Name	Consumption and cost
Type	Variable
Variable name	Material consumption
New value	Material consumption + Building volume
Type	Variable
Variable name	Total operator cost
New value	Total operator cost + Operator cost
Type	Variable
Variable name	Consumed material cost
New value	((Material consumption/1000)*7.85/1000)*Material cost
Type	Variable
Variable name	Consumed energy cost
New value	(Material consumption/1000)*Energy consumption*Energy cost
Type	Variable
Variable name	Total maintenance cost
New value	(AM maintenance cost/(365*24))*TNOW
Type	Variable
Variable name	Operator training cost
New value	(Operator training price/(365*24))*TNOW
Type	Variable
Variable name	Machine depreciation
New value	((Machine purchase price/Years of depreciation)/(365*24))*TNOW
Type	Variable
Variable name	Total AM cost
New value	Consumed material cost+Consumed energy cost+Total operator cost+Total maintenance cost+Operator training cost+Machine depreciation+Total penalty
Type	Variable
Variable name	Break even
New value	Machine purchase price/(((Total warehousing cost-Total AM cost)/TNOW)*365*24)
Type	Variable
Variable name	Machine utilization
New value	(AM Process.VATime / (TNOW+0.001))*100
Type	Variable
Variable name	Consumed material
New value	(Material consumption/1000)*7.85/1000

Type	Variable
Variable name	Consumed energy
New value	(Material consumption/1000)*Energy consumption
Type	Variable
Variable name	AM parts out
New value	AM parts out+1
Type	Variable
Variable name	Machine setup tracking
New value	(Machine setup.VATime/TNOW)*100
Type	Variable
Variable name	Machine cool down tracking
New value	(Cool down process.VATime/ TNOW)*100
Type	Variable
Variable name	Total utilization
New value	Machine utilization+Machine setup tracking+Machine cool down tracking

Once the simulation model has been run, results can be displayed. In the model window several displays are arranged to allow a quick overview about several results. Figure 3-37 shows the results of a simulation run using the parameters shown in Table 3-3. All the parameters shown in the table can be changed, and results can be recalculated. This enables the user to compare different scenarios.

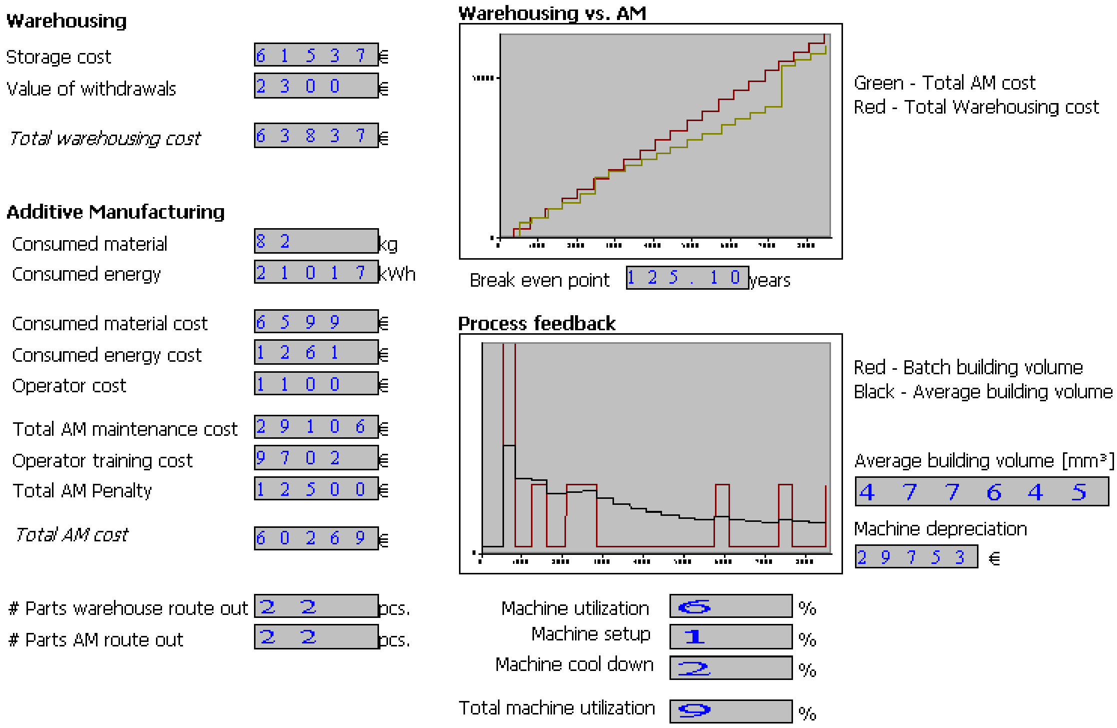


Figure 3-37: Sample results

Table 3-3: Changeable parameter

Refer-ence	Type	Variablen	Unit	Value	Description
AM Process	Variable	AM maintenance cost	€/yr	30000	Cost which is generated by required maintenance actions for AM.
AM Process	Variable	Building space depth	mm	250	Describes the building space depth of the RM machine.
AM Process	Variable	Building space height	mm	325	Describes the building space height of the RM machine.
AM Process	Variable	Building space volume	mm³	20312500	Describes the building space volume of the RM machine.
AM Process	Variable	Building space width	mm	250	Describes the building space width of the RM machine.
AM Process	Variable	Building speed AM Material 1	cm³/h	22	Describes the building speed of the RM machine using material 1.
AM Process	Variable	Building speed AM Material 2	cm³/h	23	Describes the building speed of the RM machine using material 2.

Refer-ence	Type	Variablen	Unit	Value	Description
AM Process	Variable	Building speed AM Material 3	cm³/h	24	Describes the building speed of the RM machine using material 3.
AM Process	Variable	Energy consumption	kWh/cm³	2	Energy consumption on average production. (20 % efficiency)
AM Process	Variable	Energy cost	€/kWh	0,06	Energy price valid for production.
AM Process	Variable	Machine purchase price	€	460000	Machine price when purchased
AM Process	Variable	Material cost	€/kg	80	Price of AM-material for production.
AM Process	Variable	Operator training price	€/ yr	10000	Price of operator training
AM Process	Variable	Years of depreciation	yr	15	Planned depreciation time for AM machine.
AM Process	Variable	Cool down	h	8	Required time to cool down the building space.
Global	Resource	Receptionist	Pcs	1	Number of staff at the reception.
Global	Resource	AM Machine	Pcs	1	Number of AM machines in operation.
Global	Resource	Picker Staff	Pcs	1	Number of staff picking parts.
Global	Resource	Machine specialist	Pcs	1	Number of staff specialized in AM.
Part	Attribute	Building depth	mm	30/ 20/ 30	Describes the building depth of the part. (Part 1/ Part 2/ Part 3)
Part	Attribute	Building width	mm	100/ 90/ 30	Describes the building width of the part. (Part 1/ Part 2/ Part 3)
Part	Attribute	Bulding height	mm	20/ 10/ 30	Describes the building height of the part. (Part 1/ Part 2/ Part 3)
Part	Attribute	EOQ Part 1	Pcs	11	Economic order quantity of part 1.
Part	Attribute	EOQ Part 2	Pcs	15	Economic order quantity of part 2.
Part	Attribute	EOQ Part 3	Pcs	12	Economic order quantity of part 3.
Part	Attribute	Material type 1	---	1/1/1	Material type assignment by use of integer. (Part 1/ Part 2/ Part 3)
Part	Attribute	Operator cost	€	70/ 60/ 50	Estimated cost of required operator in total. (Part 1/ Part 2/ Part 3)
Part	Attribute	Part value Part 1	€	50	Purchase price of part 1. (Example value – realistic values in later sections)
Part	Attribute	Part value Part 2	€	50	Purchase price of part 2. (Example value – realistic values in later sections)

Refer-ence	Type	Variablen	Unit	Value	Description
Part	Attribute	Part value Part 3	€	50	Purchase price of part 3. (Example value – realistic values in later sections)
Part	Attribute	Penalty Part 1	€	1000	Penalty when part 1 is not delivered in time.
Part	Attribute	Penalty Part 2	€	2000	Penalty when part 2 is not delivered in time.
Part	Attribute	Penalty Part 3	€	4000	Penalty when part 3 is not delivered in time.
Part	Attribute	Priority	---	1/1/1	Pre-assigned priority of part as production order basis. (Part 1/ Part 2/ Part 3)
Part	Attribute	Reorder point part 1	Pcs	8	Reorder point of part 1.
Part	Attribute	Reorder point part 2	Pcs	4	Reorder point of part 2.
Part	Attribute	Reorder point part 3	Pcs	5	Reorder point of part 3.
Wareh ouse	Variable	Lead time	h	7.5/36	Uniform distribution - valid for all parts
Part	Attribute	Time to manufacture	h	48/ 72/ 192	Allowed time to deliver a part. Exceeding this time leads to a penalty. (Part 1/ Part 2/ Part 3)
Ware-house	Variable	Number on stock Part 1	Pcs	8	Initiating number of part 1 on stock.
Ware-house	Variable	Number on stock Part 2	Pcs	3	Initiating number of part 2 on stock.
Ware-house	Variable	Number on stock Part 3	Pcs	3	Initiating number of part 3 on stock.
Ware-house	Variable	Storage cost	%	0,225	Storage cost in %.

For further calculations the Process Analyzer (PAN) and OptQuest are used. PAN is an Arena built-in tool which allows a variation of variables by setting up different scenarios. By running the scenarios, results are calculated and shown in a tabular form. For optimization of specific values OptQuest will be used, which is an Arena built in tool for optimization.

3.5 VERIFICATION OF THE SIMULATION MODEL

Kelton et al define the process of verification as a "...process of ensuring that the Arena model behaves in the way it was intended according to the modeling assumptions made." (Kelton, Sadowski, & Swets, 2010) Kelton et al also describe an easy verification method. The method proposes to send one entity into the process and follow its way through the simulation in a slow mode. In the presented model this was done with every entity type for each relevant parameter setting. Debugging and verification were executed continuously during development either for single parts or the complete model, since changes happened regularly throughout development. For debugging several displays, animations, extreme tests experiments with different discrete distribution times, long run tests and results were used to check the model for internal failures. The verification process assured that the model works in the intended way.

3.6 VALIDATION OF THE SIMULATION MODEL

The process of validation is described by Kelton et al as "... the process of ensuring that the model behaves the same as the real system" (Kelton, Sadowski, & Swets, 2010) In general the validation of a simulation model is assumed to be a difficult task. A good way of validation is to compare the results with those of a real system. This is important, since a model can never achieve absolute validity. Furthermore the subjective focus of involved people may affect several factors.

The presented model is likely to be problematic in that regard since data of a real system is not known or available at the current status. A validation of results is therefore not possible. To validate the model experts in simulation and AM consulted the validation of the model.

4 SIMULATION EXPERIMENTS

According to the previously described goals of the study, the simulation model is used to see how technical changes in the AM process affect the performance of the overall cost as well as logistical attributes of the spare parts (lead time in particular). In particular, technical changes considered in our simulation model are listed in Table 4-1.

Table 4-1: Overview of experiments

<table>
<tr><th>No.</th><th>Experiment</th><th>Unit</th><th>Description</th></tr>
<tr><td colspan="4">Base case</td></tr>
<tr><td colspan="2">Base case setup</td><td>cm³</td><td>Reference case for a one machine setup</td></tr>
<tr><td colspan="4">Technical investigations</td></tr>
<tr><td colspan="2">Building space volume</td><td>cm³</td><td>Variation of the building space for part generation.</td></tr>
<tr><td colspan="2">Building speed</td><td>cm³/ h</td><td>Variation of building speed applied for part generation.</td></tr>
<tr><td colspan="2">Material price</td><td>€/ kg</td><td>Variation of price of 1 kg AM raw material.</td></tr>
<tr><td colspan="2">Machine purchase price</td><td>€</td><td>Variation of purchase price of the machine.</td></tr>
<tr><td colspan="2">Cool down time</td><td>hrs</td><td>Variation of the applied cool down time.</td></tr>
<tr><td colspan="4">Additive strategy investigations</td></tr>
<tr><td colspan="2">Two machines</td><td>---</td><td rowspan="2">Basic setups:
• Fixed vs. flexible material assignment
• Waiting vs. direct production
Variables of interest:
• Mean arrival time
• Sum of setup and cool down time
• Elapse time (waiting only)
• Production start volume (waiting only)
• Material changeover time
(flexible material assignment only)</td></tr>
<tr><td colspan="2">Three machines</td><td>---</td></tr>
<tr><td colspan="2">Part size distribution</td><td>---</td><td>Several distributions of part sizes are investigated. For example 100 % small parts or 100 % big parts and other important mixtures.</td></tr>
</table>

Building space volume - A current trend in AM is increasing the building space volume of AM machines, which allows to build bigger parts during a production run. This might be an interesting topic when the time for production is not linked to a penalty, since the production run can be completed in the required time. The effect of an increased building space volume with respect to spare parts is not yet clear. In general, however, it is assumed that the increased building volume increases also the processing time, thus longer delivery times for spare parts. That might be a sensitive issue when penalties must be paid if a part is not delivered on time.

Building speed - Increasing the building speed is a main issue in AM. Increased building speeds will lead to faster processing and the effect on spare part supply should be positive.

Material cost - Material cost is also widely discussed in the literature. It is commonly agreed that the material price is a key factor and limits the application of AM in industry. The price an industrial company would be willing to pay will be investigated with respect to spare part supply.

Machine purchase price - In the literature it is often described that the purchasing price of an AM machine is too high to make it an interesting option for industrial application. It will be interesting to see how high or low the purchasing price has to be in order for the AM be an economically competitive option.

Cool down time - AM machines need a cool down time after production. Since this time can be several hours, the impact of the cool down time is also of interest for evaluation.

Two machines - It is reasonable that the application of two machines in parallel will improve the total system performance. We particularly investigate how the system will react given the following conditions due to the existence of two parallel machines. :

First set of conditions - In a two machine setup, a fixed material type can be produced by one machine only. This results in a total of two possible materials for production. This setup can run in two modes. The first mode will start the production process for each spare part request immediately after the spare part request arrives. The second mode is a waiting mode in which the system will wait until a certain amount of elapsed time or a certain amount of building space volume is filled for a production run.

Second set of conditions – In this two machine setup, both machines can produce with two kinds of materials. When the material setting is different than the designated material for the next production run, a material changeover time must be considered to simulate the exchange of production material. Also this setup will run in the waiting and no waiting mode.

Three machines - The conditions and modes of the model are similar to the two machine investigations except that three machines will be able to apply three materials.

Part size distribution - Part size is an attribute which is assumed to have a significant impact on production times. The spare part set has a specific distribution of part sizes. The total system is adjusted to these specific part sizes. A change in the distribution of the part sizes is assumed to have an effect on the system behavior, which we investigate through our simulation model.

4.1 PARAMETER OVERVIEW

Next we lay out in detail the various settings for technical parameters, which may all vary in our simulation runs.

Table 4-2: Overview of all simulation parameters

Type	Variable	Reference	Description	Formula
Variable	AM maintenance cost	AM Process	Cost which is generated by required maintenance actions for AM.	
Attribute	Arrival	Part	Contains the arrival time of each part request.	TNOW
Variable	Break even	Calculatio n	Calculates the breakeven point for AM.	Machine purchase price/(((Total warehousing cost-Total AM cost)/TNOW)*365*24)
Attribute	Building depth	Part	Describes the building depth of the part.	
Variable	Building space depth	AM Process	Describes the building space depth of the RM machine.	
Variable	Building space height	AM Process	Describes the building space height of the RM machine.	
Variable	Building space volume	AM Process	Describes the building space volume of the RM machine.	Building space depth*Building space height*Building space width
Variable	Building space width	AM Process	Describes the building space width of the RM machine.	
Variable	Building speed AM Material 1	AM Process	Describes the building speed of the RM machine using material 1.	
Variable	Building speed AM Material 2	AM Process	Describes the building speed of the RM machine using material 2.	
Variable	Building speed AM Material 3	AM Process	Describes the building speed of the RM machine using material 3.	
Attribute	Building volume	Part	Describes the building volume of the part.	Building height * Building width*Building depth
Variable	Building volume left	AM Process	Calculates the remaining building space to set up production plan.	Building volume left-Building volume
Attribute	Building width	Part	Describes the building width of the part.	

Type	Variable	Reference	Description	Formula
Attribute	Bulding height	Part	Describes the building height of the part.	
Variable	Batch building volume	AM Process	Adds the part building volumes up to a batch volume.	Batch building volume + Building volume
Variable	Number of batch	AM Process	Counts the number of part batches produced.	Number of batch + 1
Attribute	Assigned batch building volume	AM Process	Assigns the batch building volume to the last part to have a fixed value for later calculation.	Batch building volume
Variable	Building volume per batch	AM Process	Works together with "Assigned batch for building volume" and separates the batch volume logically from the continuously changing "Batch building volume". This value can be used for calculations.	Assigned batch building volume
Variable	Average building volume	AM Process	Calculates the average building volume based on a previously known average.	Average building volume*(Number of batch - 1)/ Number of batch + Building volume per batch/ Number of batch
Variable	Consumed energy cost	AM Process	Calculates the consumed energy cost.	(Material consumption/1000)*Energy consumption*Energy cost
Variable	Consumed material cost	AM Process	Calculates the consumed material cost.	((Material consumption/1000)*7.85/1000)*Material cost
Variable	Cool down	AM Process	Required time to cool down the building space.	
Variable	Energy consumption	AM Process	Energy consumption on average production.	
Variable	Energy cost	AM Process	Energy price valid for production.	
Attribute	EOQ Part 1	Part	Economic order quantity of part 1.	
Attribute	EOQ Part 2	Part	Economic order quantity of part 2.	
Attribute	EOQ Part 3	Part	Economic order quantity of part 3.	
Variable	Machine depreciation	AM Process	Calculated machine depreciation at the current point in time.	((Machine purchase price/Years of depreciation)/(365*24))*TNOW

Type	Variable	Reference	Description	Formula
Variable	Machine purchase price	AM Process	Machine price when purchased.	
Variable	Machine utilization	AM Process	Calculated average machine utilization over time.	(AM Process.VATime / (TNOW+0.001))*100
Variable	Material consumption	AM Process	Calculates material consumption by adding the build volume of each produced part.	Material consumption + Building volume
Variable	Material cost	AM Process	Price of AM-material for production.	
Attribute	Material type	Part	Material type assignment by use of integer.	
Variable	Number on stock Part 1	Warehouse	Initiating number of part 1 on stock.	
Variable	Number on stock Part 2	Warehouse	Initiating number of part 2 on stock.	
Variable	Number on stock Part 3	Warehouse	Initiating number of part 3 on stock.	
Attribute	Operator cost	Part	Estimated cost of required operator.	
Variable	Operator training cost	AM Process	Calculates operator training cost at the current point in time.	(Operator training price/(365*24))*TNOW
Variable	Operator training price	AM Process	Price of operator training	
Variable	Part 1 Penalty	Warehouse	Calculated cumulated penalty of part 1.	Part 1 Penalty + Penalty Part 1
Variable	Part 2 Penalty	Warehouse	Calculated cumulated penalty of part 2.	Part 1 Penalty + Penalty Part 1
Variable	Part 3 Penalty	Warehouse	Calculated cumulated penalty of part 3.	Part 1 Penalty + Penalty Part 1
Attribute	Part building time	Part	Time that is needed to build a part with respect to part volume and building speed.	(Building volume/1000)/Building speed AM Material 1
Variable	Part value withdrawals	Warehouse	Value of parts taken from warehouse.	Value consumed Part 1+Value consumed Part 2+Value consumed Part 3
Attribute	Part value Part 1	Part	Purchase price of part 1.	
Attribute	Part value Part 2	Part	Purchase price of part 2.	
Attribute	Part value Part 3	Part	Purchase price of part 3.	

Type	Variable	Reference	Description	Formula
Variable	Parts in queue	AM Process	Counts the parts in queue	Parts in queue+1
Attribute	Penalty	Part	Receives the penalty value of each part.	
Attribute	Penalty Part 1	Part	Penalty when part 1 is not delivered in time.	
Attribute	Penalty Part 2	Part	Penalty when part 2 is not delivered in time.	
Attribute	Penalty Part 3	Part	Penalty when part 3 is not delivered in time.	
Attribute	Priority	Part	Pre-assigned priority of part as production order basis.	
Attribute	Production priority	Part	Priority which is used for production order, dependent on several attributes.	Priority*Times in queue/(Time to manufacture/(TNOW-Arrival))
Attribute	Reorder point part 1	Part	Reorder point of part 1.	
Attribute	Reorder point part 2	Part	Reorder point of part 2.	
Attribute	Reorder point part 3	Part	Reorder point of part 3.	
Variable	Stock value Part 1	Warehouse	Represents the stock value of part 1 in the warehouse.	Number on stock Part 1 * Part value Part 1
Variable	Stock value Part 2	Warehouse	Represents the stock value of part 2 in the warehouse.	Number on stock Part 2 * Part value Part 2
Variable	Stock value Part 3	Warehouse	Represents the stock value of part 3 in the warehouse.	Number on stock Part 3 * Part value Part 3
Variable	Storage cost	Warehouse	Storage cost in %.	
Variable	Storage cost at time	Warehouse	Calculates storage cost at the current time.	Total stock value*Storage cost
Attribute	Time to manufacture	Part	Allowed time to deliver a part. Exceeding this time leads to a penalty.	
Attribute	Times in queue	Part	Number of times a part entered the queue. This influences the production priority.	Times in queue+1
Variable	Total AM cost	AM Process	Sums up all cost related to AM.	Consumed material cost+ Consumed energy cost + Total operator cost + Total maintenance cost + Operator training cost + Machine depreciation + Total penalty

Type	Variable	Reference	Description	Formula
Variable	Total maintenance cost	AM Process	Calculates total maintenance cost at the current point in time.	(AM maintenance cost/(365*24))*TNOW
Variable	Total operator cost	AM Process	Calculates total operator cost at the current point in time.	Total operator cost + Operator cost
Variable	Total penalty	AM Process	Calculates total penalty cost at the current point in time.	Total penalty + Penalty
Variable	Total stock value	Warehouse	Calculates total stock value at the current point in time.	Stock value Part 1 + Stock value Part 2 + Stock value Part 3
Variable	Total warehousing cost	Warehouse	Calculates total warehousing cost at the current point in time.	Part value consumed + Storage cost
Variable	Value withdrawals Part 1	Warehouse	Calculates the value of consumed part 1 at the current point in time.	Value consumed Part 1 + Part value Part 1
Variable	Value withdrawals Part 2	Warehouse	Calculates the value of consumed part 2 at the current point in time.	Value consumed Part 1 + Part value Part 1
Variable	Value withdrawals Part 3	Warehouse	Calculates the value of consumed part 3 at the current point in time.	Value consumed Part 1 + Part value Part 1
Variable	Years of depreciation	AM Process	Planned depreciation time for AM machine.	

4.2 NUMBER OF REPLICATIONS

The number of replications is important to ensure a robust evaluation from discrete event simulation, and we estimated the number of replication in our simulations with the framework proposed by Kelton et. al (2010). It follows a t-distribution based on the half width.

$$h = t_{n-1,1-\alpha/2} \frac{s}{\sqrt{n}} \tag{2}$$

h	Half width
$t_{n-1,1-\alpha/2}$	t-distribution critical value
s	Standard deviation
n	Number of replications

The error of the average is calculated by dividing h by the average.

Equation (2) is then solved for s to calculate the standard deviation. The parameter n and $t_{n-1,1-\alpha/2}$ are known. Arena's output after a simulation run is the average and h, dependent on n. Based on this s is calculated according to equation (3).

$$s = \frac{h * \sqrt{n}}{t_{n-1,1-\alpha/2}} \tag{3}$$

After solving the equation for n, it is possible to estimate the required replications to reach a satisfactory confidence interval.

$$n = {t_{n-1,1-\alpha/2}}^2 \frac{s^2}{h^2} \tag{4}$$

A difficulty occurs when using equation (4) is to calculate the new n. The standard deviation is not known, because the new s is dependent on the new n. To solve this, it is assumed that s is equal for the scenarios with the old and new n. The failure will be significantly reduced with an increasing number of replications.

Table 4-3 shows how the number of replications influences the quality of the results. Particularly, the table is created according to the following proceeding:

- set the initial number of replications (n_{Basis})
- run the simulation model
- fill in the values of average, half width, n and set the t-value for the confidence interval
- the new n for the next simulation run is calculated and set as n_{Basis} for the next run

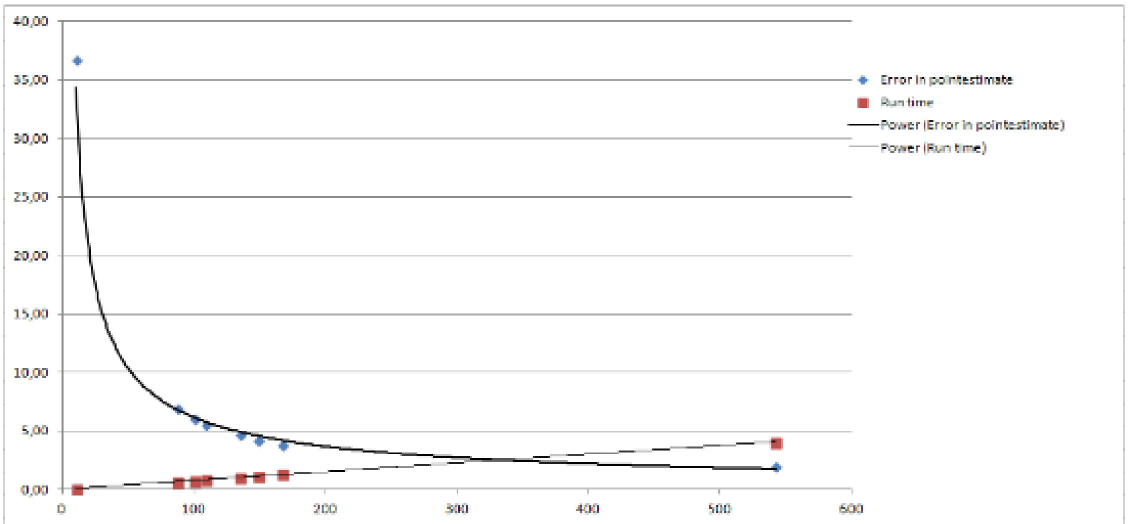
For demonstration purposes n is set to a low value of 10 in the first run. The number of estimation steps can be reduced when the initial n is set to a more appropriate value directly.

For this dissertation, an error in the point estimate of less than 5 % is the target. Table 4-3 shows the results for the model basic setup, described in the proposal. The "average" value is the total AM cost described in the model (point estimate).

It was decided to use 150 replications for a simulation run. More than 122 replications would be sufficient in order for the error to be below the target of 5%. On the other hand, the time estimate shows that the simulation time is short and a conservative number of 150 replications is acceptable and reduces h down to ~4.28 %. For every model modification, it will be checked if n is still in the range of a maximum error of 5 %. If possible, the number of replications will be reduced to safe calculation time, but the maximum error of 5 % will never be exceeded.

Table 4-3: Effects of the number of replications

		Estimate													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Average	€	47354	42275	42453	41563	42315	41830	42245	42067	42231	42013	42148	42041	42127	42057
Half width	€	17435	845	2939	1606	2579	1789	2354	1969	2195	2047	2142	2076	2125	2093
n_{basis}		10	542	87	167	100	149	109	135	118	127	121	125	122	124
$t_{n-1,1-\alpha/2}$ [95 %]		2,262	2,262	2,262	2,262	2,262	2,262	2,262	2,262	2,262	2,262	2,262	2,262	2,262	2,262
$StdDev_{Basis}$	€	24374	8699	12118	9173	11403	9657	10864	10113	10540	10197	10418	10263	10377	10304
Error in pointestimate	%	36,82	2,00	6,92	3,86	6,10	4,28	5,57	4,68	5,20	4,87	5,08	4,94	5,04	4,98
Next estimate															
Half width	€	2368	2114	2123	2078	2116	2092	2112	2103	2112	2101	2107	2102	2106	2103
Target of error in poinest.	%	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00	5,00
Number of replications		542	87	167	100	149	109	135	118	127	121	125	122	124	123
Run time of current series															
Run time	s	5	244	39	75	45	67	49	61	53	57	54	56	55	56
Run time	min	0,1	4,1	0,7	1,3	0,8	1,1	0,8	1,0	0,9	1,0	0,9	0,9	0,9	0,9



4.3 SELECTED SPARE PART SET

Another issue of the work is to define a set of spare parts used for simulation. We did not find any useful set of spare parts used in the literature, thus decided to design such a set in the current dissertation. The goal is to ensure the set of spare parts represents the average mix of a typical warehouse. A big plant, located in Neuss (Germany), agreed to provide warehouse data of one operational area out of three operational areas. The warehouse data contains ~ 2600 different kinds of spare parts and the related information for each spare part type.

The data was analyzed in several steps. First, each of the 2600 parts was evaluated to see if it may be possible to be manufactured by AM. If so, the part was marked and selected for further analysis. Evaluation was based on the available listed description of the part, material and part size. Figure 4-1 illustrates the data we were provided pertaining to several spare parts.

Inter	Platz	Material	Materialkurztext	Gesamtbesta	Gesamtwert	Anlagenzuorc	Verbrauch	Vebl.-Bestanc	Wert Vebrauc
x	019A	74089604	Zellenblech 102x225x5 mm M-N-ELB-1689	5	54,93	2223000	0	Keine Verbrau	0
x	020B	74089987	Kolbenring 85 x 77,6 x 6 x 3 Pos. 244	6	27,61	2480000	0	Keine Verbrau	0
x	019F	74089697	KUGELGELENK AM40 G 3/8" X G 1/4"	1	12,31	2370000	0	Keine Verbrau	0

Figure 4-1: Illustrative sample of warehouse data

It was found that among the 2600 parts, 630 can be manufactured by AM. Next, an ABC analysis was executed on the value of the parts. The results are displayed in Table 4-4. Low value parts with an average value of 50 € represent 75 %, middle value parts (average 200 €) represent 20 % and high value parts (average 1000 €) 5 % of the stock.

Table 4-4: Spare part parameter set

Value [€]			**Allowed time to manufacture [hr]**			**Penalty [€]**			**Volume [% of machine`s building volume]**		
low	50	75%	low	48	5%	low	2500	75%	low	0,005	75%
mid	200	20%	mid	72	20%	mid	5000	20%	mid	0,05	20%
high	1000	5%	high	192	75%	high	10000	5%	high	0,15	5%

In the next step boundaries were set during discussions with experts of the plant, based on operational observations. If AM can be applied for a part, the allowed time to manufacture is set to low (48 h) for 5 %, middle (72 h) for 20 % and high (192 h) for 75 % of the parts. Allowed time to manufacture describes the maximum allowed time in which a spare part must be produced and delivered. If it is not possible to deliver the spare part, a penalty will be charged. Penalty is therefore an indicator of the system performance.

Also the values for the different penalties were set. Observations and analysis of operation allowed to estimate operational losses on a monetary basis. It was agreed to use 2,500 € as low, 5,000 € as mid and 10,000 € as high average penalty for simulation. The fact of penalties makes preventive maintenance scenarios an interesting field for future research since it will allow for scheduling part production runs, which can certainly improve the AM situation. The presented model is not set up to simulate preventive maintenance strategies upfront the AM performance simulation. The spare part requests are created randomly, which also represents a typical behavior for spare parts with low turnover rates. Furthermore, if regular intervals for part replacements are planned, parts can be ordered on time and do not need to be stocked. This can also be true if parts simply need to be reworked.

The building volume values are estimated by the available machine data and the allowed time to manufacture. In our estimation, the machine Eosint M 280 (400 Watt Laser) was used. For example, the allowed time to manufacture (mid - 72 hr) multiplied with the average building speed of the machine (23 cm^3/hr) results in a product, representing the maximum build volume of the part (1380 cm^3), which is ~ 6.7 % of the total building volume of the machine. To have a time buffer, the value is reduced to a more practical value, 5 % in this example. The distribution (75 %, 20 %, 5 %) was set.

Table 4-5: Extract of machine data of Eosint M 280 (400 Watt Laser)

AM machine data	Part size max. length [mm]	250
	Part size max. width [mm]	250
	Part size max. height [mm]	325
	Average building speed [cm³/hr]	23
	Building volume [cm³]	20312,5

The values used in these tables can be different since they are based on the available warehouse data and the related operational observations.

With the set values in Table 4-4 it is possible to list all possible combinations of low, mid, and high values. To illustrate, Table 4-6 outlines the first 7 of 81 possible combinations. Based on these combinations, further assumptions are possible. For each combination the probability can be assigned and calculated. This is done by multiplying each individual probability.

For example for part 1: 0.75 * 0.05 * 0.75 * 0.75 = 0.02109

Table 4-6: Logical combinations (first 7 of 81)

	Logic				**Probability**				
Part No.	Value	Allowed time to manufacture	Penalty	Volume	Value	Allowed time to manufacture	Penalty	Volume	**Total Probability = 1**
1	low	low	low	low	0.75	0.05	0.75	0.75	0.02109
2	low	low	low	mid	0.75	0.05	0.75	0.20	0.00562
3	low	low	low	high	0.75	0.05	0.75	0.05	0.00141
4	low	low	mid	low	0.75	0.05	0.20	0.75	0.00563
5	low	low	mid	mid	0.75	0.05	0.20	0.20	0.00150
6	low	low	mid	high	0.75	0.05	0.20	0.05	0.00038
7	low	low	high	low	0.75	0.05	0.05	0.75	0.00141

When this is done for each part, the table can be sorted by the individual values of the total probability. The individual probability value represents the probability that this specific part will be requested and must be delivered. When the probabilities are sorted and cumulated, they can be displayed. It becomes obvious that the first 30 part types represent 95 % of all requests. The other 51 types represent only 5 % of all requests. Even if 95 % of the system utilization can be displayed by 30 kinds of spare parts, it was decided to keep all 81 kinds of spare parts in the model. This is because these parts will block storage space, whether they are being used or not, and therefore contribute to inventory cost. It is our belief that these low probability part types might significantly impact the spare part simulation, and therefore represent a real world situation where rare failures occur.

Table 4-7: Spare parts with sorted probability (first 9 of 81)

	Logic				**Probability**				**Calculations**	
Part No. sorted	Value	Allowed time to manu-facture	Penalty	Volume	Value	Allowed time to manu-facture	Penalt y	Volume	Total Probability = 1	Probability cumulated
1	low	high	low	low	0.75	0.75	0.75	0.75	0.31641	0.316406
2	low	mid	low	low	0.75	0.20	0.75	0.75	0.08438	0.400781
3	low	high	low	mid	0.75	0.75	0.75	0.20	0.08438	0.485156
4	low	high	mid	low	0.75	0.75	0.20	0.75	0.08438	0.569531
5	mid	high	low	low	0.20	0.75	0.75	0.75	0.08438	0.653906
6	low	mid	low	mid	0.75	0.20	0.75	0.20	0.02250	0.676406
7	low	mid	mid	low	0.75	0.20	0.20	0.75	0.02250	0.698906

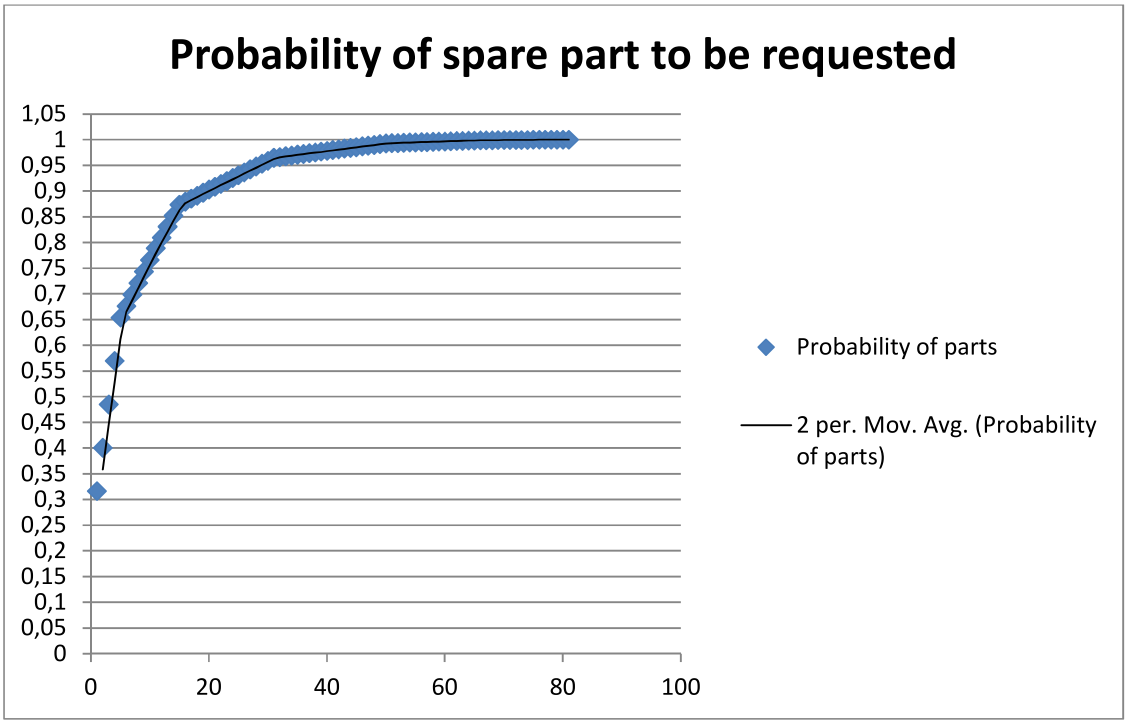


Figure 4-2: Probability of spare part to be requested

Next a priority is assigned to each kind of part by use of a pairwise importance matrix and comparison thereafter. In the pairwise importance matrix, each attribute is compared with all other attributes, stating which attribute should be prioritized or if the importance of two is equal. For the resulting three cases, the following values are used:

- Attribute is less important than the other attribute: 1
- Attribute is equal to the other attribute: 2
- Attribute is more important the other attribute: 3

For example:

Value is less important than Penalty → 1 or Volume is more important than Penalty → 3)

When all combinations are evaluated, the values of the each column are summed up, which represents the weight of the attribute in the relevant column. The weight can be normalized and used for further calculations. Table 4-8 shows the set preferences including the weight and normalized weight of each attribute.

Table 4-8: Paired comparison

	Value	Allowed time to manufacture	Penalty	Volume	Weight	Normalized weigth
Value		1	1	1	3	0.125
Allowed time to deliver	3		3	3	9	0.375
Penalty	3	1		1	5	0.208333
Volume	3	1	3		7	0.291667
				Total	24	1

For each attribute a basic priority can be assigned. For value, penalty and volume, it is assumed that a low value in the logic part has a basic priority of 1. Consequently, mid has a value of 2 and high a value of 3. While for example a low penalty does not need a high priority, it is the opposite for the allowed time to manufacture. Here, low represents a high time pressure and therefore a high priority. The setting is - low equals 3, mid equals 2, high equals 1. When the values are assigned, the weighted priority can be calculated by multiplying the basic priority of each attribute with the normalized weight of the attribute. For example for part type 1:

$$1 * 0.125 + 3 * 0.375 + 1 * 0.208333 + 1 * 0.291667 = 1.7500$$

Then the actual priority is assigned accordingly:

Priority = 1	1	<=	weighted priority <	1.66667
Priority = 2	1.66667	<=	weighted priority <	2.333337
Priority = 3	2.333337	<=	weighted priority <	3

Table 4-9: Priority calculation

	Logic				Priority					
No.	Value	Allowed time to manufacture	Penalty	Volume	Value	Allowed time to manufacture	Penalty	Volume	Weighted priority	Priority
1	low	low	low	low	1	3	1	1	1.7500	2
2	low	low	low	mid	1	3	1	2	2.0417	2
3	low	low	low	high	1	3	1	3	2.3333	2
4	low	low	mid	low	1	3	2	1	1.9583	2
5	low	low	mid	mid	1	3	2	2	2.2500	2
6	low	low	mid	high	1	3	2	3	2.5417	3
7	low	low	high	low	1	3	3	1	2.1667	2
8	low	low	high	mid	1	3	3	2	2.4583	3
9	low	low	high	high	1	3	3	3	2.7500	3

In the last step the table must be cleared of combinations which are not possible. This means that combinations where a high volume and a mid or low allowed time to manufacture occur, are deleted from the spare part set. It will never be possible to produce a high volume part in mid or low "Allowed time to manufacture". The same is also true for mid volume parts and low "Allowed time to manufacture". After clearing the table, 81-27 = 54 spare part types remain. The probabilities must then be corrected (Total probability must sum up to 1) since the eliminated parts are no longer part of the spare part set.

Table 4-10 was prepared in accordance with the previously described proceeding and lists the 54 spare part types, relevant for simulation, and sorted by probability. Only results are presented.

Table 4-10: Spare part types for simulation

		Logic				Priority		Calculations		
Sorted	No.	Value	Allowed time to deliver	Penalty	Volume	Weighted priority	Priority	Corrected Total Probability = 1	Production time [hr]	Corrected Probability cumulated
1	19	low	high	low	low	1,0000	1	0,323689	4	0,323689
2	10	low	mid	low	low	1,3750	1	0,086317	4	0,410006
3	20	low	high	low	mid	1,2917	1	0,086317	44	0,496324
4	22	low	high	mid	low	1,2083	1	0,086317	4	0,582641
5	46	mid	high	low	low	1,1250	1	0,086317	4	0,668958
6	11	low	mid	low	mid	1,6667	1	0,023018	44	0,691976
7	13	low	mid	mid	low	1,5833	1	0,023018	4	0,714994
8	37	mid	mid	low	low	1,5000	1	0,023018	4	0,738012
9	47	mid	high	low	mid	1,4167	1	0,023018	44	0,761029
10	49	mid	high	mid	low	1,3333	1	0,023018	4	0,784047
11	23	low	high	mid	mid	1,5000	1	0,023018	44	0,807065
12	1	low	low	low	low	1,7500	2	0,021579	4	0,828645
13	21	low	high	low	high	1,5833	1	0,021579	132	0,850224
14	25	low	high	high	low	1,4167	1	0,021579	4	0,871803
15	73	high	high	low	low	1,2500	1	0,021579	4	0,893382
16	14	low	mid	mid	mid	1,8750	2	0,006138	44	0,899520
17	38	mid	mid	low	mid	1,7917	2	0,006138	44	0,905659
18	40	mid	mid	mid	low	1,7083	2	0,006138	4	0,911797
19	50	mid	high	mid	mid	1,6250	1	0,006138	44	0,917935
20	4	low	low	mid	low	1,9583	2	0,005754	4	0,923689
21	16	low	mid	high	low	1,7917	2	0,005754	4	0,929444
22	28	mid	low	low	low	1,8750	2	0,005754	4	0,935198
23	48	mid	high	low	high	1,7083	2	0,005754	132	0,940953
24	52	mid	high	high	low	1,5417	1	0,005754	4	0,946707
25	64	high	mid	low	low	1,6250	1	0,005754	4	0,952462
26	74	high	high	low	mid	1,5417	1	0,005754	44	0,958216
27	76	high	high	mid	low	1,4583	1	0,005754	4	0,963971
28	24	low	high	mid	high	1,7917	2	0,005754	132	0,969725
29	26	low	high	high	mid	1,7083	2	0,005754	44	0,975480
30	41	mid	mid	mid	mid	2,0000	2	0,001637	44	0,977116
31	17	low	mid	high	mid	2,0833	2	0,001535	44	0,978651
32	31	mid	low	mid	low	2,0833	2	0,001535	4	0,980185
33	43	mid	mid	high	low	1,9167	2	0,001535	4	0,981720
34	51	mid	high	mid	high	1,9167	2	0,001535	132	0,983254
35	53	mid	high	high	mid	1,8333	2	0,001535	44	0,984789
36	65	high	mid	low	mid	1,9167	2	0,001535	44	0,986324

		Logic				Priority		Calculations		
Sorted	No.	Value	Allowed time to deliver	Penalty	Volume	Weighted priority	Priority	Corrected Total Probability = 1	Production time [hr]	Corrected Probability cumulated
37	67	high	mid	mid	low	1,8333	2	0,001535	4	0,987858
38	77	high	high	mid	mid	1,7500	2	0,001535	44	0,989393
39	7	low	low	high	low	2,1667	2	0,001439	4	0,990831
40	55	high	low	low	low	2,0000	2	0,001439	4	0,992270
41	75	high	high	low	high	1,8333	2	0,001439	132	0,993708
42	79	high	high	high	low	1,6667	1	0,001439	4	0,995147
43	27	low	high	high	high	2,0000	2	0,001439	132	0,996586
44	44	mid	mid	high	mid	2,2083	2	0,000409	44	0,996995
45	68	high	mid	mid	mid	2,1250	2	0,000409	44	0,997404
46	34	mid	low	high	low	2,2917	2	0,000384	4	0,997788
47	54	mid	high	high	high	2,1250	2	0,000384	132	0,998171
48	58	high	low	mid	low	2,2083	2	0,000384	4	0,998555
49	70	high	mid	high	low	2,0417	2	0,000384	4	0,998939
50	78	high	high	mid	high	2,0417	2	0,000384	132	0,999322
51	80	high	high	high	mid	1,9583	2	0,000384	44	0,999706
52	71	high	mid	high	mid	2,3333	2	0,000102	44	0,999808
53	61	high	low	high	low	2,4167	3	0,000096	4	0,999904
54	81	high	high	high	high	2,2500	2	0,000096	132	1,000000

5 BASE CASE SIMULATION

The base case is a reference case for all further extensions of the model. It is important to evaluate the impact and therefore the significance of changes in the parameter set. The base case enables the direct comparison with respect to changes in the parameter set.

5.1 MODEL ADJUSTMENT

The simulation experiments require changes in the basic model described in the previous sections. Recall that Section 4.3 mentions that no individual parts are used, while in fact the simulation uses a set of spare parts with certain characteristics. This is important for the calculation of storage cost. While the base case model calculates the storage cost by summing up the product of the number of parts on stock times price times storage cost, the same is not possible for a general spare part set. For example:

The total spare part set consists of approximately 630 parts and represents a stock value of 285,000 €. The general spare part set includes 54 parts representing only a fraction of the actual stock value.

The model is corrected to compensate this effect. Compensation is done by using the known stock value, used as average[6], and breaking it down to an hourly basis. The time related storage cost can then again be calculated by multiplying it with the parameter "storage cost" [%].

[6] Due to the high stock value variations are assumed to be marginal.

Calculation:

$$\frac{Actual\ stock\ value * Storage\ cost\ [\%] * Current\ run\ time\ of\ the\ model}{12\ months * 30\ days * 24\ hours} = Time\ related\ storage\ cost \tag{5}$$

For example after a one year run time of the simulation model the result for the storage cost at this time is calculated:

$$\frac{285{,}000\ € * 15\ \% * 8{,}760\ h}{12\ months * 30\ days * 24\ hours} * 5 = 42{,}583\ €$$

The simulation model will always update the storage cost at time according to the present run time.

All items in the selected spare part stock were optimized to the specific EOQ, reorder point and lead time for each spare part type. The target was to have a minimum stock level without creating penalties.

The second adjustment to the base case model is the removal of the depreciation out of the total cost of AM. In the basic model an existing warehouse is assumed where the depreciation time has ended. In this case, depreciation cost of AM are a significant cost factor and should be included in the total AM cost. Since the main focus of this work is comparing the performance of AM to warehousing, depreciation is not considered as a cost factor included in the total cost, neither for the warehouse nor for the AM machine. Further more information about building cost for warehouses was not available, so taking the depreciation of the AM machine into account would only produce misleading results. However, the depreciation of the AM machine will be a result which can be used if further data becomes available.

Lastly, the general spare part set is included in the model and the replication length was adjusted to 8640 hours, representing 1 year of operation.

The create module was set to create entities according to a Poisson distribution with a mean of 100 hrs as a basic setting. The mean of the distribution represents the mean arrival time of the spare part requests. The mean arrival time is used to stress or relax the system, which allows identifying an “upper limit” at which the system is working stable with maximum utilization, without creating no or minor penalties.For example when the mean inter-arrival time decreases, more part requests will enter the system and the system’s stress is increased. When the mean inter-arrival time increases, less part requests will enter the system and the system will be more relaxed. The effect of these changes is displayed best by “AM parts out”. This variable describes the number of parts which left the system after they were produced by the AM machine. As long as the system is in a stable state, “AM parts out” is equal to the delivered parts of the warehouse route. The upper limit is defined as the point where cost of the AM option equals that the warehousing option.

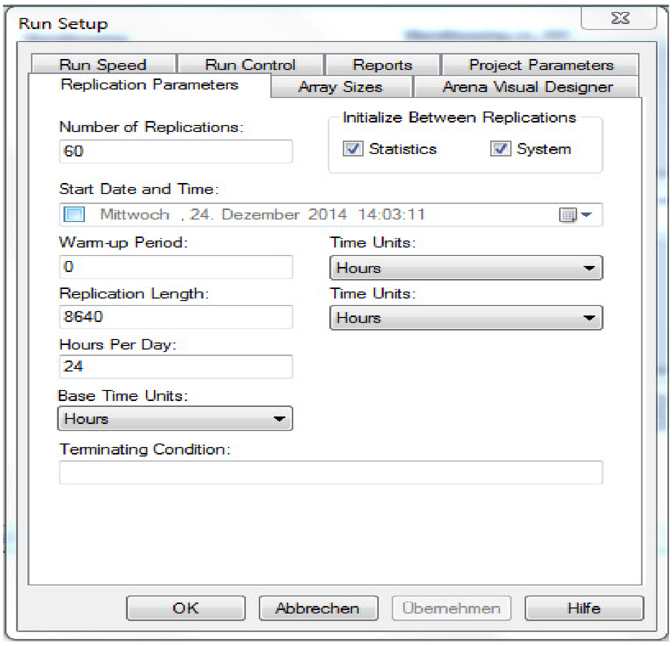


Figure 5-1: Changes in replication parameters

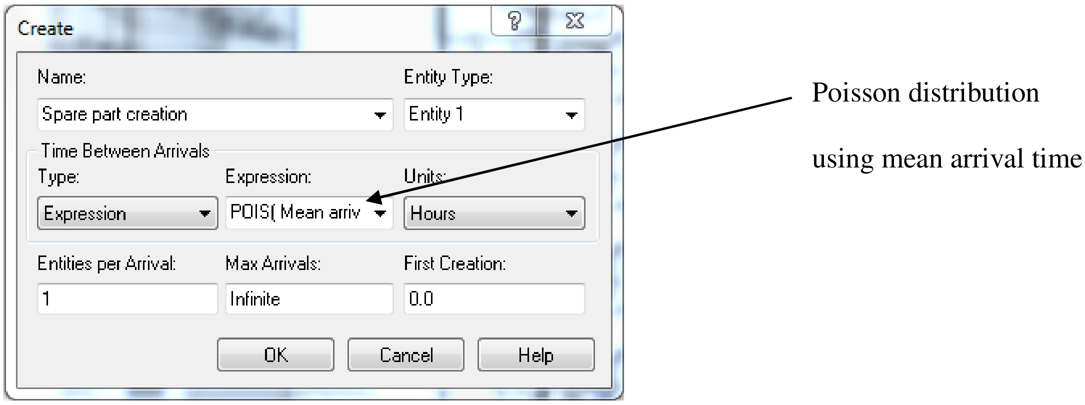


Figure 5-2: Changes in create module

To reach an acceptable half width of less than five percent, 60 replications are used. The half width is checked for every simulation setup and was never bigger than the accepted 5 % (typically around 3 %).

Output	Average	Half Width	Minimum Average	Maximum Average
Total AM cost statistic	73493.78	1.918,33	59415.21	91953.46
Total warehousing cost statistic	74190.58	510,59	69176.27	81680.14

Figure 5-3: Verification of half width

5.2 PROCEEDING

First of all, an upper limit search is executed to define a limit for the system performance in the base case. An upper limit search stresses the system until the system exits the stable state. This provides a first impression of how the system reacts to changes. The limit search is executed using two independent simulation runs. First a rough and then a detailed limit search. Each scenario (one row is one scenario) will run 60 times to create the accepted half width.

5.3 RESULTS AND FINDINGS

Table 5-1: Results of upper limit search

Upper limit search - rough	Controls	Responses																		
Unit	h	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Arrival (mean)	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depreciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Search Upper limit 1.1	1500	55436	19	4878	1532	293	300	25745	0	36452	1	1	1	3	406462	26318	,---	0	0	6
Search Upper limit 1.2	1300	57840	23	5759	1808	346	350	26797	0	38233	1	2	1	3	411321	27393	,---	0	0	7
Search Upper limit 1.3	1100	57530	25	6452	2026	387	400	26453	0	38083	1	2	1	4	403176	27040	,---	0	0	8
Search Upper limit 1.4	900	60435	30	7768	2439	466	500	27823	0	40503	1	2	1	4	388359	28441	,---	0	0	10
Search Upper limit 1.5	700	63163	40	10087	3167	605	648	28791	0	42809	1	3	1	5	388576	29431	,---	0	0	13
Search Upper limit 1.6	500	64315	57	14449	4537	867	895	29067	0	45055	2	4	2	7	403665	29713	,---	0	0	18
Search Upper limit 1.7	300	65845	90	23015	7227	1381	1457	29018	0	48755	3	6	3	12	395036	29663	,---	0	0	29
Search Upper limit 1.8	100	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	30061	50	0	5	87
Search Upper limit 1.9	10	173511	1377	350726	110128	21044	22846	28119	1518458	1709967	1	97	1	100	386299	28743	706	167	1832	457

Upper limit search - detail	Controls	Responses																		
Unit	h	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Arrival (mean)	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depreciation	Average time in queue	Average number of parts in queue	Number of parts in queue total	AM parts out
Search Upper limit 2.1	170	69198	161	40997	12873	2460	2554	29265	0	56908	5	11	5	21	401331	29916	,---	0	0	51
Search Upper limit 2.2	160	69671	173	44147	13862	2649	2710	29278	125	58383	5	12	5	22	407170	29929	5	0	1	54
Search Upper limit 2.3	150	70144	183	46714	14668	2803	2892	29338	292	59772	6	12	5	23	403962	29990	9	0	2	58
Search Upper limit 2.4	140	70574	199	50773	15943	3046	3097	29324	875	62060	6	13	6	25	409695	29976	16	0	3	62
Search Upper limit 2.5	130	71180	214	54606	17146	3276	3329	29311	1083	63917	6	15	6	27	410052	29962	27	0	3	67
Search Upper limit 2.6	120	72104	230	58528	18378	3512	3612	29364	1417	66070	7	16	7	29	404922	30017	37	0	3	72
Search Upper limit 2.7	110	72746	246	62791	19716	3767	3933	29351	2167	68717	8	17	7	32	399037	30003	44	0	4	79
Search Upper limit 2.8	100	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	30061	50	0	5	87
Search Upper limit 2.9	90	75118	304	77492	24332	4650	4802	29390	5208	78178	9	21	9	39	403511	30043	53	0	7	96
Search Upper limit 2.10	80	77316	341	86957	27304	5217	5395	29421	7000	84145	10	23	10	43	402876	30075	45	0	10	108
Search Upper limit 2.11	70	78155	380	96782	30390	5807	6154	29441	9292	90898	11	26	11	48	393467	30096	37	0	16	123
Search Upper limit 2.12	60	81932	440	112059	35187	6724	7191	29435	16417	104765	13	30	13	56	389576	30090	32	0	33	144
Search Upper limit 2.13	50	84622	523	133259	41843	7996	8622	29466	35542	133290	15	35	15	65	386618	30121	34	0	58	172
Search Upper limit 2.14	40	90977	654	166689	52340	10001	10723	29461	86667	199013	17	44	17	78	388515	30116	39	0	105	214
Search Upper limit 2.15	30	99977	845	215214	67577	12913	14288	29456	221958	356010	17	57	17	91	376724	30110	45	1	207	286
Search Upper limit 2.16	20	118255	1251	318657	100058	19119	20451	29032	1040792	1219129	7	85	7	99	390566	29677	139	7	420	409
Search Upper limit 2.17	10	173511	1377	350726	110128	21044	22846	28119	1518458	1709967	1	97	1	100	386299	28743	706	167	1832	457

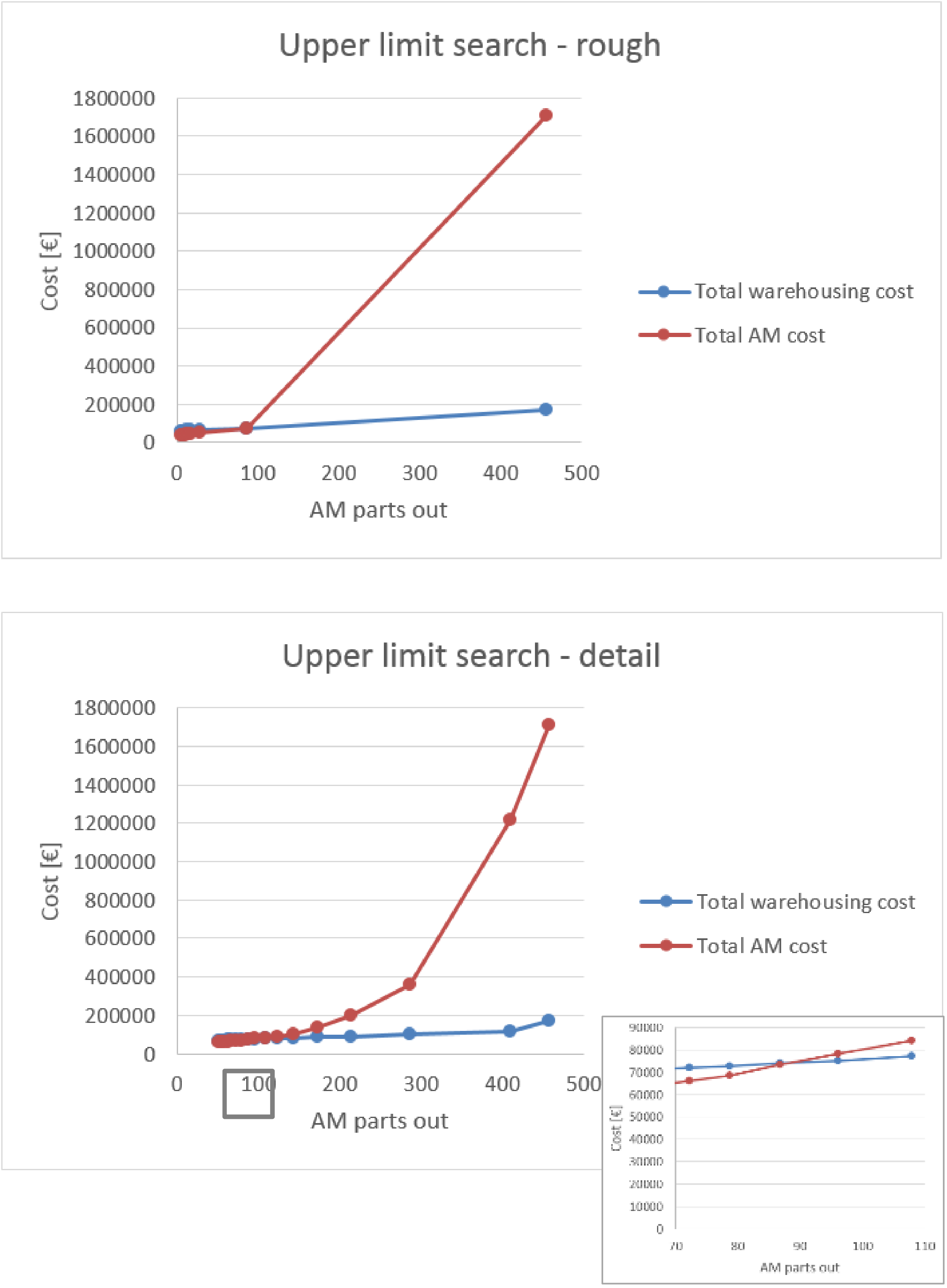


Figure 5-4: Upper limit search

We now compare further setups (a setup means a set of several scenarios) of the technical investigations against the base case. Also, the base cases of technical extensions can be compared against the given base case with a defined upper limit.

Figure 5-4 summarizes the detailed results of the upper limit search of the base case. The rough overview of upper limit search shows significant cost increase at an output of more than 100 parts, representing an upper limit of 90 hrs. This section was analyzed in detail. The cost of AM and warehousing are equal at an output between 90 and 100 parts, representing an upper limit between 90 and 100 hours. 100 hours mean inter-arrival time is therefore the selected standard upper limit for entity creation, since penalties increase strongly at a higher utilization. It must be mentioned that the upper limit correlates strongly with the total machine utilization. An increased total machine utilization of approximately 39 % leads to a strong increase in the total penalty. Consequently the system is no longer interesting for spare part supply on demand if the total AM machine utilization is above an accepted level of penalties, what is equivalent to an insufficient performance of the AM setup.

The upper limit search of the base case showed an important effect. When the machine utilization exceeds a certain level, in the current setup 39 %, the system is not able to provide a proper service level with respect to penalties. Observations of the running simulation model lead to the conclusion that the more parts are placed in a production run, the more time the production run will take. This increases the machine utilization, the chance that a new part request must wait in queue for the next production run, and therefore the chance for a higher penalty. Figure 5-5 illustrates this correlation.

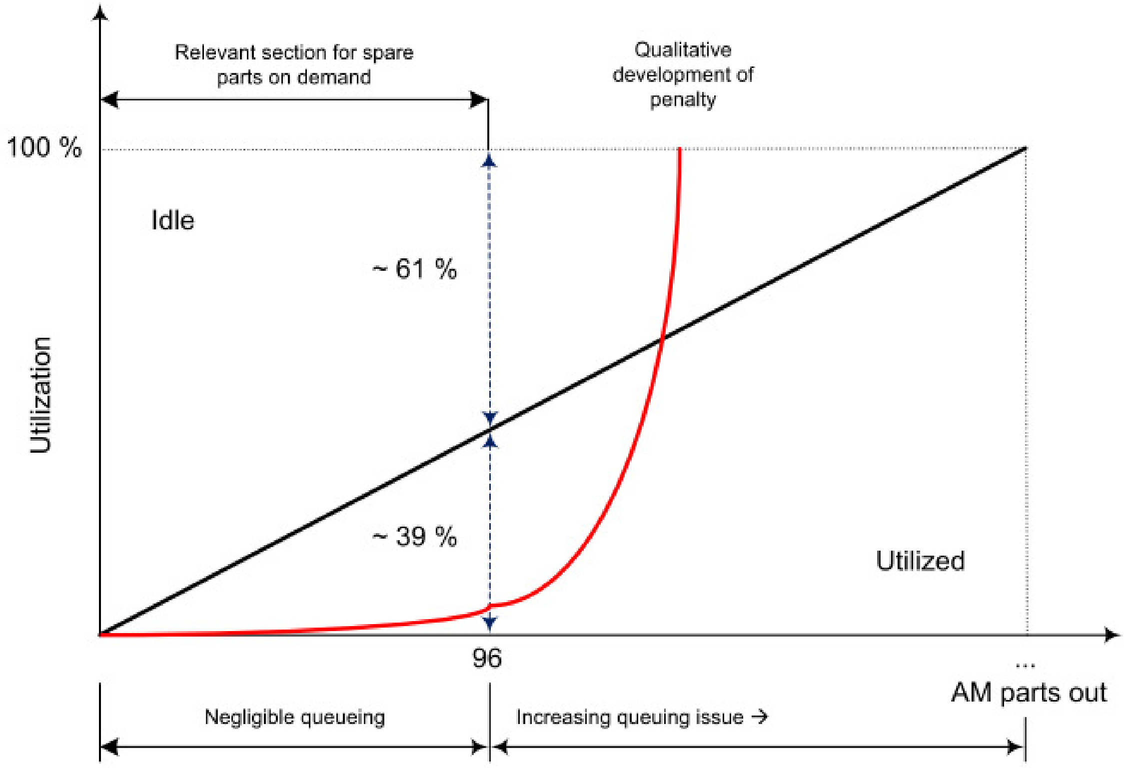


Figure 5-5: Correlation between machine utilization and queuing

6 TECHNICAL INVESTIGATIONS

Technical investigations are conducted mainly for two reasons. First, it can be used as a verification of the simulation model. When results of the planned experiments are predictable even without simulation, these predicted results can help to verify the efficiency and correctness of the simulation model. It is important to have a valid model before performing more complex experiments as discussed in chapter 7. Second, the technical investigations can provide some insights on effects of various parameters on the system. Typically a hypothesis regarding results for a specific setup can be generated through these investigations. The planned experiments allow us to see the actual effect of changes on the complete system and will allow for further conclusions with respect to the relevant hypothesis.

6.1 BUILDING SPACE VOLUME

The effect of an increased building space volume with respect to spare parts is not yet clarified. The following hypothesis is investigated for clarification:

- Increased building space volume increases the processing time and delivery time.

The calculations regarding the building space volume use the same simulation model which is used for the base case. To execute the simulation the first scenario of the setup is set to a minimum building space volume which can take only the biggest spare part. For the following scenarios the building space volume is increased stepwise to see if any effects in the responses occur. Effects on the results will be discussed.

6.1.1 RESULTS AND DISCUSSION

Table 6-1: Results for building space increase

	Controls					Responses																		
Unit	h	cm³	mm	mm	mm	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Arrival (mean)	Building space volume	Building space depth	Building space height	Building space width	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Scenario 1	100	3049	145	145	145	74115	274	69685	21881	4181	4332	29409	2833	72439	5	18	8	32	402003	30063	48	0	5	87
Scenario 2	100	5256	145	250	145	74155	275	70002	21981	4200	4332	29409	2875	72599	5	19	8	32	403846	30062	49	0	5	87
Scenario 3	100	14000	200	350	200	74136	275	69937	21960	4196	4333	29406	3375	73071	7	19	8	34	403423	30059	50	0	5	87
Scenario 4	100	40500	300	450	300	74107	275	69989	21976	4199	4333	29402	4208	73919	12	19	8	38	403747	30055	52	0	5	87
Scenario 5	100	88000	400	550	400	74015	274	69919	21955	4195	4321	29391	16375	86033	19	19	8	46	404408	30044	52	0	6	86
Scenario 6	100	162500	500	650	500	74095	274	69889	21945	4193	4317	29398	30750	100402	31	19	8	57	404830	30051	46	0	10	86

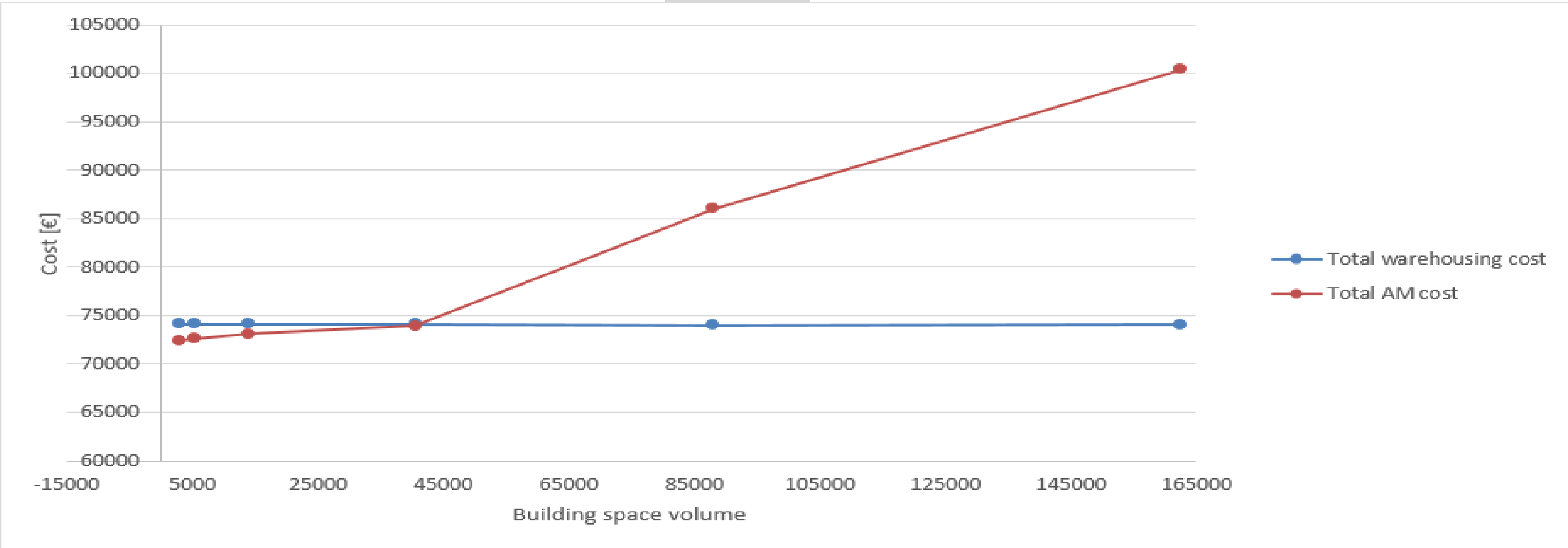


Figure 6-1: Building space volume vs. AM and warehousing cost

The first experiments show the influence of the building space. It can be confirmed that an increase in the building volume increases also the processing time, and thus enlarges the delivery time for spare parts. Table 6-1 shows the effect of the building space volume to the machine setup time. The machine setup takes longer when the building space volume increases, which leads to a penalty increase. Additionally, a bigger building space allows for bigger parts. Naturally, bigger parts will take more time to be produced, but producing more or bigger parts in the same building space volume is restricted by the total machine utilization.

The above simulated result suggests that compared to the base case no changes occur in the total warehousing cost. The effect of changes in the AM cost can be explained by the machine utilization, especially the machine setup. When the machine is utilized more than 38 %, a sufficient service level cannot be reached. At a service level of 38 %, only a small number of parts (5 of 87) need to wait in queue and at no point in time was there more than one part produced in the building space. After this limit, queuing occurs and the total processing time increases due to multi part production, which results in longer queue, and creates an unstable system. Therefore, the total machine utilization is an appropriate generic measure to evaluate the effect of changes in the system.

To improve the system performance in a spare part environment the machine setup time should be minimized to allow for higher building space volumes (due to preheating and atmosphere creation). Under the given set of conditions it can be concluded that it is preferable to adjust the building space volume to the maximum part size, instead of generating unused building space volume with the related drawbacks (for example more material must be heated, more unused powder must be scrapped, a bigger machine is necessary, etc.).

6.2 BUILDING SPEED

The following hypotheses are investigated with respect to building speed:

- Increased building speed will lead to faster processing, which has a positive impact on the spare part supply.

The calculations regarding the building speed use the same simulation model, which is used for the base case.

For execution of experiments the mean arrival and building speed are the parameter of variation. Mean arrival is changed from 10 to 150 hr with an increment of 10 hr while the building speed is varied between 10 cm^3/ hr and 100 cm^3/ hr with an increment of 10 cm^3/ hr. This results in 150 combinations which allow to analyze the building speed with respect to the upper limit of the system.

6.2.1 RESULTS AND DISCUSSION

Table 6-2: Results of building speed variation

	Controls		Responses																	
Unit	hours	cm³/h	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Mean arrival	Building speed	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Building speed 1.1	150	10	70303	179	45539	14318	2736	2875	29255	25833	84769	5	27	5	37	396457	29905	90	0	5	58
Building speed 1.2	140	10	70792	193	49140	15430	2948	3086	29248	30292	90754	6	29	6	40	398088	29898	92	0	7	62
Building speed 1.3	130	10	71307	204	51894	16295	3114	3318	29280	32542	94309	6	30	6	42	390930	29931	92	0	8	66
Building speed 1.4	120	10	71906	218	55543	17441	3333	3590	29220	35875	99199	7	33	6	46	386824	29870	73	0	13	72
Building speed 1.5	110	10	72947	238	60621	19035	3637	3911	29283	41208	106836	7	35	7	49	387651	29934	63	0	21	78
Building speed 1.6	100	10	73873	262	66718	20949	4003	4294	29329	54458	122810	8	39	7	54	388607	29981	66	0	27	86
Building speed 1.7	90	10	75299	298	75864	23821	4552	4773	29298	74625	146836	8	44	8	60	397405	29949	80	0	35	95
Building speed 1.8	80	10	76477	325	82923	26038	4975	5358	29328	90500	165976	9	48	8	66	387004	29980	85	0	44	107
Building speed 1.9	70	10	78841	372	94663	29724	5680	6095	29358	130625	211268	9	55	9	73	388358	30010	94	1	63	122
Building speed 1.10	60	10	81166	436	111033	34864	6662	7051	29193	215250	302751	9	65	8	82	393999	29841	107	1	92	141
Building speed 1.11	50	10	84946	504	128460	40336	7708	8348	29190	328292	423604	8	75	7	90	385497	29839	143	2	132	167
Building speed 1.12	40	10	90141	573	145998	45843	8760	9587	28285	523458	625362	5	88	4	97	384145	28913	251	6	191	192
Building speed 1.13	30	10	99946	579	147470	46305	8848	9568	26289	605042	704815	2	96	2	100	391138	26873	627	24	262	191
Building speed 1.14	20	10	118253	586	149271	46871	8956	9814	26125	645667	746141	1	98	1	100	385282	26705	1104	83	500	196
Building speed 1.15	10	10	174518	578	147331	46262	8840	9581	25616	650292	749128	1	98	1	100	389212	26185	1420	297	1346	192
Building speed 2.1	150	20	70117	188	48004	15073	2880	2893	29333	10375	70332	6	14	5	25	414957	29985	19	0	3	58
Building speed 2.2	140	20	70661	199	50663	15908	3040	3095	29319	11042	72176	6	15	6	27	409017	29970	29	0	3	62
Building speed 2.3	130	20	71209	215	54686	17171	3281	3330	29321	12208	75086	6	16	6	29	410516	29973	40	0	3	67
Building speed 2.4	120	20	71961	228	58057	18230	3483	3606	29329	13333	77758	7	17	7	31	402420	29981	48	0	4	72
Building speed 2.5	110	20	72920	251	63922	20072	3835	3933	29331	15958	82906	8	19	7	34	406252	29983	55	0	4	79
Building speed 2.6	100	20	73570	271	69157	21715	4149	4331	29376	17167	88530	6	20	6	37	399357	30029	58	0	5	87
Building speed 2.7	90	20	75306	306	77876	24453	4673	4796	29405	21500	94629	9	23	9	41	406053	30059	52	0	8	96
Building speed 2.8	80	20	77102	337	85763	26930	5146	5391	29415	23000	99686	10	25	10	45	397781	30069	44	0	11	108
Building speed 2.9	70	20	79081	384	97818	30715	5869	6176	29438	31042	113052	11	28	11	51	395878	30092	39	0	21	124
Building speed 2.10	60	20	81804	438	111622	35049	6697	7170	29456	43667	131867	13	32	13	58	388819	30111	35	0	40	144
Building speed 2.11	50	20	85193	527	134264	42159	8056	8624	29471	68583	166717	15	39	14	68	389203	30126	40	0	65	172
Building speed 2.12	40	20	91087	652	166103	52156	9966	10724	29474	135625	247770	16	48	16	80	387304	30129	46	1	116	214
Building speed 2.13	30	20	99463	870	221569	69573	13294	14177	29373	352167	488375	15	65	14	93	391009	30026	62	2	226	284
Building speed 2.14	20	20	118460	1190	303273	95228	18196	19572	28609	1156125	1327266	4	91	4	100	388515	29245	205	10	417	391
Building speed 2.15	10	20	173771	1243	316635	99423	18998	20516	27839	1376458	1552515	1	97	1	100	388929	28456	783	191	1851	410
Building speed 3.1	150	30	70205	184	46823	14702	2809	2896	29316	0.,000	59495	6	9	5	20	404198	29967	,---	0	0	58
Building speed 3.2	140	30	70774	196	49875	15661	2992	3103	29337	0.,000	60872	6	10	6	21	401806	29989	,---	0	0	62
Building speed 3.3	130	30	71306	209	53197	16704	3192	3340	29365	0.000	62390	6	10	6	23	398013	30018	2	0	0	67
Building speed 3.4	120	30	71935	230	58606	18402	3516	3613	29372	0.,000	64695	7	11	7	25	405348	30025	5	0	1	72
Building speed 3.5	110	30	72633	246	62782	19713	3767	3931	29362	42	66602	8	12	7	27	399403	30014	12	0	3	79
Building speed 3.6	100	30	73927	275	70170	22033	4210	4330	29410	375	70162	8	14	8	30	404967	30063	20	0	4	87
Building speed 3.7	90	30	75212	301	76608	24055	4596	4805	29411	708	73379	9	15	9	33	398524	30064	29	0	4	96
Building speed 3.8	80	30	76954	338	86116	27040	5167	5409	29438	1542	78409	10	17	10	37	397867	30092	35	0	6	108

	Controls		Responses																	
Unit	hours	cm³/h	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Mean arrival	Building speed	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Building speed 3.9	70	30	78639	389	99033	31096	5942	6173	29454	3167	85649	12	19	11	42	401019	30108	37	0	9	123
Building speed 3.10	60	30	82173	443	112982	35476	6779	7193	29463	7667	96399	14	22	13	49	392602	30117	30	0	15	144
Building speed 3.11	50	30	85496	524	133379	41881	8003	8630	29497	10083	107926	16	26	15	57	386295	30152	25	0	34	173
Building speed 3.12	40	30	90798	658	167728	52667	10064	10770	29490	21667	134487	19	32	18	70	389450	30145	26	0	76	215
Building speed 3.13	30	30	99281	876	223057	70040	13383	14371	29501	81583	218713	22	43	21	86	388101	30157	30	1	171	287
Building speed 3.14	20	30	118475	1297	330396	103744	19824	21350	29455	433292	617483	17	64	17	98	386942	30110	44	2	415	427
Building speed 3.15	10	30	173396	1878	478510	150252	28711	31223	28501	2055292	2303479	2	96	2	100	385059	29135	463	87	1478	624
Building speed 4.1	150	40	70205	184	46931	14755	2819	2898	29339	0,,000	59591	6	7	5	18	405309	29991	,---	0	0	58
Building speed 4.2	140	40	70783	196	50025	15708	3002	3103	29328	0,,000	60916	6	7	6	19	402948	29980	,---	0	0	62
Building speed 4.3	130	40	71410	210	53453	16784	3207	3342	29353	0,,000	62470	6	8	6	20	399608	30005	,---	0	0	67
Building speed 4.4	120	40	72146	227	57895	18179	3474	3618	29371	0,,000	64433	7	8	7	22	399921	30024	,---	0	0	72
Building speed 4.5	110	40	72950	250	63617	19976	3817	3943	29392	0,,000	66924	8	9	7	24	403541	30045	,---	0	0	79
Building speed 4.6	100	40	73919	276	70344	22088	4221	4338	29432	0,,000	69889	8	10	8	27	405398	30086	4	0	1	87
Building speed 4.7	90	40	75400	300	76536	24032	4592	4807	29405	0,,000	72637	9	11	9	29	398016	30058	8	0	3	96
Building speed 4.8	80	40	76796	339	86248	27082	5175	5410	29460	0,,000	76947	10	13	10	33	398349	30115	14	0	4	108
Building speed 4.9	70	40	78749	379	96626	30341	5798	6182	29449	458	82043	12	14	12	37	390638	30103	22	0	6	124
Building speed 4.10	60	40	81995	447	114001	35796	6840	7200	29470	1292	90421	14	17	13	44	395873	30125	27	0	9	144
Building speed 4.11	50	40	86106	542	138003	43333	8280	8645	29474	2667	102223	16	20	16	52	399083	30129	23	0	19	173
Building speed 4.12	40	40	91296	660	168264	52835	10096	10787	29514	8458	121527	20	24	19	63	389893	30169	17	0	50	216
Building speed 4.13	30	40	99865	867	220990	69391	13259	14368	29520	22292	158670	25	32	24	81	384468	30176	19	0	134	287
Building speed 4.14	20	40	117325	1298	330575	103801	19835	21468	29505	140583	325026	25	48	24	96	385052	30160	25	1	395	429
Building speed 4.15	10	40	174092	2416	615596	193297	36936	39998	28905	2400708	2709479	4	91	4	100	385379	29547	167	18	876	800
Building speed 5.1	150	50	70205	185	47024	14766	2821	2899	29341	0,,000	59608	6	5	5	16	405309	29993	,---	0	0	58
Building speed 5.2	140	50	70783	196	50028	15709	3002	3103	29332	0,,000	60924	6	6	6	18	402948	29984	,---	0	0	62
Building speed 5.3	130	50	71410	210	53453	16784	3207	3342	29349	0,,000	62465	6	6	6	19	399608	30001	,---	0	0	67
Building speed 5.4	120	50	72146	228	58076	18236	3485	3618	29366	0,,000	64493	7	7	7	20	401158	30018	,---	0	0	72
Building speed 5.5	110	50	72985	250	63585	19966	3815	3944	29392	0,,000	66915	8	7	7	22	403036	30046	,---	0	0	79
Building speed 5.6	100	50	74098	275	70132	22021	4208	4339	29418	0,,000	69793	8	8	8	25	403988	30072	,---	0	0	87
Building speed 5.7	90	50	75275	301	76687	24080	4601	4811	29435	0,,000	72738	9	9	9	27	398596	30089	,---	0	0	96
Building speed 5.8	80	50	76516	344	87709	27541	5263	5406	29441	0,,000	77464	10	10	10	31	405653	30095	5	0	2	108
Building speed 5.9	70	50	78557	383	97537	30627	5852	6178	29449	0,,000	81922	12	11	11	35	394596	30104	10	0	4	124
Building speed 5.10	60	50	81653	440	112103	35200	6726	7209	29477	0,,000	88438	14	13	13	40	388529	30132	17	0	6	144
Building speed 5.11	50	50	85759	523	133374	41879	8002	8648	29502	667	98532	17	15	16	48	385614	30158	20	0	11	173
Building speed 5.12	40	50	90631	659	167783	52684	10067	10778	29501	2500	115363	20	19	20	59	389141	30156	16	0	33	216
Building speed 5.13	30	50	99632	894	227851	71545	13671	14373	29522	10375	149327	26	26	25	77	396271	30178	16	0	110	287
Building speed 5.14	20	50	119474	1301	331561	104110	19894	21589	29525	57958	242918	29	38	28	95	383963	30181	18	1	382	432
Building speed 5.15	10	50	173215	2547	648991	203783	38939	42399	29435	1298708	1623077	12	76	12	99	382776	30090	54	5	850	848

Simulation run	Mean arrival	Building speed	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
	Controls		Responses																		
Unit	hours	cm³/h	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Building speed 6.1	150	60	70205	185	47027	14767	2822	2900	29346	0,,000	59616	6	5	5	16	405309	29998	,---	0	0	58
Building speed 6.2	140	60	70783	197	50130	15741	3008	3104	29340	0,,000	60973	6	5	6	17	404343	29992	,---	0	0	62
Building speed 6.3	130	60	71410	210	53486	16795	3209	3343	29354	0,,000	62485	6	5	6	18	399774	30006	,---	0	0	67
Building speed 6.4	120	60	72146	228	58076	18236	3485	3618	29363	0,,000	64490	7	6	7	19	401044	30016	,---	0	0	72
Building speed 6.5	110	60	72985	250	63585	19966	3815	3944	29389	0,,000	66910	8	6	7	21	403036	30042	,---	0	0	79
Building speed 6.6	100	60	74101	276	70349	22089	4221	4341	29425	0,,000	69884	8	7	8	23	405103	30078	,---	0	0	87
Building speed 6.7	90	60	75422	303	77078	24203	4625	4816	29438	0,,000	72893	9	7	9	26	400119	30092	,---	0	0	96
Building speed 6.8	80	60	76806	336	85635	26889	5138	5412	29441	0,,000	76693	10	8	10	29	395623	30095	,---	0	0	108
Building speed 6.9	70	60	78462	392	99792	31335	5988	6180	29459	0,,000	82781	12	10	11	33	403618	30114	5	0	2	124
Building speed 6.10	60	60	81527	449	114413	35926	6865	7205	29475	0,,000	89295	14	11	13	38	396913	30130	10	0	5	144
Building speed 6.11	50	60	85737	526	133982	42070	8039	8645	29497	0,,000	98083	17	13	16	46	387439	30152	16	0	9	173
Building speed 6.12	40	60	91094	656	167206	52503	10032	10796	29518	958	113646	21	16	20	57	387252	30173	15	0	23	216
Building speed 6.13	30	60	100190	883	225015	70655	13501	14403	29538	4500	142442	26	22	26	74	390581	30195	12	0	86	288
Building speed 6.14	20	60	118805	1322	336694	105722	20202	21581	29534	31000	217883	32	33	31	95	390005	30190	15	1	369	432
Building speed 6.15	10	60	174292	2564	653342	205150	39201	42768	29495	589750	916194	18	63	17	99	381970	30150	33	3	848	855
Building speed 7.1	150	70	70205	185	47027	14767	2822	2900	29343	0,,000	59612	6	4	5	15	405309	29995	,---	0	0	58
Building speed 7.2	140	70	70783	197	50232	15773	3014	3105	29348	0,,000	61022	6	4	6	16	404478	30000	,---	0	0	62
Building speed 7.3	130	70	71410	210	53486	16795	3209	3343	29352	0,,000	62482	6	4	6	17	399774	30004	,---	0	0	67
Building speed 7.4	120	70	72146	228	58109	18246	3487	3619	29368	0,,000	64509	7	5	7	19	401168	30020	,---	0	0	72
Building speed 7.5	110	70	72985	250	63585	19966	3815	3944	29386	0,,000	66906	8	5	7	20	403036	30039	,---	0	0	79
Building speed 7.6	100	70	74101	276	70349	22089	4221	4341	29422	0,,000	69881	8	6	8	22	405103	30076	,---	0	0	87
Building speed 7.7	90	70	75416	304	77486	24331	4649	4816	29436	0,,000	73044	9	6	9	25	402218	30090	,---	0	0	96
Building speed 7.8	80	70	76951	338	86170	27057	5170	5415	29444	0,,000	76901	10	7	10	28	397842	30098	,---	0	0	108
Building speed 7.9	70	70	78649	384	97880	30734	5873	6182	29463	0,,000	82073	12	8	11	31	395833	30118	,---	0	0	124
Building speed 7.10	60	70	81404	450	114548	35968	6873	7209	29470	0,,000	89344	14	10	13	37	397182	30125	6	0	3	144
Building speed 7.11	50	70	85571	533	135851	42657	8151	8641	29495	42	98818	17	11	16	44	393220	30150	11	0	8	173
Building speed 7.12	40	70	90947	665	169337	53172	10160	10790	29521	42	113525	21	14	20	55	392517	30177	14	0	17	216
Building speed 7.13	30	70	100148	878	223617	70216	13417	14417	29535	1250	138680	27	19	26	71	387881	30192	11	0	68	288
Building speed 7.14	20	70	119100	1331	339199	106509	20352	21563	29537	19417	207224	33	28	32	94	393249	30194	13	1	355	431
Building speed 7.15	10	70	173341	2598	661847	207820	39711	42840	29500	297958	627663	22	55	21	98	386289	30156	24	2	845	857
Building speed 8.1	150	80	70205	185	47027	14767	2822	2900	29341	0,,000	59609	6	3	5	14	405309	29993	,---	0	0	58
Building speed 8.2	140	80	70783	197	50265	15783	3016	3106	29355	0,,000	61045	6	4	6	15	404478	30008	,---	0	0	62
Building speed 8.3	130	80	71410	210	53489	16796	3209	3343	29356	0,,000	62490	6	4	6	17	399774	30008	,---	0	0	67
Building speed 8.4	120	80	72146	228	58211	18278	3493	3620	29376	0,,000	64559	7	4	7	18	401794	30029	,---	0	0	72
Building speed 8.5	110	80	72985	250	63585	19966	3815	3944	29384	0,,000	66903	8	5	7	20	403036	30037	,---	0	0	79
Building speed 8.6	100	80	74101	276	70349	22089	4221	4341	29421	0,,000	69879	8	5	8	22	405103	30075	,---	0	0	87
Building speed 8.7	90	80	75416	304	77486	24331	4649	4816	29435	0,,000	73042	9	6	9	24	402218	30089	,---	0	0	96
Building speed 8.8	80	80	76978	341	86777	27248	5207	5416	29446	0,,000	77132	10	6	10	27	400692	30100	,---	0	0	108
Building speed 8.9	70	80	78605	386	98401	30898	5904	6185	29462	0,,000	82269	12	7	12	31	397698	30116	,---	0	0	124
Building speed 8.10	60	80	81433	452	115070	36132	6904	7206	29472	0,,000	89538	14	8	13	36	399140	30127	4	0	2	144

	Controls		Responses																		
Unit	hours	cm³/h	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Mean arrival	Building speed	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Building speed 8.11	50	80	85326	536	136652	42909	8199	8641	29504	0,.000	99088	17	10	16	43	395507	30160	8	0	6	173
Building speed 8.12	40	80	91698	658	167693	52655	10062	10802	29504	0,.000	112858	21	12	20	53	388037	30160	12	0	13	216
Building speed 8.13	30	80	100329	898	228895	71873	13734	14417	29542	625	140038	27	17	26	70	396851	30198	10	0	58	288
Building speed 8.14	20	80	118322	1300	331118	103971	19867	21571	29542	11208	196006	35	24	34	93	383779	30198	12	0	341	431
Building speed 8.15	10	80	173411	2589	659689	207142	39581	42823	29510	184792	513685	25	48	25	98	385230	30166	20	2	841	856
Building speed 9.1	150	90	70205	185	47027	14767	2822	2900	29339	0,.000	59607	6	3	5	14	405309	29991	,---	0	0	58
Building speed 9.2	140	90	70783	197	50265	15783	3016	3106	29353	0,.000	61043	6	3	6	15	404478	30006	,---	0	0	62
Building speed 9.3	130	90	71410	210	53489	16796	3209	3343	29355	0,.000	62488	6	3	6	16	399774	30007	,---	0	0	67
Building speed 9.4	120	90	72146	228	58211	18278	3493	3620	29375	0,.000	64557	7	4	7	17	401794	30027	,---	0	0	72
Building speed 9.5	110	90	72985	250	63585	19966	3815	3944	29382	0,.000	66901	8	4	7	19	403036	30035	,---	0	0	79
Building speed 9.6	100	90	74101	276	70349	22089	4221	4341	29420	0,.000	69877	8	5	8	21	405220	30073	,---	0	0	87
Building speed 9.7	90	90	75416	304	77486	24331	4649	4816	29433	0,.000	73040	9	5	9	23	402304	30087	,---	0	0	96
Building speed 9.8	80	90	76976	341	86811	27259	5209	5417	29448	0,.000	77148	10	6	10	26	400692	30102	,---	0	0	108
Building speed 9.9	70	90	78727	389	98993	31084	5940	6188	29458	0,.000	82489	12	6	12	30	399942	30113	,---	0	0	124
Building speed 9.10	60	90	81609	440	111996	35167	6720	7211	29486	0,.000	88411	14	7	13	34	388228	30141	,---	0	1	144
Building speed 9.11	50	90	85411	537	136914	42991	8215	8651	29518	0,.000	99214	17	9	16	41	395605	30174	6	0	4	173
Building speed 9.12	40	90	91251	661	168531	52919	10112	10813	29521	0,.000	113205	21	11	20	52	389848	30177	10	0	11	216
Building speed 9.13	30	90	99965	885	225449	70791	13527	14404	29532	83	138181	27	15	27	68	391225	30188	9	0	50	288
Building speed 9.14	20	90	118641	1284	327127	102718	19628	21521	29543	4792	188049	36	21	35	92	380053	30200	11	0	330	430
Building speed 9.15	10	90	174900	2602	662951	208167	39777	42991	29530	119625	449933	28	43	27	98	385474	30186	18	2	841	860
Building speed 10.1	150	100	70205	185	47027	14767	2822	2900	29338	0,.000	59605	6	3	5	14	405309	29990	,---	0	0	58
Building speed 10.2	140	100	70783	197	50265	15783	3016	3106	29352	0,.000	61041	6	3	6	15	404478	30004	,---	0	0	62
Building speed 10.3	130	100	71410	210	53591	16828	3215	3344	29363	0,.000	62537	6	3	6	16	400471	30015	,---	0	0	67
Building speed 10.4	120	100	72146	229	58312	18310	3499	3621	29383	0,.000	64607	7	3	7	17	402404	30036	,---	0	0	72
Building speed 10.5	110	100	72985	250	63585	19966	3815	3944	29381	0,.000	66900	8	4	7	19	403160	30034	,---	0	0	79
Building speed 10.6	100	100	74101	276	70382	22100	4223	4342	29424	0,.000	69897	8	4	8	21	405333	30078	,---	0	0	87
Building speed 10.7	90	100	75416	304	77553	24351	4653	4818	29444	0,.000	73081	9	5	9	23	402411	30098	,---	0	0	96
Building speed 10.8	80	100	76976	341	86811	27259	5209	5417	29447	0,.000	77146	10	5	10	26	400692	30101	,---	0	0	108
Building speed 10.9	70	100	78751	390	99438	31224	5966	6188	29455	0,.000	82651	12	6	12	29	401797	30109	,---	0	0	124
Building speed 10.10	60	100	81655	447	113836	35744	6830	7216	29493	0,.000	89115	14	7	13	34	394302	30149	,---	0	0	144
Building speed 10.11	50	100	85153	534	135946	42687	8157	8646	29497	0,.000	98818	17	8	16	41	393043	30152	5	0	2	173
Building speed 10.12	40	100	91129	662	168572	52932	10114	10788	29511	0,.000	113182	21	10	20	50	390747	30166	8	0	9	216
Building speed 10.13	30	100	100477	882	224722	70563	13483	14386	29524	83	137881	27	13	27	67	390545	30180	9	0	43	288
Building speed 10.14	20	100	118440	1310	333704	104783	20022	21575	29541	2292	188060	37	19	36	92	386742	30197	10	0	324	432
Building speed 10.15	10	100	173869	2612	665602	208999	39936	42913	29526	78917	410133	30	39	29	97	387750	30182	16	2	838	858

It is confirmed that an increase in building speed has a positive impact on the spare part supply. However, not that from a cost perspective there is a limit to production expenses. Further, compensation of building space volume increase can be confirmed partly only, since a cost increase can be created.

It can be seen that an increase in building speed leads to a decrease in the total AM penalty until the machine utilization reaches approximately 38 % (similar to the base case setting). These findings are supported by the results of average time in queue, average number of parts in queue, and parts in queue total decrease. For the current base case model setup, no significant cost reduction is generated by a building speed of more than 40 cm³ /hr. Results are displayed in Figure 6-2 and Figure 6-3.

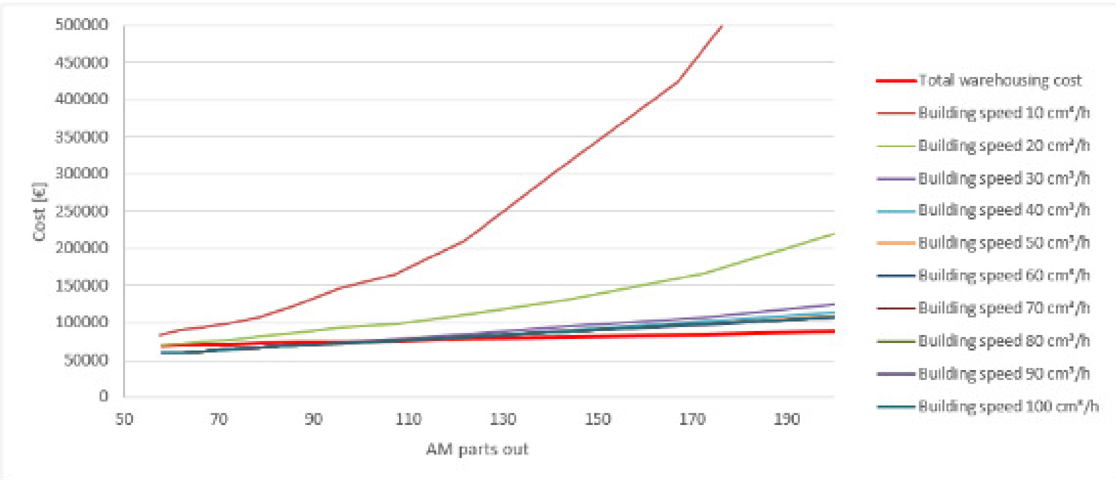


Figure 6-2: Building speed and upper limit search

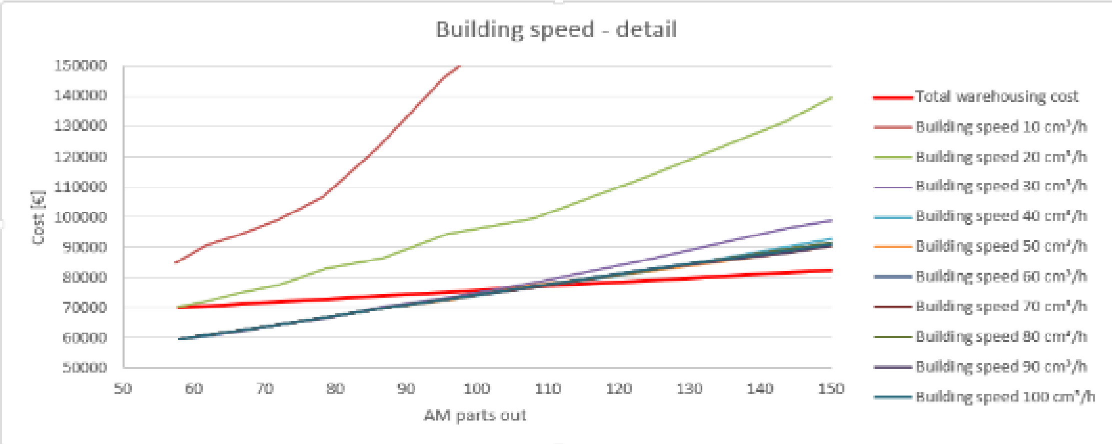


Figure 6-3: Building speed and upper limit search - details

The results can also be analyzed by constant building speed. 40 cm³/ hr is selected here since no further cost improvement is obvious for the current setup.[7] By keeping the building speed constant while decreasing the upper limit another interesting effect becomes apparent. At the point where the mean arrival is 70 hr the first penalty occurs but the Total AM cost already exceeded the Total warehousing cost. Compared to the base setting this means that at a high enough building speed the penalty is no longer an issue, but the production related variable operation, material and energy consumption cost are. This is also supported by the fact that the Total machine utilization can increase significantly when the building speed increases. The building machine utilization can therefore be increased as long as the level of penalty is within the accepted range.

This leads to the finding that increasing the building speed strongly increases the production capacity, which seems to be a logical conclusion[8]. In consequence, production cost and service level related factors need to be evaluated to find an acceptable balance.

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[7] The effect of the building speed variation is assumed to be very specific for the presented case. Another case can show significant effects to changes in the building speed.
[8] Doubling the production speed approximately doubled the production capability in this case.

Another interesting issue occurs in the context of the machine utilization and process speed. As can be seen in Table 6-2 there is a change in machine time results. At lower building speeds the machine production time takes the major part of the total machine utilization time, while machine setup and cool-down time are less significant. When the building speed increases the machine setup and cool-down time become more significant, since both are assumed to be constant for simulation. This observation can be justified by the fixed building space volume. When the simulation model is running the building space volume will be filled and a certain average building volume will occur. Since the machine production time is dependent upon the building speed, the actual machine production time will decrease while setup and cool-down time are constant. When the building space volume is completely filled, it is not possible to place one more part in the production run and arriving spare part requests need to wait in queue. At these high utilizations the effect can be observed best. But in general queuing should be avoided to achieve fast delivery times for the spare parts, since spare parts on demand should be delivered as fast as possible in the allowed time (there lies the difference between optimization for production and spare parts on demand).

Another interesting aspect here is that the building space fill up is executed as a volumetric approach. Since typically no more than one part should be in production in order to have a stable system this assumption fits the purpose. It is also possible to align the process times, depending on the part height instead of the part volume. This change of philosophy can then allow a placement of two parts next to each other while the building time will be defined by the total building height of the entire batch. This case will be analyzed during the technical extensions.

6.3 MATERIAL PRICE

Since it is commonly agreed that the material price is a key factor and limits the application of AM in industry, the following is investigated:

- The price a company would be willing to pay for material.

The calculations regarding the material price use the same simulation model which was used for the base case.

In this experiment the material price is increased stepwise starting at 10 €/ kg, up to the maximum price of 150 €/ kg. Effects on the responses will be discussed.

6.3.1 RESULTS AND DISCUSSION

Table 6-3: Results of material price variation

	Controls		Responses																		
Unit	hours	cm^3/h	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm^3	€ at time	hours	Parts	Parts	Parts
Simulation run	Mean arrival	Material price	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Material price 1.1	100	10	74191	275	70160	2754	4210	4336	29407	3708	54217	8	19	8	35	404530	30061	50	0	5	87
Material price 1.2	100	20	74191	275	70160	5508	4210	4336	29407	3708	56971	8	19	8	35	404530	30061	50	0	5	87
Material price 1.3	100	30	74191	275	70160	8261	4210	4336	29407	3708	59725	8	19	8	35	404530	30061	50	0	5	87
Material price 1.4	100	40	74191	275	70160	11015	4210	4336	29407	3708	62479	8	19	8	35	404530	30061	50	0	5	87
Material price 1.5	100	50	74191	275	70160	13769	4210	4336	29407	3708	65232	8	19	8	35	404530	30061	50	0	5	87
Material price 1.6	100	60	74191	275	70160	16523	4210	4336	29407	3708	67986	8	19	8	35	404530	30061	50	0	5	87
Material price 1.7	100	70	74191	275	70160	19277	4210	4336	29407	3708	70740	8	19	8	35	404530	30061	50	0	5	87
Material price 1.8	100	80	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	30061	50	0	5	87
Material price 1.9	100	90	74191	275	70160	24784	4210	4336	29407	3708	76248	8	19	8	35	404530	30061	50	0	5	87
Material price 1.10	100	100	74191	275	70160	27538	4210	4336	29407	3708	79001	8	19	8	35	404530	30061	50	0	5	87
Material price 1.11	100	110	74191	275	70160	30292	4210	4336	29407	3708	81755	8	19	8	35	404530	30061	50	0	5	87
Material price 1.12	100	120	74191	275	70160	33045	4210	4336	29407	3708	84509	8	19	8	35	404530	30061	50	0	5	87
Material price 1.13	100	130	74191	275	70160	35799	4210	4336	29407	3708	87263	8	19	8	35	404530	30061	50	0	5	87
Material price 1.14	100	140	74191	275	70160	38553	4210	4336	29407	3708	90017	8	19	8	35	404530	30061	50	0	5	87
Material price 1.15	100	150	74191	275	70160	41307	4210	4336	29407	3708	92770	8	19	8	35	404530	30061	50	0	5	87

Figure 6-4: Cost compared to building material price

Generally, the price a company is willing to pay must be as low as possible. But the calculation shows that even a higher price can be reasonable for the given set of conditions.

It is obvious that the material price related costs follow a linear function which influences the total AM cost. Based on the model setup, this is not surprising since the material cost is the product of consumed material and the material price. Therefore a decreasing material price will directly improve the Total AM cost. At the current Total AM cost (material price: 80 €/ kg) the material price makes consumed material cost/ Total AM cost = 22030€/ 73494 € ≈ 30 % of the Total AM cost. Since the material cost follows a linear function, it can be concluded that each 2.67 € decrease in the material price will lower the Total AM cost by 1 % for the current model setup.

To estimate an acceptable price for the material the real warehouse data can be taken into account, since there is a difference between the actual spare part requests of the real warehouse and the possible spare part requests of the simulation model. The real warehouse got 50 spare part requests, while the simulation goes for an upper limit which allows for 87 spare part requests as a limit to work economical (see Chapter 8.2.1 for details). With this information an acceptable price for the material can be estimated due to the linear behavior of the results in the simulation. Taking the simulation results as a basis, the price can be scaled to the acceptable price for the actual number of spare parts delivered.

$$Material\ price * \frac{Max.\ \#\ of\ parts}{Actual\ number\ of\ parts} = Max. Material\ Price \tag{6}$$

$$80€/kg/\left(\frac{87}{57}\right) = 122\ €/kg$$

For the assumed situation, 57% of the actual required parts are needed. Consequently, as long as the material price does not exceed 122 €/ kg, AM is economical for the current situation.

This approximation can be corrected further by considering energy and operator cost. Less material will need less material and operator cost, which will also allow a further material price increase.

Calculations are only valid as long as only the material price is varied, as no other variables are changed for this analysis.

6.4 MACHINE PURCHASE PRICE

For the machine price, literature indicates that the machine purchase price is a key factor and limits the application of AM in industry. The following is investigated:

- Influence of the machine purchase price regarding the decision for AM.
- Indication of a useful depreciation time for an AM machine.

The calculations regarding the machine purchase price use the same simulation model which was used for the base case.

The experiment is executed in two steps. As a first step the machine purchase price is increased stepwise from 100,000 € to 1,000,000 €. The depreciation time is kept constant. In a second step the machine purchase price will be kept constant and the years of depreciation will be changed from 2 to 20 years. Responses will be analyzed to check how the machine purchase price and the depreciation time influence the results.

6.4.1 RESULTS AND DISCUSSION

Table 6-4: Results of machine purchase price variation

	Controls			Responses																	
Unit	hours	€	year	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Mean arrival	Machine purchase price	Years of depre-ciation	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Purchase price 1.1	100	100000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	6535	50	0	5	87
Purchase price 1.2	100	200000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	13070	50	0	5	87
Purchase price 1.3	100	300000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	19605	50	0	5	87
Purchase price 1.4	100	400000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	26140	50	0	5	87
Purchase price 1.5	100	500000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	32675	50	0	5	87
Purchase price 1.6	100	600000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	39210	50	0	5	87
Purchase price 1.7	100	700000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	45745	50	0	5	87
Purchase price 1.8	100	800000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	52280	50	0	5	87
Purchase price 1.9	100	900000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	58815	50	0	5	87
Purchase price 1.10	100	1000000	15	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	65349	50	0	5	87

Table 6-5: Results of depreciation time variation

	Controls			Responses																	
Unit	hours	€	year	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Mean arrival	Machine purchase price	Years of depre-ciation	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Depreciation 1.1	100	460000	2	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	225456	50	0	5	87
Depreciation 1.2	100	460000	4	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	112728	50	0	5	87
Depreciation 1.3	100	460000	6	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	75152	50	0	5	87
Depreciation 1.4	100	460000	8	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	56364	50	0	5	87
Depreciation 1.5	100	460000	10	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	45091	50	0	5	87
Depreciation 1.6	100	460000	12	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	37576	50	0	5	87
Depreciation 1.7	100	460000	14	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	32208	50	0	5	87
Depreciation 1.8	100	460000	16	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	28182	50	0	5	87
Depreciation 1.9	100	460000	18	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	25051	50	0	5	87
Depreciation 1.10	100	460000	20	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	22546	50	0	5	87

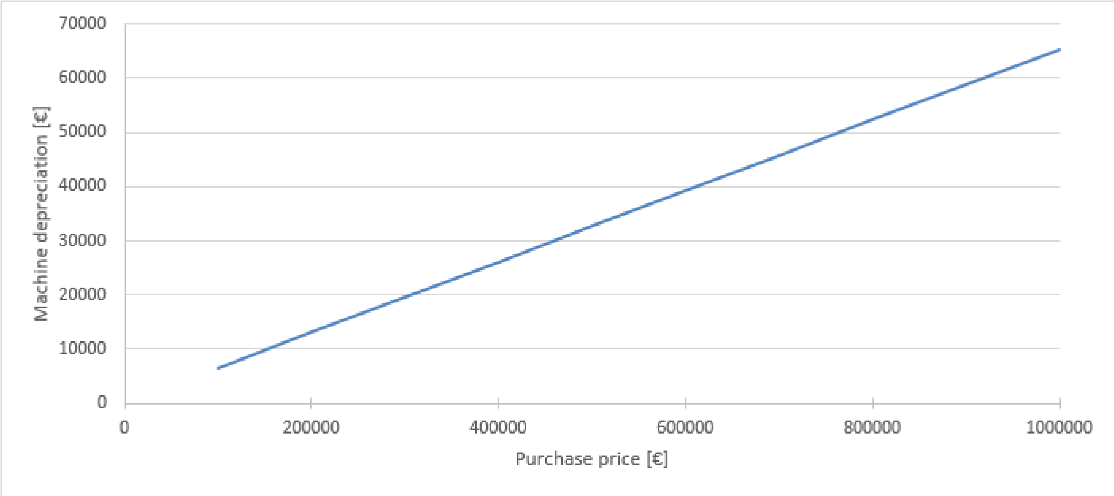


Figure 6-5: Machine depreciation vs. purchase price

Figure 6-5 illustrates the linear relation between the machine purchase price and the machine depreciation. It must be mentioned that no depreciation factors of warehousing are included in calculations of the warehousing route (for example depreciation of the building – it must be individually evaluated if it is better to buy an AM machine or build up more storage space, which also creates cost. This is especially true when storage space is strongly limited and therefore valuable). The depreciation factors of warehousing and AM need to be compared directly for the specific case to reach a valuable response. Therefore the depreciation of the AM machine is excluded from the Total AM cost. A maximum price limit for an AM machine cannot be defined on this basis. However, the lower the price of the AM machine will be, the more the cost will improve.

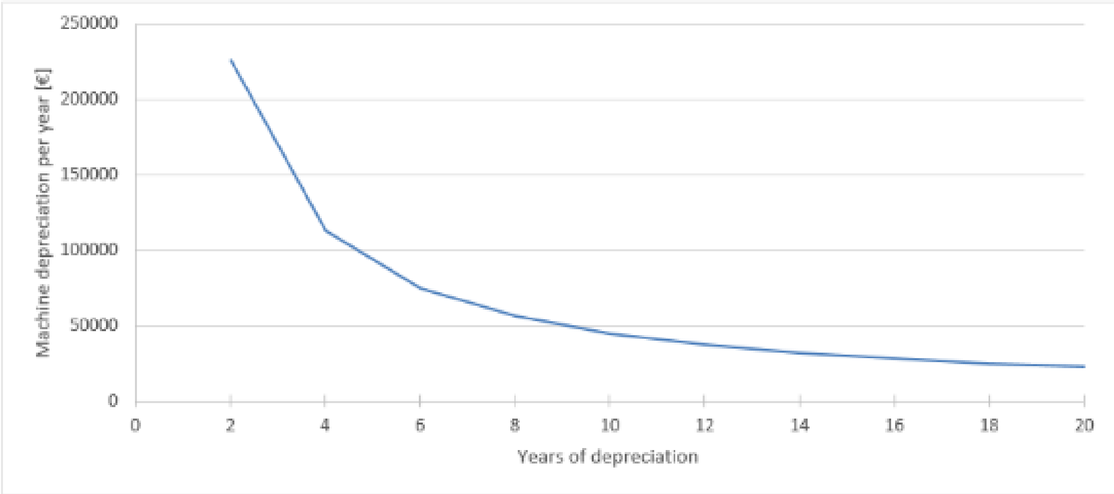


Figure 6-6: Years of depreciation vs. machine depreciation

Figure 6-7 shows the influence of depreciation time. The biggest cost impact occurs at a depreciation time between 2 and 8 years. In consequence this means if the depreciation time is bigger than 8 years the effect on the yearly depreciation tends to stabilize at a certain level.

6.5 COOL DOWN TIME

The following hypotheses is investigated with respect to cool down time:

- A decrease of cool down time leads to faster processing and improved spare part supply.

The calculations regarding the cool down time use the same simulation model which was used for the base case.

To analyze the influence of the cool down time, it is varied stepwise from 1 hr to 12 hr. For each cool down time the upper limit is decreased from 150 hr to 10 hr to stress the system at several levels and reach a clear response in the total AM cost.

6.5.1 RESULTS AND DISCUSSION

Table 6-6: Results of cool down time variation

	Controls		Responses																		
Unit	hours	hours	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Cool down time	Mean arrival	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Cool down 1.1	0	150	70152	187	47588	14943	2855	2893	29303	42	59802	6	13	0	18	411406	29954	5	0	1	58
Cool down 1.2	0	140	70553	195	49799	15637	2988	3095	29304	125	60917	6	13	0	19	402216	29955	11	0	2	62
Cool down 1.3	0	130	71135	215	54689	17172	3281	3333	29321	500	63381	6	15	0	21	409990	29972	19	0	3	67
Cool down 1.4	0	120	72032	229	58344	18320	3501	3615	29365	917	65506	7	15	0	22	403271	30018	30	0	3	72
Cool down 1.5	0	110	72871	249	63357	19894	3801	3930	29314	1292	68003	8	17	0	24	402875	29965	39	0	4	79
Cool down 1.6	0	100	73989	272	69255	21746	4155	4332	29401	1958	71393	8	18	0	27	399842	30055	46	0	4	87
Cool down 1.7	0	90	75271	305	77812	24433	4669	4816	29432	3333	76494	9	21	0	30	404778	30086	51	0	6	96
Cool down 1.8	0	80	77075	339	86401	27130	5184	5405	29419	4750	81694	10	23	0	33	403628	30072	52	0	7	108
Cool down 1.9	0	70	78856	389	99154	31134	5949	6174	29433	6750	89251	11	26	0	38	416158	30087	42	0	12	123
Cool down 1.10	0	60	81469	442	112500	35325	6750	7188	29459	10333	98874	13	30	0	43	409735	30113	39	0	20	144
Cool down 1.11	0	50	85692	519	132256	41528	7935	8638	29474	19208	116608	15	35	0	50	411115	30129	31	0	45	173
Cool down 1.12	0	40	91498	655	166950	52422	10017	10765	29443	58208	170670	18	44	0	62	447871	30098	39	0	82	215
Cool down 1.13	0	30	100327	877	223511	70182	13411	14291	29455	178167	315324	19	59	0	78	568145	30109	46	1	168	286
Cool down 1.14	0	20	118316	1249	318095	99882	19086	20899	29214	858792	1037610	11	85	0	96	1638506	29863	106	5	387	418
Cool down 1.15	0	10	173085	1392	354572	111336	21274	23178	28073	1532875	1726093	2	98	0	100	11721218	28697	698	163	1804	464
Cool down 2.1	1	150	70171	186	47493	14913	2850	2893	29307	42	59773	6	13	1	19	411172	29958	6	0	1	58
Cool down 2.2	1	140	70552	195	49739	15618	2984	3095	29307	208	60982	6	13	1	20	401723	29958	12	0	2	62
Cool down 2.3	1	130	71172	215	54751	17192	3285	3333	29319	625	63528	6	15	1	22	410540	29971	20	0	3	67
Cool down 2.4	1	120	72032	229	58344	18320	3501	3615	29369	917	65511	7	15	1	23	403334	30022	31	0	3	72
Cool down 2.5	1	110	72871	249	63357	19894	3801	3930	29317	1292	68007	8	17	1	25	402875	29969	40	0	4	79
Cool down 2.6	1	100	73981	274	69848	21932	4191	4331	29400	2042	71695	8	18	1	28	402990	30053	46	0	5	87
Cool down 2.7	1	90	75266	304	77371	24294	4642	4813	29426	3458	76443	9	20	1	31	401623	30080	52	0	5	96
Cool down 2.8	1	80	77229	342	87170	27371	5230	5403	29432	5000	82246	10	23	1	35	403354	30086	48	0	8	108
Cool down 2.9	1	70	78749	387	98667	30981	5920	6169	29442	7458	89785	11	26	1	39	399734	30097	42	0	12	123
Cool down 2.10	1	60	81518	438	111575	35034	6694	7189	29470	10625	98837	13	29	2	44	387885	30125	38	0	21	144
Cool down 2.11	1	50	85501	532	135619	42584	8137	8623	29470	23167	121804	15	36	2	53	393227	30125	33	0	48	172
Cool down 2.12	1	40	91365	652	166173	52178	9970	10768	29447	59000	171179	18	44	2	64	385952	30101	37	0	84	215
Cool down 2.13	1	30	100462	865	220361	69193	13222	14317	29455	185667	321672	19	58	2	80	384800	30110	48	1	169	286
Cool down 2.14	1	20	117784	1252	319005	100168	19140	20787	29245	891208	1070297	11	85	1	97	384721	29895	117	5	393	416
Cool down 2.15	1	10	174660	1390	354177	111212	21251	23005	28109	1537167	1730112	2	98	0	100	386929	28733	699	165	1828	460
Cool down 3.1	2	150	70124	186	47293	14850	2838	2893	29300	42	59689	6	13	1	20	408802	29951	6	0	1	58
Cool down 3.2	2	140	70493	196	50030	15709	3002	3093	29280	292	61135	6	13	1	21	405108	29930	12	0	2	62
Cool down 3.3	2	130	71177	215	54718	17181	3283	3333	29316	875	63760	6	15	2	23	410316	29967	21	0	3	67
Cool down 3.4	2	120	72032	229	58314	18311	3499	3615	29372	1042	65629	7	15	2	24	403128	30025	32	0	3	72
Cool down 3.5	2	110	72842	249	63482	19934	3809	3929	29314	1375	68132	8	17	2	26	403677	29966	41	0	4	79
Cool down 3.6	2	100	74114	272	69326	21768	4160	4331	29398	2167	71623	8	18	2	29	400043	30052	47	0	4	87
Cool down 3.7	2	90	75154	303	77104	24211	4626	4811	29418	3625	76496	9	20	2	32	400552	30071	52	0	6	96
Cool down 3.8	2	80	77042	336	85679	26903	5141	5398	29420	5042	81710	10	23	2	35	396709	30074	49	0	8	108
Cool down 3.9	2	70	79097	386	98432	30908	5906	6169	29445	7583	89825	11	26	3	40	398910	30099	42	0	12	123
Cool down 3.10	2	60	81615	440	112061	35187	6724	7198	29446	11833	100203	13	30	3	46	389257	30101	36	0	23	144

	Controls		Responses																		
Unit	hours	hours	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Cool down time	Mean arrival	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Cool down 3.11	2	50	85372	518	132067	41469	7924	8636	29475	24958	122287	15	35	4	54	382657	30130	33	0	48	173
Cool down 3.12	2	40	91117	653	167909	52724	10075	10763	29481	63000	175869	18	44	4	67	390254	30137	38	0	88	215
Cool down 3.13	2	30	99952	873	222522	69872	13351	14300	29449	191500	328289	19	59	5	82	389101	30104	48	1	176	286
Cool down 3.14	2	20	118539	1243	316666	99433	19000	20643	29139	891375	1069302	10	85	3	98	384550	29786	117	6	395	413
Cool down 3.15	2	10	172033	1381	351826	110473	21110	22908	27940	1527792	1719536	2	98	0	100	385957	28561	696	163	1789	458
Cool down 4.1	3	150	70125	185	47105	14791	2826	2893	29307	42	59627	6	13	2	20	407176	29958	6	0	1	58
Cool down 4.2	3	140	70499	196	50060	15719	3004	3093	29282	292	61149	6	13	2	21	404597	29932	12	0	2	62
Cool down 4.3	3	130	71177	214	54613	17148	3277	3331	29297	917	63736	6	15	2	23	409750	29948	22	0	3	67
Cool down 4.4	3	120	72006	229	58311	18310	3499	3614	29372	1083	65668	7	15	3	25	403214	30025	32	0	3	72
Cool down 4.5	3	110	72824	249	63439	19920	3806	3930	29330	1458	68221	8	17	3	27	403358	29982	41	0	4	79
Cool down 4.6	3	100	74059	273	69567	21844	4174	4333	29404	2333	71890	8	18	3	30	401305	30058	47	0	5	87
Cool down 4.7	3	90	75176	303	77324	24280	4639	4813	29421	3958	76919	9	20	3	33	401496	30075	52	0	6	96
Cool down 4.8	3	80	77090	335	85349	26799	5121	5393	29416	5250	81784	10	23	4	37	395751	30070	48	0	8	108
Cool down 4.9	3	70	79046	394	100336	31505	6020	6177	29463	9125	92112	11	27	4	42	406094	30118	41	0	14	124
Cool down 4.10	3	60	81549	439	111768	35095	6706	7198	29444	12000	100257	13	30	5	48	388133	30098	36	0	25	144
Cool down 4.11	3	50	85011	523	133300	41856	7998	8630	29459	26792	124555	15	35	6	56	386182	30114	32	0	51	173
Cool down 4.12	3	40	90873	654	166723	52351	10003	10761	29492	62250	174688	18	44	6	68	387373	30147	38	0	90	215
Cool down 4.13	3	30	100392	871	221938	69689	13316	14298	29457	206583	343162	18	59	7	84	388171	30111	49	1	180	286
Cool down 4.14	3	20	117953	1256	319975	100472	19199	20599	29062	940750	1119769	9	86	3	98	389305	29708	120	6	405	412
Cool down 4.15	3	10	172777	1384	352490	110682	21149	23089	28038	1541500	1733804	2	98	1	100	383691	28661	699	165	1817	462
Cool down 5.1	4	150	70146	185	47173	14812	2830	2893	29312	125	59742	6	13	3	21	407764	29963	7	0	1	58
Cool down 5.2	4	140	70532	197	50268	15784	3016	3093	29290	333	61280	6	13	3	22	406149	29940	13	0	2	62
Cool down 5.3	4	130	71177	214	54610	17147	3277	3330	29297	917	63733	6	15	3	24	409867	29948	23	0	3	67
Cool down 5.4	4	120	72006	229	58311	18310	3499	3614	29375	1083	65673	7	15	3	26	403214	30028	33	0	3	72
Cool down 5.5	4	110	72814	249	63333	19887	3800	3930	29333	1458	68186	8	17	4	28	402762	29985	42	0	4	79
Cool down 5.6	4	100	74055	273	69594	21853	4176	4332	29402	2667	72229	8	18	4	31	401480	30055	48	0	5	87
Cool down 5.7	4	90	75230	302	77031	24188	4622	4812	29413	4125	76964	9	20	4	34	400125	30067	52	0	6	96
Cool down 5.8	4	80	77000	339	86303	27099	5178	5394	29409	5917	82800	10	23	5	38	399986	30062	47	0	9	108
Cool down 5.9	4	70	78882	387	98681	30986	5921	6176	29455	8000	90356	11	26	6	43	399455	30110	41	0	14	124
Cool down 5.10	4	60	81746	438	111500	35011	6690	7203	29465	14417	102607	13	29	6	49	386962	30120	35	0	26	144
Cool down 5.11	4	50	84838	520	132357	41560	7941	8636	29478	28708	126150	15	35	7	58	383353	30133	33	0	51	173
Cool down 5.12	4	40	90426	645	164362	51610	9862	10767	29467	60792	172318	18	43	9	70	381544	30121	37	0	90	215
Cool down 5.13	4	30	99605	871	221977	69701	13319	14310	29473	215875	352501	18	59	9	85	387893	30128	49	1	185	286
Cool down 5.14	4	20	118636	1261	321312	100892	19279	20645	29131	976875	1156532	9	86	4	99	390167	29779	124	6	410	413
Cool down 5.15	4	10	172504	1374	350106	109933	21006	22751	27922	1508792	1699712	2	98	1	100	387049	28543	695	163	1782	455
Cool down 6.1	5	150	70152	184	46790	14692	2807	2892	29316	167	59645	6	12	3	21	404639	29967	7	0	1	58
Cool down 6.2	5	140	70533	198	50362	15814	3022	3094	29299	417	61412	6	13	4	23	406817	29950	14	0	2	62
Cool down 6.3	5	130	71180	214	54610	17147	3277	3330	29301	917	63739	6	15	4	25	409867	29952	24	0	3	67
Cool down 6.4	5	120	72006	229	58308	18309	3498	3613	29372	1208	65792	7	15	4	27	403214	30025	35	0	3	72
Cool down 6.5	5	110	72792	248	63106	19815	3786	3930	29338	1625	68274	8	17	5	29	401344	29990	43	0	4	79
Cool down 6.6	5	100	74145	274	69685	21881	4181	4332	29410	2875	72482	8	18	5	32	402003	30063	49	0	5	87
Cool down 6.7	5	90	75196	300	76515	24026	4591	4813	29411	4417	77061	9	20	6	35	397429	30064	52	0	6	96
Cool down 6.8	5	80	76989	336	85613	26883	5137	5393	29417	6000	82636	10	23	6	39	396815	30071	47	0	9	108

	Controls		Responses																		
Unit	hours	hours	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Cool down time	Mean arrival	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Cool down 6.9	5	70	79037	385	98172	30826	5890	6167	29466	8833	91004	11	26	7	44	397925	30120	41	0	14	123
Cool down 6.10	5	60	81929	445	113305	35578	6798	7194	29432	15292	104104	13	30	8	51	393803	30086	35	0	28	144
Cool down 6.11	5	50	85070	517	131668	41344	7900	8638	29487	29167	126364	15	35	9	59	381199	30142	33	0	52	173
Cool down 6.12	5	40	91244	643	163795	51432	9828	10768	29451	72125	183420	18	43	11	72	380233	30106	40	0	93	215
Cool down 6.13	5	30	100223	867	220914	69367	13255	14261	29443	217500	353640	18	58	11	87	387280	30098	49	1	190	285
Cool down 6.14	5	20	118638	1239	315597	99098	18936	20606	29033	954917	1132267	9	85	5	99	383535	29679	117	6	413	412
Cool down 6.15	5	10	173330	1382	351986	110524	21119	23113	28094	1536167	1728381	1	98	1	100	382914	28719	698	163	1802	462
Cool down 7.1	6	150	70133	184	46842	14708	2811	2892	29319	208	59711	6	12	4	22	405051	29971	8	0	2	58
Cool down 7.2	6	140	70557	199	50792	15949	3048	3096	29312	542	61717	6	13	4	24	410011	29964	15	0	3	62
Cool down 7.3	6	130	71180	214	54606	17146	3276	3329	29304	917	63740	6	15	5	26	410052	29955	25	0	3	67
Cool down 7.4	6	120	72031	229	58444	18351	3507	3613	29370	1333	65965	7	15	5	28	404229	30023	35	0	3	72
Cool down 7.5	6	110	72740	246	62654	19673	3759	3928	29337	1708	68185	8	17	6	30	398770	29989	43	0	4	79
Cool down 7.6	6	100	74157	275	70082	22006	4205	4329	29390	3250	72977	8	19	6	33	404634	30043	49	0	5	87
Cool down 7.7	6	90	75263	301	76801	24115	4608	4811	29415	4417	77171	9	20	7	36	399009	30069	53	0	6	96
Cool down 7.8	6	80	77145	342	87208	27383	5233	5397	29425	6667	83913	10	23	7	41	403996	30079	47	0	10	108
Cool down 7.9	6	70	78808	384	97941	30754	5876	6163	29446	8250	90305	11	26	8	46	397304	30101	39	0	15	123
Cool down 7.10	6	60	81653	443	112957	35469	6777	7187	29438	14958	103641	13	30	10	53	393368	30092	34	0	30	144
Cool down 7.11	6	50	85344	523	133183	41820	7991	8621	29477	32000	129735	15	35	11	61	386248	30132	34	0	55	172
Cool down 7.12	6	40	91069	642	163576	51363	9815	10717	29443	73125	184276	17	43	13	73	381618	30097	38	0	97	214
Cool down 7.13	6	30	100841	856	218053	68468	13083	14275	29435	212667	347740	18	58	13	88	381992	30089	47	1	194	286
Cool down 7.14	6	20	117966	1255	319762	100405	19186	20643	29153	1001208	1180313	8	85	6	99	387987	29801	126	6	419	413
Cool down 7.15	6	10	173768	1377	350821	110158	21049	22834	28029	1523333	1714747	1	97	1	100	386188	28652	705	168	1835	457
Cool down 8.1	7	150	70168	184	46854	14712	2811	2893	29329	292	59812	6	12	5	23	404974	29980	9	0	2	58
Cool down 8.2	7	140	70564	200	50989	16010	3059	3096	29315	708	61960	6	14	5	25	411572	29966	15	0	3	62
Cool down 8.3	7	130	71180	214	54606	17146	3276	3329	29307	1042	63870	6	15	5	26	410052	29959	26	0	3	67
Cool down 8.4	7	120	72081	230	58561	18388	3514	3613	29363	1417	66081	7	16	6	28	405065	30015	36	0	3	72
Cool down 8.5	7	110	72700	246	62702	19688	3762	3931	29345	1875	68384	8	17	6	31	398764	29997	44	0	4	79
Cool down 8.6	7	100	74110	275	69967	21970	4198	4333	29412	3375	73091	8	19	7	34	403598	30065	50	0	5	87
Cool down 8.7	7	90	75238	304	77429	24313	4646	4811	29408	4583	77563	9	20	8	38	402163	30061	53	0	6	96
Cool down 8.8	7	80	77092	343	87292	27410	5237	5398	29412	6875	84136	10	23	9	42	404250	30066	46	0	10	108
Cool down 8.9	7	70	78766	383	97532	30625	5852	6161	29446	8333	90232	11	26	10	47	395791	30100	38	0	15	123
Cool down 8.10	7	60	81565	445	113494	35637	6810	7192	29463	14375	103297	13	30	11	54	394517	30117	33	0	32	144
Cool down 8.11	7	50	85399	519	132176	41503	7931	8621	29458	35250	132582	15	35	13	63	383364	30113	34	0	56	172
Cool down 8.12	7	40	90730	637	162226	50939	9734	10758	29483	70708	181449	18	43	15	75	376960	30138	37	0	100	215
Cool down 8.13	7	30	100279	873	222304	69803	13338	14292	29458	239125	375836	17	59	14	90	388891	30113	49	1	205	286
Cool down 8.14	7	20	117902	1243	316591	99409	18995	20568	29081	993208	1170956	8	85	7	99	385470	29727	120	6	420	411
Cool down 8.15	7	10	173505	1377	350894	110181	21054	23159	28097	1539375	1731231	1	97	1	100	380285	28721	703	164	1808	463
Cool down 9.1	8	150	70144	183	46714	14668	2803	2892	29338	292	59772	6	12	5	23	403962	29990	9	0	2	58
Cool down 9.2	8	140	70574	199	50773	15943	3046	3097	29324	875	62060	6	13	6	25	409695	29976	16	0	3	62
Cool down 9.3	8	130	71180	214	54606	17146	3276	3329	29311	1083	63917	6	15	6	27	410052	29962	27	0	3	67
Cool down 9.4	8	120	72104	230	58528	18378	3512	3612	29364	1417	66070	7	16	7	29	404922	30017	37	0	3	72
Cool down 9.5	8	110	72746	246	62791	19716	3767	3933	29351	2167	68717	8	17	7	32	399037	30003	44	0	4	79
Cool down 9.6	8	100	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	30061	50	0	5	87

	Controls		Responses																		
Unit	hours	hours	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Simulation run	Cool down time	Mean arrival	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
Cool down 9.6	8	100	74191	275	70160	22030	4210	4336	29407	3708	73494	8	19	8	35	404530	30061	50	0	5	87
Cool down 9.7	8	90	75118	304	77492	24332	4650	4802	29390	5208	78178	9	21	9	39	403511	30043	53	0	7	96
Cool down 9.8	8	80	77316	341	86957	27304	5217	5395	29421	7000	84145	10	23	10	43	402876	30075	45	0	10	108
Cool down 9.9	8	70	78155	380	96782	30390	5807	6154	29441	9292	90898	11	26	11	48	393467	30096	37	0	16	123
Cool down 9.10	8	60	81932	440	112059	35187	6724	7191	29435	16417	104765	13	30	13	56	389576	30090	32	0	33	144
Cool down 9.11	8	50	84622	523	133259	41843	7996	8622	29466	35542	133290	15	35	15	65	386618	30121	34	0	58	172
Cool down 9.12	8	40	90977	654	166689	52340	10001	10723	29461	86667	199013	17	44	17	78	388515	30116	39	0	105	214
Cool down 9.13	8	30	99977	845	215214	67577	12913	14288	29456	221958	356010	17	57	17	91	376724	30110	45	1	207	286
Cool down 9.14	8	20	118255	1251	318657	100058	19119	20451	29032	1040792	1219129	7	85	7	99	390566	29677	139	7	420	409
Cool down 9.15	8	10	173511	1377	350726	110128	21044	22846	28119	1518458	1709967	1	97	1	100	386299	28743	706	167	1832	457
Cool down 10.1	9	150	70123	183	46745	14678	2805	2890	29329	292	59770	6	12	6	24	404488	29981	10	0	2	58
Cool down 10.2	9	140	70593	199	50578	15882	3035	3095	29328	875	61990	6	13	7	26	408380	29979	17	0	3	62
Cool down 10.3	9	130	71180	214	54606	17146	3276	3329	29315	1083	63921	6	15	7	28	410052	29966	28	0	3	67
Cool down 10.4	9	120	72104	230	58525	18377	3511	3611	29366	1542	66196	7	16	8	30	404970	30019	38	0	3	72
Cool down 10.5	9	110	72783	247	62851	19735	3771	3933	29351	2333	68907	8	17	8	33	399413	30003	45	0	4	79
Cool down 10.6	9	100	74207	275	70152	22028	4209	4336	29409	3792	73576	8	19	9	36	404379	30062	51	0	5	87
Cool down 10.7	9	90	75199	305	77741	24411	4664	4802	29381	5333	78384	9	21	10	40	404794	30034	51	0	7	96
Cool down 10.8	9	80	77446	340	86625	27200	5197	5398	29443	6958	84010	10	23	11	44	401146	30097	44	0	10	108
Cool down 10.9	9	70	78092	387	98499	30929	5910	6156	29448	10167	92426	11	26	12	50	400033	30103	38	0	17	123
Cool down 10.10	9	60	82136	432	110145	34586	6609	7190	29445	16208	103853	13	29	14	57	382957	30100	32	0	34	144
Cool down 10.11	9	50	84815	523	133128	41802	7988	8621	29473	38417	136124	15	35	17	67	386107	30128	34	0	60	172
Cool down 10.12	9	40	91008	641	163325	51284	9799	10727	29456	83000	194085	17	43	19	79	380569	30111	38	0	107	215
Cool down 10.13	9	30	99888	865	220328	69183	13220	14316	29471	260583	396596	17	58	18	93	384867	30126	48	1	220	286
Cool down 10.14	9	20	118653	1243	316704	99445	19002	20300	28974	1040458	1217838	7	85	7	99	391306	29618	145	7	421	406
Cool down 10.15	9	10	172366	1374	350166	109952	21010	22653	28109	1510732	1701885	1	97	2	100	389093	28733	710	170	1853	453
Cool down 11.1	10	150	70124	184	46912	14730	2815	2890	29324	375	59909	6	12	7	25	405824	29976	10	0	2	58
Cool down 11.2	10	140	70593	199	50575	15881	3034	3094	29323	875	61982	6	13	7	27	408380	29975	18	0	3	62
Cool down 11.2	10	140	70593	199	50575	15881	3034	3094	29323	875	61982	6	13	7	27	408380	29975	18	0	3	62
Cool down 11.3	10	130	71180	214	54603	17145	3276	3328	29311	1167	63997	6	15	8	29	410052	29962	29	0	3	67
Cool down 11.4	10	120	72103	230	58488	18365	3509	3609	29357	1583	66210	7	16	8	31	404942	30009	39	0	3	72
Cool down 11.5	10	110	72801	245	62356	19580	3741	3928	29324	2458	68805	8	17	9	33	396777	29975	46	0	4	79
Cool down 11.6	10	100	74184	275	70190	22040	4211	4336	29406	4042	73836	8	19	10	37	404503	30059	51	0	5	87
Cool down 11.7	10	90	75387	301	76746	24098	4605	4798	29376	5042	77711	9	20	11	41	399843	30029	51	0	7	96
Cool down 11.8	10	80	77486	338	86063	27024	5164	5390	29434	6708	83531	10	23	12	45	399008	30088	44	0	10	108
Cool down 11.9	10	70	78333	386	98220	30841	5893	6160	29441	10000	92149	11	26	14	51	398588	30096	37	0	17	123
Cool down 11.10	10	60	82199	425	108156	33961	6489	7180	29428	16833	103701	13	29	16	58	376606	30082	31	0	35	144
Cool down 11.11	10	50	84917	529	134763	42316	8086	8592	29449	41333	139591	15	36	18	69	392232	30103	35	0	62	172
Cool down 11.12	10	40	91162	643	163842	51446	9831	10739	29454	98542	209830	17	43	20	81	381376	30109	40	1	111	215
Cool down 11.13	10	30	100076	874	222640	69909	13358	14233	29427	276250	412986	16	59	19	94	391350	30081	49	1	228	285
Cool down 11.14	10	20	117821	1235	314577	98777	18875	20313	28990	1030333	1206951	7	85	8	99	388504	29634	138	7	421	406
Cool down 11.15	10	10	172916	1364	347638	109158	20858	22874	27947	1523583	1713737	1	97	2	100	382492	28568	702	164	1781	457
Cool down 12.1	11	150	70126	184	46788	14692	2807	2889	29321	500	59982	6	12	7	25	405042	29972	11	0	2	58
Cool down 12.2	11	140	70625	200	50900	15983	3054	3094	29327	958	62192	6	14	8	27	411083	29979	19	0	3	62

Simulation run	Cool down time	Mean arrival	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Operator cost	Total AM maintenance cost	Total AM Penalty	Total AM cost	Machine setup time	Machine production time	Machine cool down time	Total machine utilization time	Average building volume	Machine depre-ciation	Average time in queue	Average number of parts in queue	Parts in queue total	AM parts out
	Controls		Responses																		
Unit	hours	hours	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	mm³	€ at time	hours	Parts	Parts	Parts
Cool down 12.3	11	130	71180	214	54573	17136	3274	3328	29314	1292	64116	6	14	9	29	409827	29966	30	0	3	67
Cool down 12.4	11	120	72103	230	58485	18364	3509	3608	29355	1583	66204	7	16	9	32	405022	30007	40	0	3	72
Cool down 12.5	11	110	72837	246	62571	19647	3754	3927	29320	2708	69129	8	17	10	34	398223	29971	47	0	4	79
Cool down 12.6	11	100	74185	275	70112	22015	4207	4333	29401	4083	73840	8	19	11	38	404306	30055	52	0	5	87
Cool down 12.7	11	90	75472	301	76640	24065	4598	4794	29365	5458	78069	9	20	12	42	399696	30017	51	0	7	96
Cool down 12.8	11	80	77254	335	85418	26821	5125	5398	29430	7458	84042	10	23	14	46	395433	30084	43	0	11	108
Cool down 12.9	11	70	78570	377	95958	30131	5757	6152	29440	10167	91460	11	25	15	52	389885	30094	35	0	18	123
Cool down 12.10	11	60	81869	433	110270	34625	6616	7193	29446	18958	106655	13	29	17	60	383295	30101	31	0	37	144
Cool down 12.11	11	50	85260	524	133589	41947	8015	8598	29428	41750	139547	15	35	20	70	388498	30082	35	0	63	172
Cool down 12.12	11	40	91008	646	164704	51717	9882	10728	29474	97583	209209	17	43	22	83	383933	30129	39	1	117	215
Cool down 12.13	11	30	99946	882	224649	70540	13479	14266	29462	303125	440691	15	59	21	95	393755	30116	49	1	239	285
Cool down 12.14	11	20	118064	1237	315144	98955	18909	20213	28901	1060250	1236861	6	85	8	99	391436	29543	148	7	421	404
Cool down 12.15	11	10	173926	1365	347698	109177	20862	22426	28037	1496208	1686057	1	97	2	100	390231	28661	712	171	1856	449
Cool down 13.1	12	150	70106	184	46788	14692	2807	2889	29322	667	60151	6	12	8	26	404917	29974	12	0	2	58
Cool down 13.2	12	140	70659	199	50761	15939	3046	3095	29335	1000	62192	6	13	9	28	409837	29987	20	0	3	62
Cool down 13.3	12	130	71180	214	54540	17125	3272	3328	29309	1333	64137	6	14	9	30	409724	29960	31	0	3	67
Cool down 13.4	12	120	72121	230	58673	18423	3520	3607	29351	1792	66477	7	16	10	33	406614	30004	41	0	3	72
Cool down 13.5	12	110	72817	246	62583	19651	3755	3928	29326	2708	69142	8	17	11	35	398222	29977	47	0	4	79
Cool down 13.6	12	100	74060	277	70521	22144	4231	4332	29396	4542	74443	8	19	12	39	407045	30049	52	0	5	87
Cool down 13.7	12	90	75510	305	77807	24432	4668	4791	29371	5833	78886	9	21	13	43	406055	30024	49	0	8	96
Cool down 13.8	12	80	77137	337	85927	26981	5156	5398	29455	7167	83975	10	23	15	48	397872	30109	42	0	11	108
Cool down 13.9	12	70	78820	383	97684	30673	5861	6158	29460	11875	93846	11	26	16	54	396525	30114	35	0	20	123
Cool down 13.10	12	60	81432	435	110838	34803	6650	7187	29440	22458	110352	13	29	19	62	385603	30094	31	0	39	144
Cool down 13.11	12	50	84856	537	136892	42984	8214	8593	29438	49208	148249	15	36	22	73	398453	30092	36	0	68	172
Cool down 13.12	12	40	90588	650	165547	51982	9933	10726	29448	108167	220072	17	44	24	84	385967	30103	41	1	121	215
Cool down 13.13	12	30	99801	855	217824	68397	13069	14231	29428	297792	432725	16	58	23	96	382720	30081	49	1	243	285
Cool down 13.14	12	20	118051	1245	317281	99626	19037	20313	29010	1101292	1278947	6	85	8	100	391700	29654	147	7	424	406
Cool down 13.15	12	10	173363	1369	348914	109559	20935	22644	28133	1505500	1696148	1	97	2	100	386855	28758	714	172	1871	453

It can be confirmed that a reduced cool down time leads to faster processing and improved spare part supply. However, from a cost perspective the potential is limited.

The results show that cool down time has only a slight influence on the results as long as the system is in a stable state below ~ 38 % total machine utilization. The lower the utilization is, the smaller the effect is on the total AM cost. When ~ 38 % total machine utilization is exceeded the penalties start to increase significantly, so it is no longer possible to maintain a proper service level. Figure 6-7 and Figure 6-8 show the tolerance of the presented system with respect to cool down time. Allowing a cool down time of 12 hrs has a significant impact on the overall system performance, represented by the Total AM cost. A limit for the system performance is found at this point since an allowed cool down time of 12 hr has a significant impact on the Total AM cost. The cool down times between 2 and 11 hrs cause only small variations in the Total AM cost and the delivered parts. The more the system is stressed the stronger the system will react on variations of the cool down time, especially when the found limit of 12 hrs is exceeded.

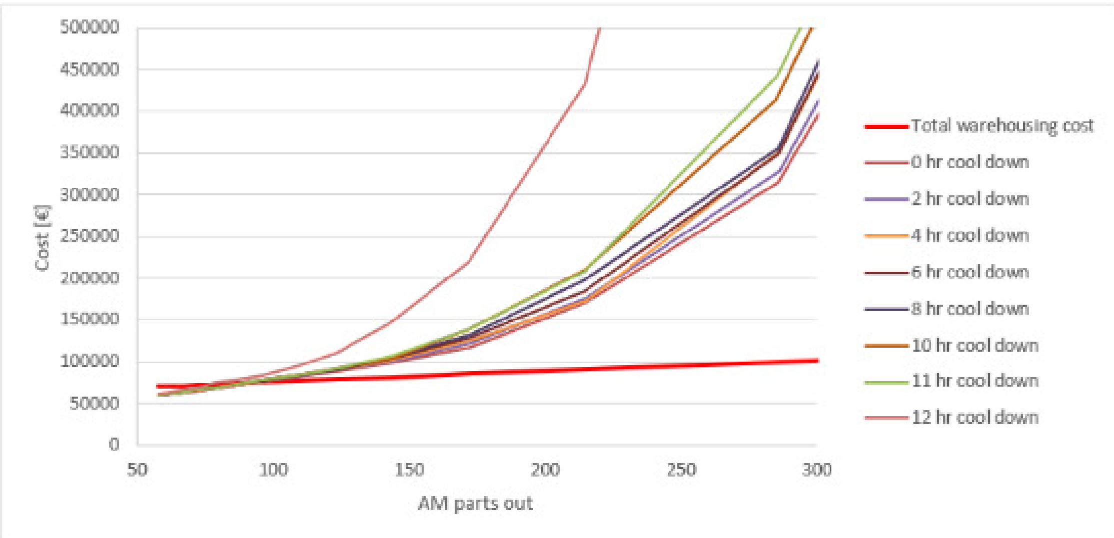


Figure 6-7: Cool down time variation

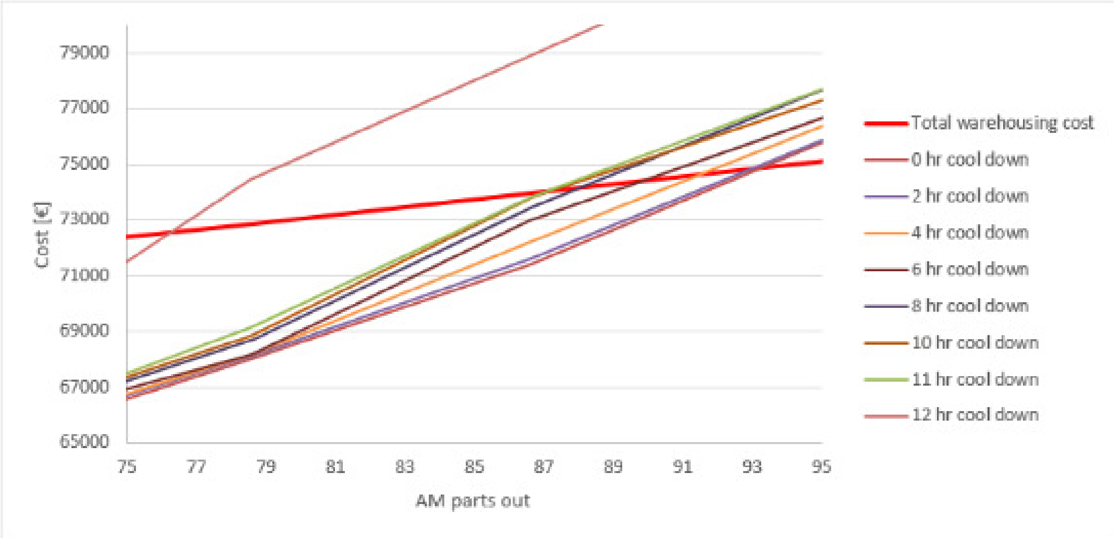


Figure 6-8: Cool down time variation - detail

As for the machine setup and building speed, a faster cool down will create a higher system output which can increase the variable production cost. The system must need to be balanced.

7 ADDITIVE STRATEGY INVESTIGATION

Based on the results from the basic model analysis, further investigations were made for various AM strategies. These strategies were designed to simulate multiple potential real-world strategies for AM spare part services, such as multiple machines and combination of queuing scenarios. In addition, since part size appears to have significant influence on the performance of the AM system. In order to evaluate the sensitivity of strategies to the average size distribution of the spare parts, part sets will vary size distributions and perform simulations. Since the simulation model requires specific information as input parameters the results of calculation can only be valid for the specific case. However, for the presented setup it will be possible to see trends or specific system behavior. For the multi-machine strategy study, details of each scenarios are briefly described below:

1. Two machines with fixed material assignments - Each machine will be dedicated to fabricate only one fixed type of material. One of the two possible materials will be assigned to each new spare part request. The spare part requests will then be assigned to the corresponding machines accordingly.
2. Two machines with flexible material assignments - Each machine will be able to switch to either of the two materials for a new production run. Similar to the first strategy, one of the two possible materials will be assigned to each new spare part request. The spare part requests will be assigned to the machines according to their availability. If material switch occurred between builds for either machine, additional setup time will be included for that particular machine.

3. Three machines with a fixed material assignment - Each machine will be dedicated to fabricate only one fixed type of material. One of three possible materials will be assigned to each spare part request. The spare part requests will be assigned to the corresponding machines accordingly.
4. Three machines with flexible material assignment - Each machine will be able to switch to either of the three materials for a new production run. One of the three possible materials will be assigned to each spare part request. The spare part requests will be assigned to the machines according to their availability. If material switch occurred between builds for either machine, additional setup time will be included for that particular machine.

For each of these four strategies, two modes were evaluated for individual AM systems:

(a) No-waiting - In this mode arriving spare part requests will be forwarded to production immediately if a machine is idle. If no machine is idle, arriving spare part requests are sent to a queue. When a machine becomes idle again the parts in queue will be prioritized and sent to production directly.

(b) Waiting – Similar to the no-waiting mode, spare part requests will be sent to production directly, however the production will not start for a specific duration or until a certain building space volume is filled. This could potentially increase the chance that multiple parts can enter the production run without the need to wait in the queues.

For the part size distribution study, the simulated scenario was defined as below:

5. Part size distribution – A two-machine strategy with one type of material was set up. Several distribution models of part sizes, such as big parts only or an equally distributed mix of small, mid and big parts were analyzed. In addition, both waiting and no-waiting mode as described previously were also investigated for each part size distribution models.

For each of those strategies the following input and performance parameters were investigated:

- Upper limit/Mean part arrival
- Setup and cool down time
- Elapsed time (only for setups in waiting mode)
- Production Start volume (only for setups in waiting mode)
- Material changeover time (for flexible material strategies)

The mean part arrival time is an important control parameter and is used in all simulations to vary the mean arrival rate of spare part requests. Therefore it is an entire approach adopted in all simulations. The mean arrival time has the ability to find specific performance levels of the system. Finding these specific performance levels is described as upper limit search.Upper limit search – An upper limit search is intended to stress the system until a certain limit is reached by decreasing the mean arrival time of spare part requests that increases the actual arrival of spare part requests. In the following investigations three different stress levels were of interest.

- *Low arrival rate* – none to minor penalties occur until this point (marked green).
- *Upper limit* – a penalty of less than 5000 € is charged. The system runs stably with a defined penalty. The upper limit is the standard indicator for the system performance. (marked yellow).
- *High arrival rate* – The system is still able to handle the spare part request, but a heavy penalty occurs. Typically the average number of parts in queue is below one. If the average number of parts in queue is larger than one the system is assumed to be unstable. As later results will show the spare part requests arrive in a higher frequency than the system can deliver (marked red). This is at least true for the current sytem setup and can be different in other cases. This effect is related to the total production time of the parts.

Investigations of setup and cool down time, elapse time, start volume and material change over time were relatively straightforward and since these parameter created a direct in- or decrease in the cost results of the simulations.

The general proceeding for all investigated strategies to be investigated will run in the no waiting and waiting mode, in the following setups:

- Upper limit search - 10 to 150 hrs
- Setup and cool down time - 3 to 36 hrs at low, upper limit and high arrival rate
- Start volume - 0 to 100 % at upper limit
- Elapse time – 0 to 12 hrs at upper limit
- Material changeover time – 1 to 10 hrs at low, upper limit and high arrival rate

The described values are varied during simulations. Each variation is named and numbered accordingly. The material changeover time is investigated only when a material changeover is applied in the according strategy.

Results and findings will be discussed for each strategy individually in this section. Selected results are presented in this chapter. The tables containing all results of simulation runs are available in the appendix.

7.1 TWO MACHINES WITH FIXED MATERIAL ASSIGNMENTS

As described earlier, two machines with a fixed material assignment is to be modeled. Each machine will be dedicated to fabricate only one fixed type of material. One of the two possible materials will be assigned to each spare part request. The spare part requests will be assigned to the machines accordingly. Changes with respect to the upper limit, setup and cool down time, elapse time and start volume were investigated.

7.1.1 MODEL ADJUSTMENTS

The model for this strategy as shown in Figure 7-1 is a modification of the base case. The main change was the arrival and queueing logic of the AM route.

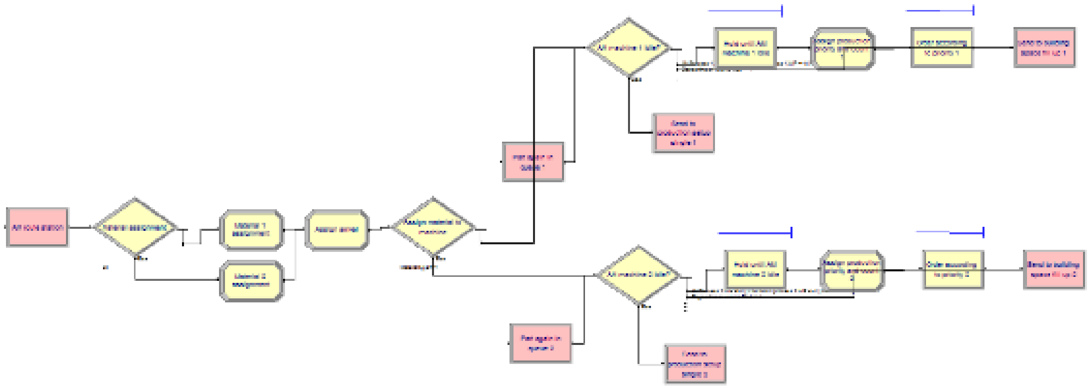


Figure 7-1: Adjusted AM rout arrival and queueing logic

Each of the two machines is dedicated to produce one of the two materials as oppose to the basic setup, in which only one material is assigned to the spare parts. Therefore the material type assignment must be added to the model. This is done by a decide module which assigns the two material with a 50% chance each.[9] After that the arrival time is assigned to the part the same way as in the basic model.

[9] It is assumed that an equal distribution of materials will represent the best setup to allow for further conclusions, based on a similar stress level of both machines. Another distribution would make one machine a bottleneck, creating a reduced system performance, what would also reduce the generality of the model when the results are compared with other strategies which can react better to different materials.

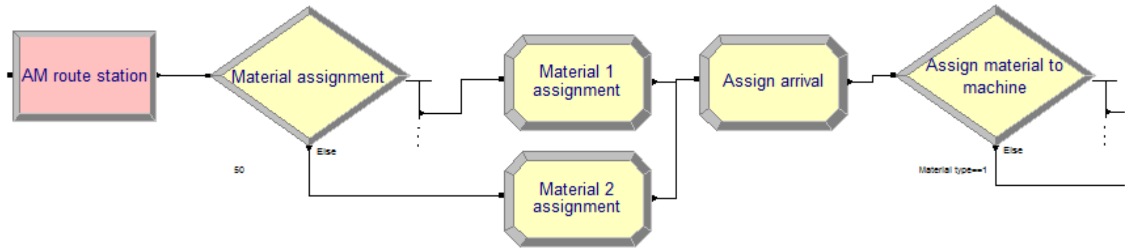


Figure 7-2: Material assignment

After the assignment of the arrival time the spare part request enters a decide module which checks for the assigned material. Spare part requests with assigned material type 1 will follow path one, those with material type 2 will follow path two. Paths one and two are copies of the basic setup and are adjusted to be independent of each other until the finished parts leave the system.

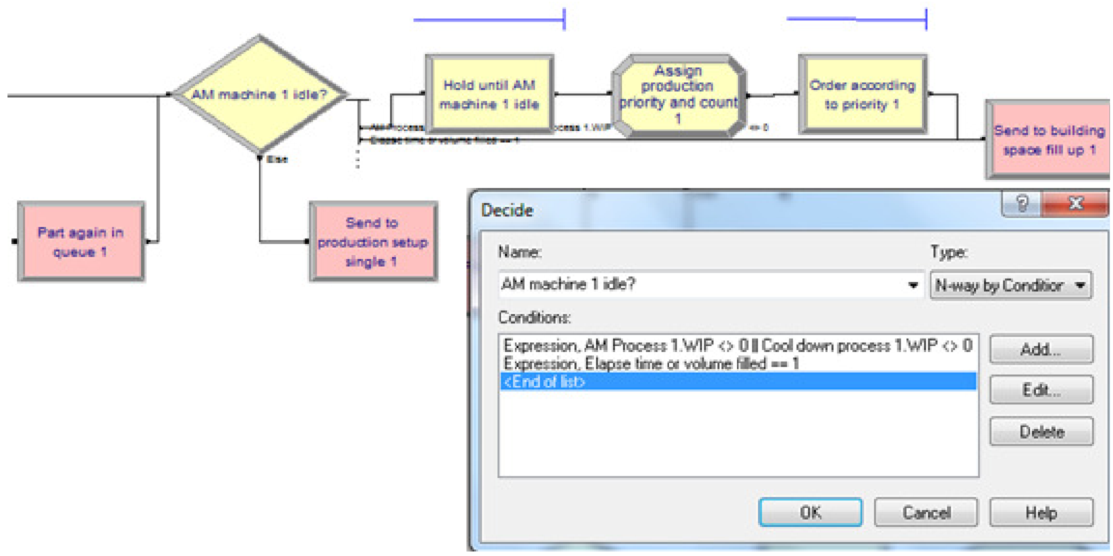


Figure 7-3: Modification of queueing logic

For each queuing logic an additional check function was added to the decide module of AM idle status checking, which determines whether the model should run in the waiting or no-waiting mode. This works as a switch during simulation runs. If the variable “Elapse time or volume filled” is 0, the model logic will follow the established mode as previously described. If “Elapse time or volume filled” is set to 1, the newly generated part arrivals will enter the “Building volume counter logic" module, where a separate "waiting logic" is integrated. The rest of the logic has the same functionality as the setup in the base case.

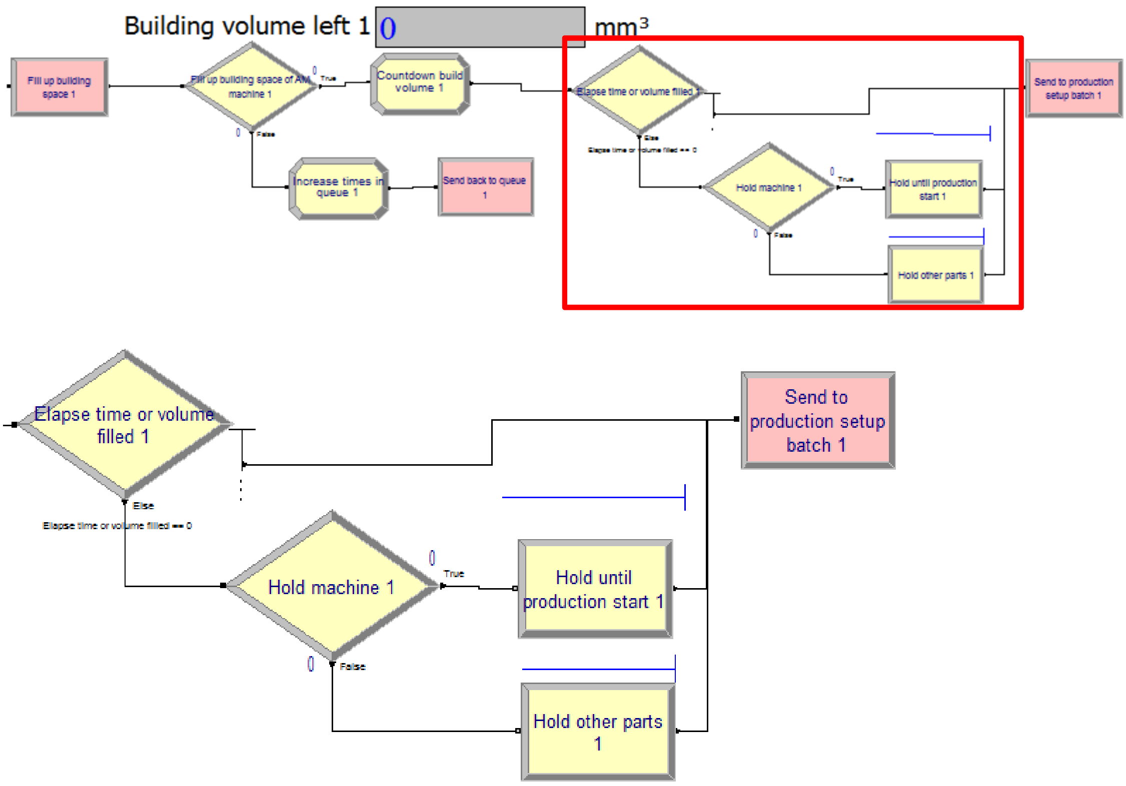


Figure 7-4: Changes in building volume counter logic

When a part enters in the building volume counter logic it flows downstream in the model following the path according to the basic model until it enters at the decide module "Elapse time or volume filled 1". When the model is set to the waiting mode the spare part request bypasses the normal queue and setup logic and begins the waiting until a specific time elapsed or a specific volume is filled. When either time elapsed or a "production start volume" is reached, the spare part request will be forwarded back to the basic model to continue the standard production setup. All other variables and settings are adjusted according to these changes of the model.

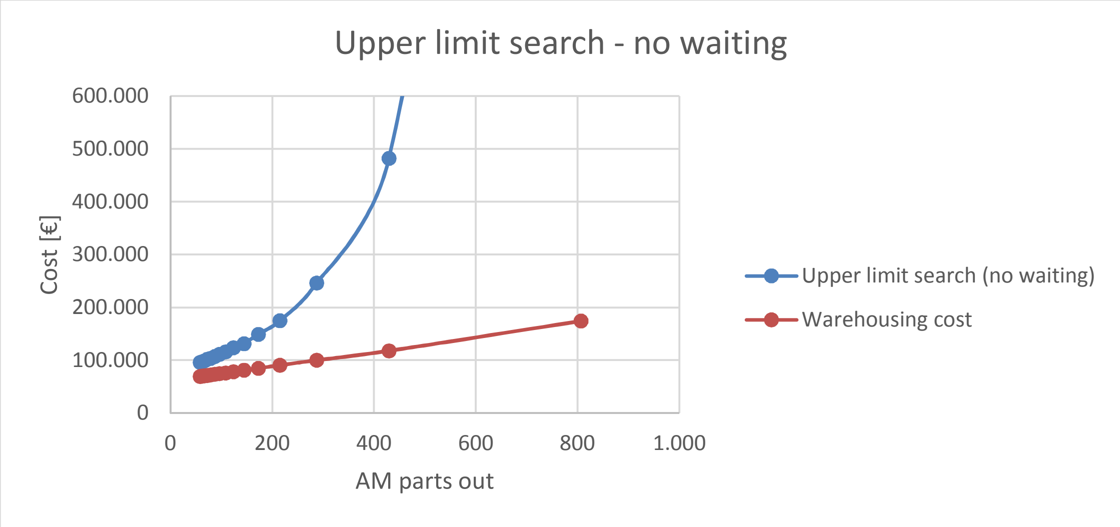
7.1.2 RESULTS AND DISCUSSION

The results of the upper limit search are presented in Table 7-1, Figure 7-5 and Figure 7-6. In comparison to the base case (chapter 5) the performance of the system improves as expected.

Compared to the base case the upper limit improved by 40 %, AM parts out by 66 % and the system utilization is reduced by 19 %. The highest possible arrival rate is at a mean arrival of 20 hrs. When high penalties are accepted the system can deliver up to 429 parts applying the highest arrival rate. Looking at the AM parts out, the system output did not double due to the second machine. This is due to the fixed material setup. If for example two parts of the same material arrive, the system will behave like a one machine strategy, with the results that one part request must wait in queue, while the other machine must wait idle. This decreases also the total system utilization at the upper limit.

Table 7-1: Results of two machines with fixed material assignment- Upper limit No-waiting/ Waiting

		Base case	Two machines with fixed material assignment						Upper limit - changes compared to base case [%]	
			No waiting			Waiting				
Control		Upper limit	Low arrival rate	Upper limit	High arrival rate	Low arrival rate	Upper limit	High arrival rate	No waiting	Waiting
Mean arrival	**hr**	**100**	**130**	**60**	**20**	**130**	**70**	**20**	60%	70%
Cost related responses										
Total warehousing cost	€	55436	70873	81403	117856	70873	78402	117891	147%	141%
Total AM cost	€	73494	98913	131635	482313	99006	122822	508942	179%	167%
Consumed material cost	€	22030	15465	34664	105093	15451	29487	105102	157%	134%
Consumed energy cost	€	4210	2955	6623	20081	2952	5634	20083	157%	134%
Operator cost	€	4336	3332	7206	21470	3329	6172	21489	166%	142%
Total maintenance cost	€	29407	57745	58573	58907	57705	58396	58825	199%	199%
Total AM penalty	€	3708	166	5041	257125	333	3666	283833	136%	99%
AM process related responses										
Consumed material	kg	275	193	433	1313	193	368	1313	157%	134%
Consumed energy	kWh	70160	49251	110396	334693	49208	93907	334720	157%	134%
System setup time	%	8	3	7	15	3	6	15	86%	74%
System utilization time	%	19	7	15	44	7	13	44	77%	66%
Systen cool down time	%	8	3	7	15	3	6	14	83%	72%
Total system utilization	%	35	13	28	74	13	24	73	81%	69%
Average building volume	mm³	404530	369511	382907	389408	369507	380333	389230	95%	94%
Machine depreciation	€	30061	59028	59875	60216	58987	59694	60133	199%	199%
Average time in queue	hr	50	---	30	39	---	27	38	60%	54%
Average number of parts in queue	pcs.	0,001	0,002	0,027	0,642	0,003	0,017	0,725	2700%	1700%
Number of parts in queue total	pcs.	5	1	15	285	1	10	317	300%	200%
AM parts out	pcs.	87	67	144	429	67	123	430	166%	141%



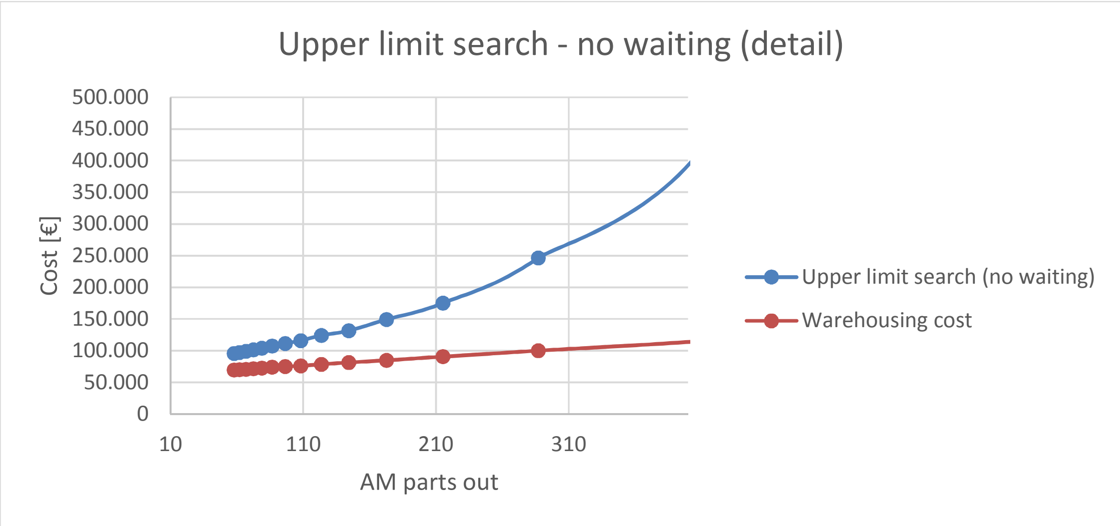
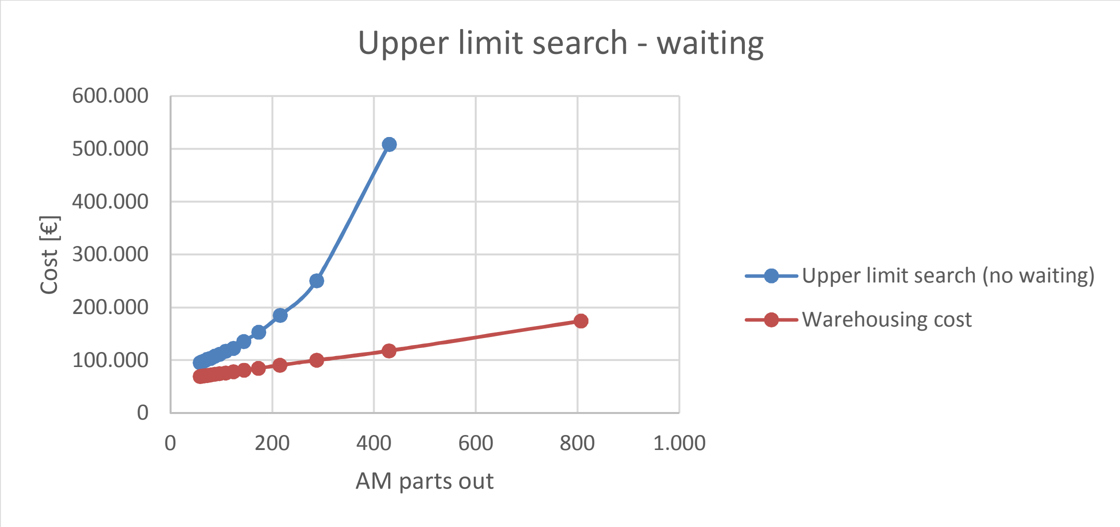


Figure 7-5: Two machines with fixed material - Upper limit search - No waiting



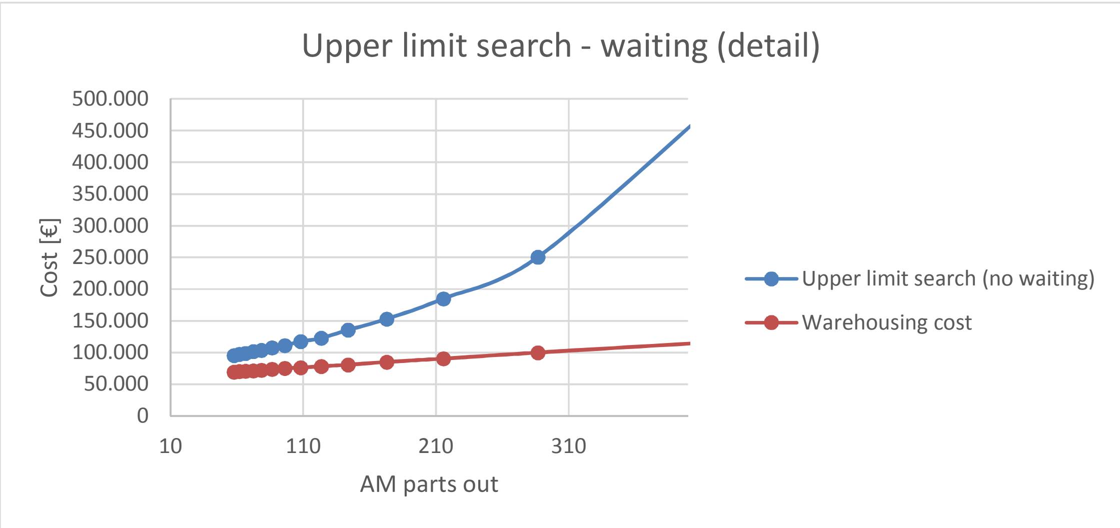


Figure 7-6: Two machines with fixed material - Upper limit search - Waiting

When the waiting mode is applied to the model, the upper limit is reduced, indicating a less efficient performance from the system. This results in a mean arrival time of 70 hrs with a part output of 123 parts. Consequently the machine utilization decreased to 24 %, since less parts can be produced due to waiting.

It was found that for all the simulated scenarios waiting is generally an unfavorable option. This is expected to be caused primarily by the current part set designs. For all the scenarios the part set was setup to have the maximum mean arrival time to be 20 hrs which ensures the stable operation of the system as discussed in previous chapters. However, since the maximum waiting time before a production run starts is set to 12 hrs, it became unlikely that a second part will enter the production before the waiting period is over, which result in a net delay for the production part in the machines and increases the probability to create additional penalties. It is now in question if a generic scenario where waiting is advantageous exists. An advantageous scenario setup was found in section 7.5.

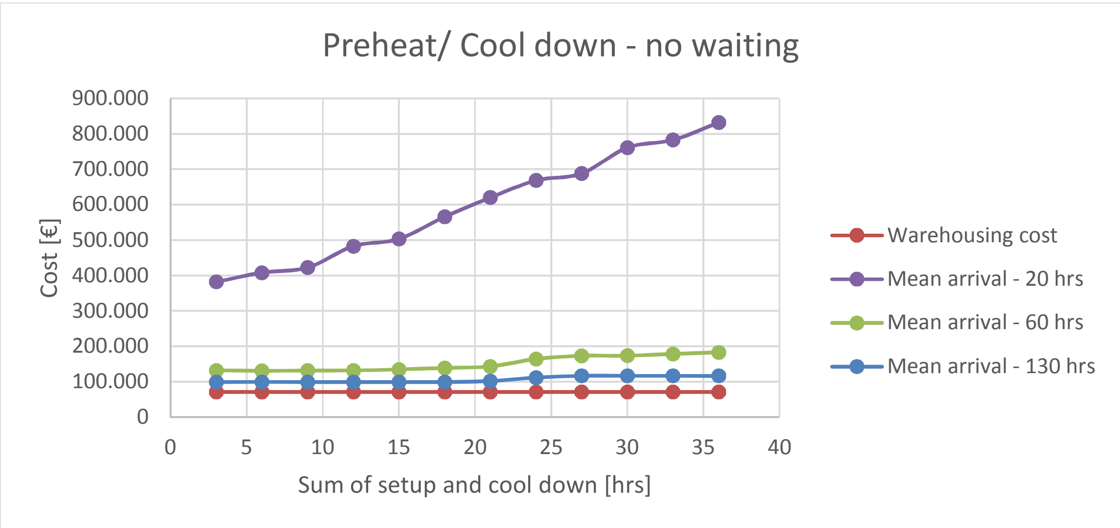


Figure 7-7: Two machines with fixed material - Setup & cool down time – No waiting

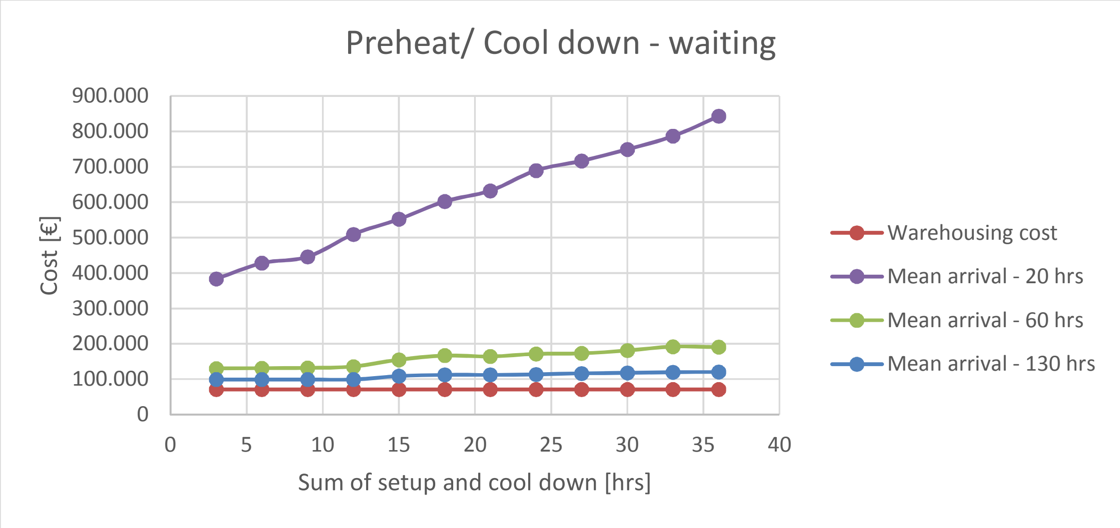


Figure 7-8: Two machines with fixed material - Setup & cool down time – Waiting

The effect of preheat and cool down is illustrated by Figure 7-7 Figure 7-8. The results clearly showed that the faster parts arrive, the more sensitive the system becomes with respect to setup and cool down times (simulated with high, medium and low inter-arrival times). This is reasonable since longer setup and cool down time will reduce the productivity of the system. Also, the no-waiting mode was found to be more efficient than the waiting mode in these cases since the same part set design was used.

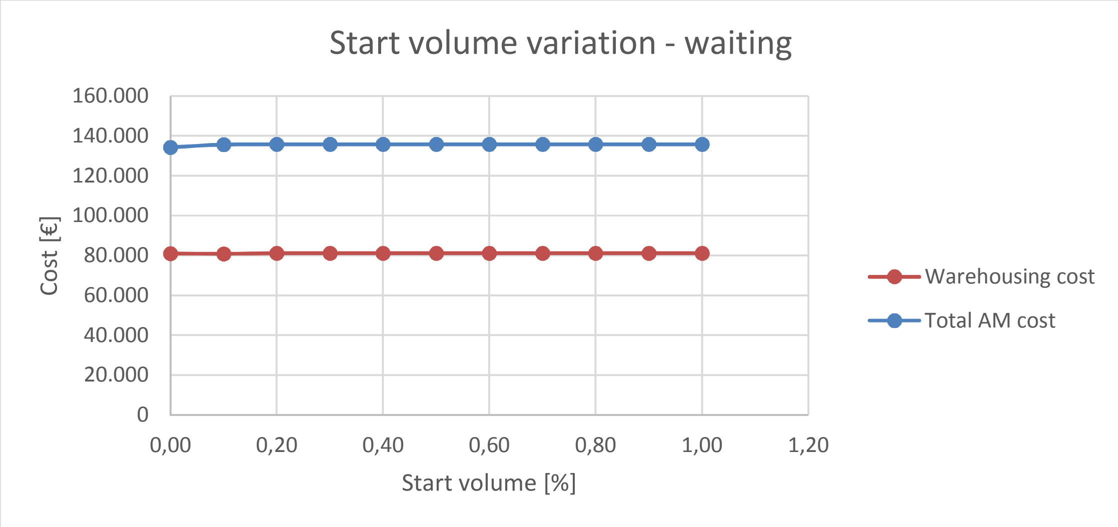


Figure 7-9: Two machines with fixed material - Start volume - Waiting

Figure 7-9 shows that the start volume variation does not have an effect of the system performance. With the part set designs used in the simulations there is never a second part arrival during waiting as long as the system is in a stable state. As described before this is due to the fact that the waiting time is shorter than the inter-arrival time of new spare part requests. The results might be different when the properties of the specific spare part set change. If for example the allowed time to manufacture is much longer, penalties are negligible or the overall production times change the situation might change.

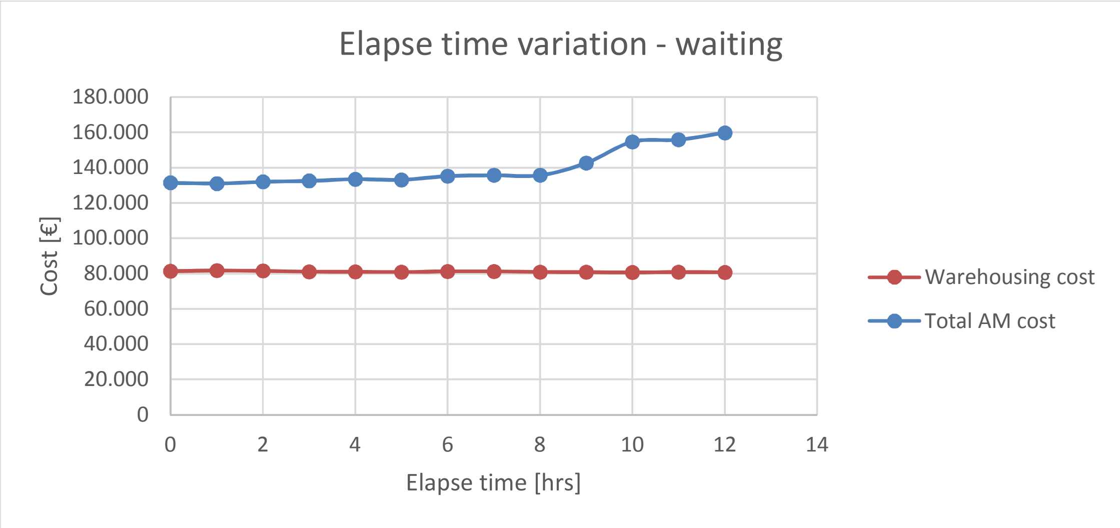


Figure 7-10: Two machines with fixed material – Elapse time – Waiting

Changes in the elapse time have an effect on the system, since an increased elapse time decreases the overall system availability, which is not assumed to be beneficial. This is due to the fact that a production start is postponed without adding a second part into the production run.

7.2 TWO MACHINES WITH FLEXIBLE MATERIAL ASSIGNMENT

In this strategy each machines is able to switch to either of the two materials for a new production run. One of the two possible materials will be assigned to each spare part request. The spare part requests will be assigned to the machines according to their availability. Since thorough machine cleaning is needed in operation whenever a change of material is needed, additional setup time will be needed for the system, which was modeled for this strategy.

Changes with respect to the upper limit, setup and cool down time, elapse time and start volume, and material change over time were investigated.

7.2.1 MODEL ADJUSTMENT

The modifications with the base model were mostly focused on the AM route arrival and queueing logic as shown in Figure 7-11.

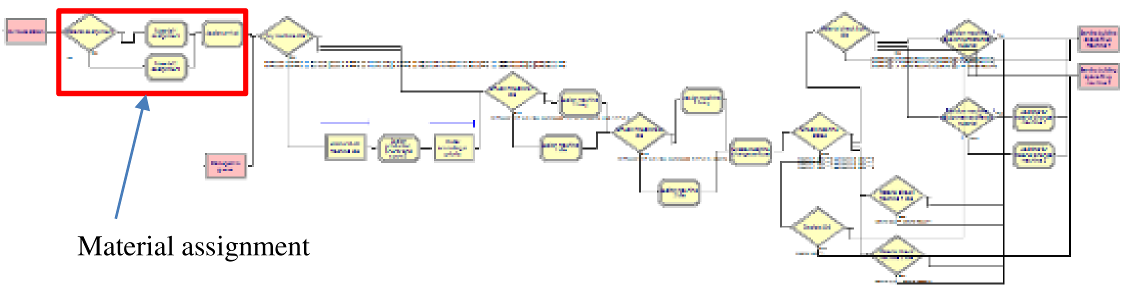


Figure 7-11: Adjusted AM route arrival and queueing logic

In the basic setup only one material is assigned to the spare parts. Therefore the material type must be reassigned. Similar to the strategies of two machines with a fixed material assignment, this was done by a decide module which assigns the two material with a 50 % chance each. The arrival time is assigned to the part the same way as in the basic model. In addition, the downstream part queuing logics remain identical to the two-machine strategies with fixed material assignment as described previously.

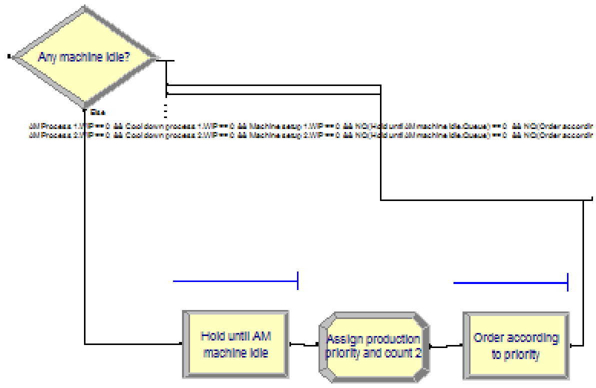


Figure 7-12: Check for idle machine

In order to facilitate the machine assignment in the model, machine states were assigned to the spare part requests as additional attributes. The states are 0 for an idle machine and 1 for a busy machine. In addition, a new attribute is created for each part called “material change”, which is set to 0 by default which stands for no material change. It will be changed to 1 if a material change for a production run takes place.

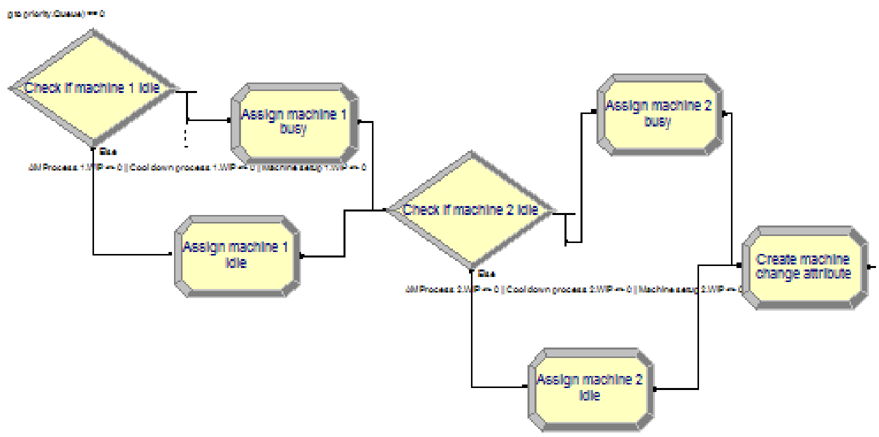


Figure 7-13: Machine states follow up by part attributes

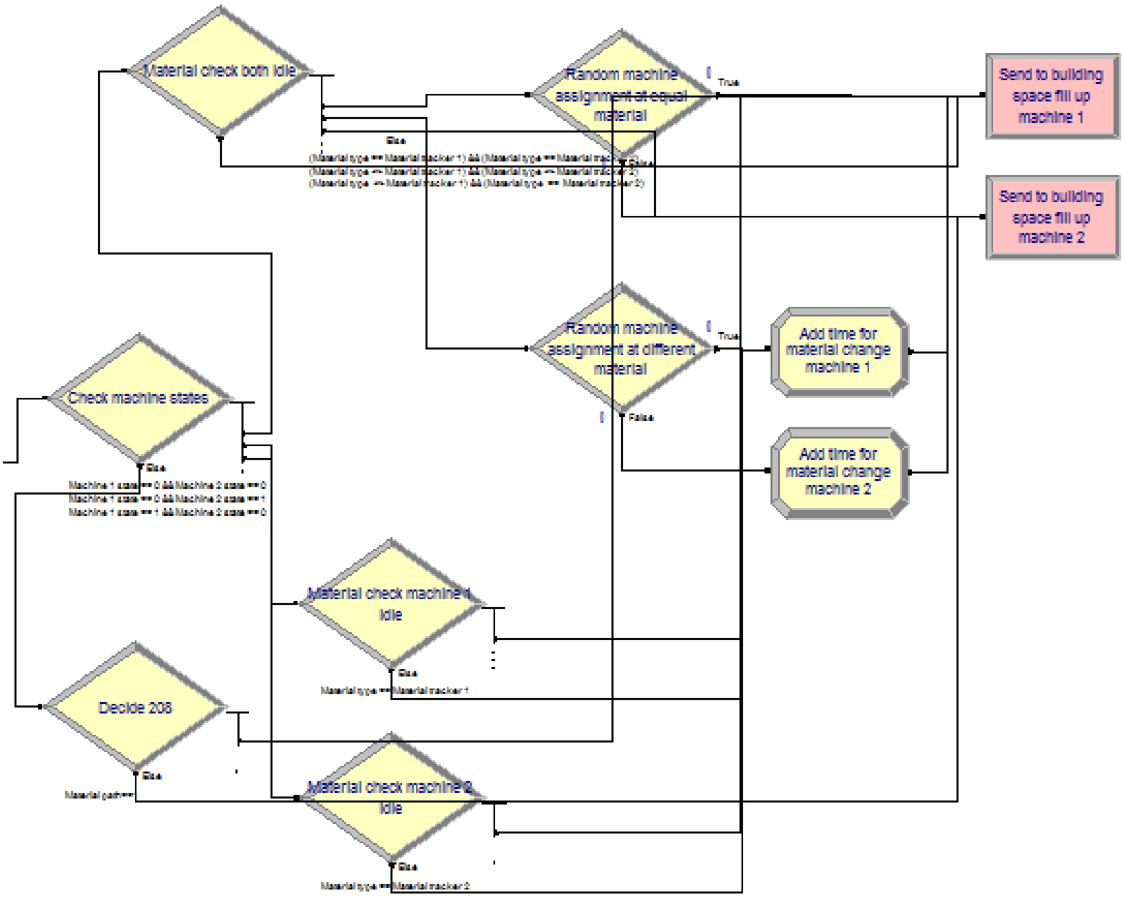


Figure 7-14: Machine assignment and material changeover logic

The new attributes were used in the machine assignment and material changeover logics. In the first step it was checked which machine is idle or busy. In a two machine setup this leads to four possible combinations. Table 7-2 illustrates these combinations in the "check for idle machine" section. Each combination of the consequent step is dependent upon the material of the requested part and the currently applied material of the machine. Each of the possible material combinations requires different actions, which are also listed in Table 7-2. After this step an independent downstream logic path is setup for each machine in the model.

Table 7-2: Machine assignment and material changeover logic

Check for idle machines

Machine 1	Machine 2	Description	Action
0	0	Both machines idle	Forward to combination 0-0
1	0	Machine 2 idle	Forward to combination 1-0
0	1	Machine 1 idle	Forward to combination 0-1
1	1	Both machines utilized	Can not happen - Spare part requests will wait in queue until one machine is idle

Combination 0-0 - Material check

Material 1	Material 2	Description	Action
0	0	Both machines apply required material type	Assign Machine 1 or 2 randomly
1	0	Machine 1 does not apply required material type, Machine 2 applies required material type	Assign machine 2
0	1	Machine 1 applies required material type, Machine 2 does not apply required material type	Assign Machine 1
1	1	Non of the machines apply the required material type	Assign Machine 1 or 2 randomly and execute material change

Combination 1-0 - Material check

Material 1	Material 2	Description	Action
---	0	Machine 2 applies the required material type	Assign Machine 2
---	1	Machine 2 does not apply the required material type	Assign Machine 2 and execute material change

Combination 0-1 - Material check

Material 1	Material 2	Description	Action
0	---	Machine 1 applies the required material type	Assign Machine 1
1	---	Machine 1 does not apply the required material type	Assign Machine 1 and execute material change

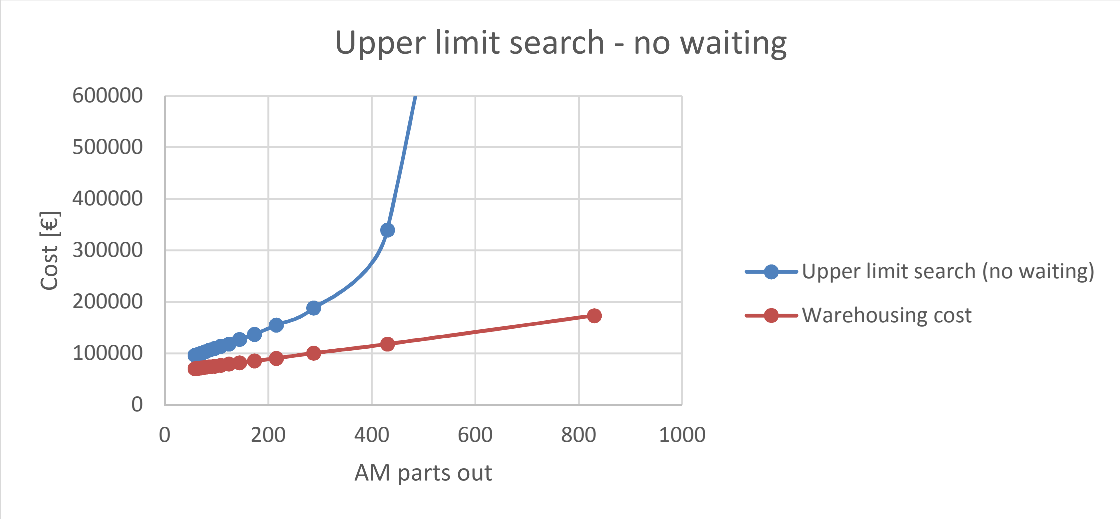
The rest of the model is identical to the base case setup or the two machines with fixed material setup, with the only exception that the material changeover time is added to the production setup time when material change takes place.

7.2.2 RESULTS AND DISCUSSION

The results of the upper limit search are presented in Table 7-3. In comparison to the one machine setup the performance of the system improved as expected. When only one machine is applied AM parts out is 86 parts at the upper limit. In the two machine setup with flexible material assignment the machine utilization equals out at 44 %. The highest possible arrival rate is at a mean arrival of 20 hrs, creating significant penalties at a part output of 430 parts. Compared to the two machines with a fixed material assignment the results for mean arrival, AM parts out and total system utilization improved. A more detailed comparison of all strategies will follow in chapter 8.

Table 7-3: Two machines with flexible material assignment - Upper limit No waiting/ Waiting

		Base case	Two machines with flexible material assignment						Upper limit - changes compared to base case [%]	
			Mean arrival No waiting			Mean arrival Waiting				
Control		Upper limit	Low arrival rate	Upper limit	High arrival rate	Low arrival rate	Upper limit	High arrival rate	No waiting	Waiting
Mean arrival	**hr**	**100**				**120**	**70**	**20**	0%	70%
Cost related responses										
Total warehousing cost	€	55436	60	40	10	72062	78751	117681	0%	142%
Total AM cost	€	73494	81601	90498	173380	102295	120773	378359	123%	164%
Consumed material cost	€	22030	34688	53087	201068	17058	28534	102863	241%	130%
Consumed energy cost	€	4210	6628	10144	38420	3259	5452	19655	241%	130%
Operator cost	€	4336	7208	10778	41495	3615	6163	21474	249%	142%
Total maintenance cost	€	29407	58673	58777	58304	57990	58498	58931	200%	199%
Total AM penalty	€	3708	291	2583	2E+06	1041	2625	155791	70%	71%
AM process related responses										
Consumed material	kg	275	433	663	2513	213	356	1285	241%	129%
Consumed energy	kWh	70160	110473	169069	640346	54326	90874	327590	241%	130%
System setup time	%	8	8	12	8	4	6	23	147%	81%
System utilization time	%	19	15	22	85	7	12	43	118%	64%
Systen cool down time	%	8	7	10	6	3	6	17	125%	72%
Total system utilization	%	35	29	44	99	14	24	83	126%	70%
Average building volume	mm³	404530	384452	393624	386716	377651	370109	382680	97%	91%
Machine depreciation	€	30061	59977	60083	59600	59279	59798	60240	200%	199%
Average time in queue	hr	50	---	19,264	78,027	---	---	18,353	39%	---
Average number of parts in queue	pcs.	0,001	0,002	0,023	1,566	0	0,001	0,718	2300%	100%
Number of parts in queue total	pcs.	5	1	9	1268	0	1	335	186%	20%
AM parts out	pcs.	87	144	216	830	72	123	430	248%	142%



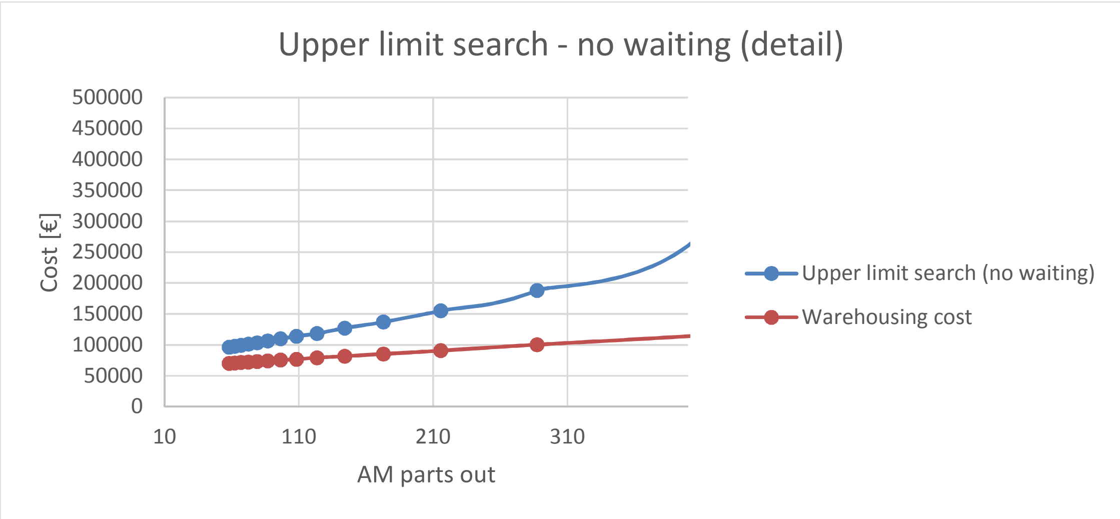
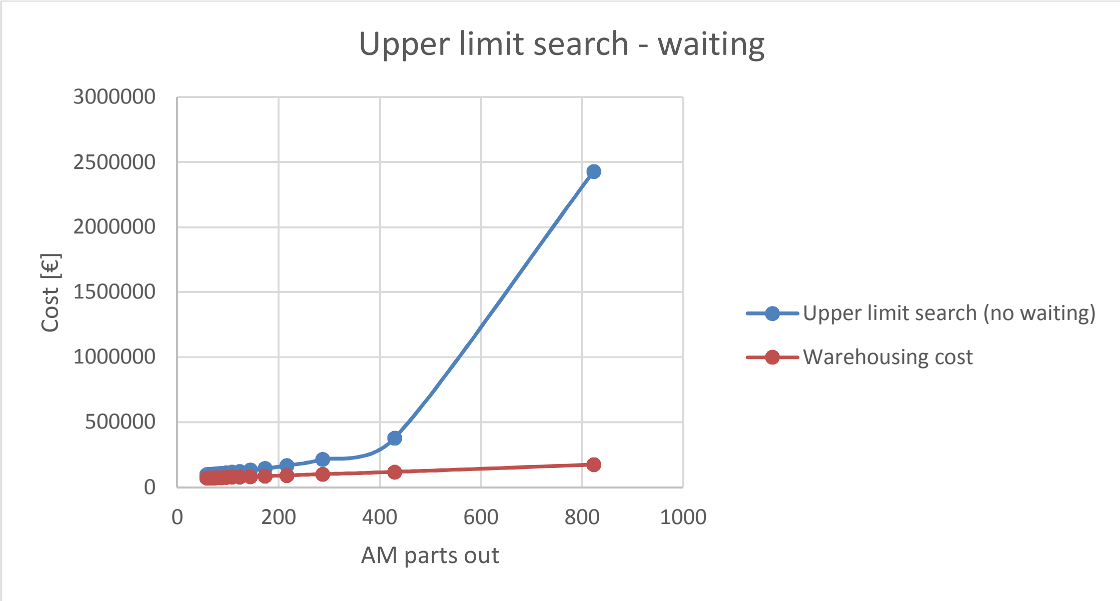


Figure 7-15: Two machines with flexible material - Upper limit search - No waiting



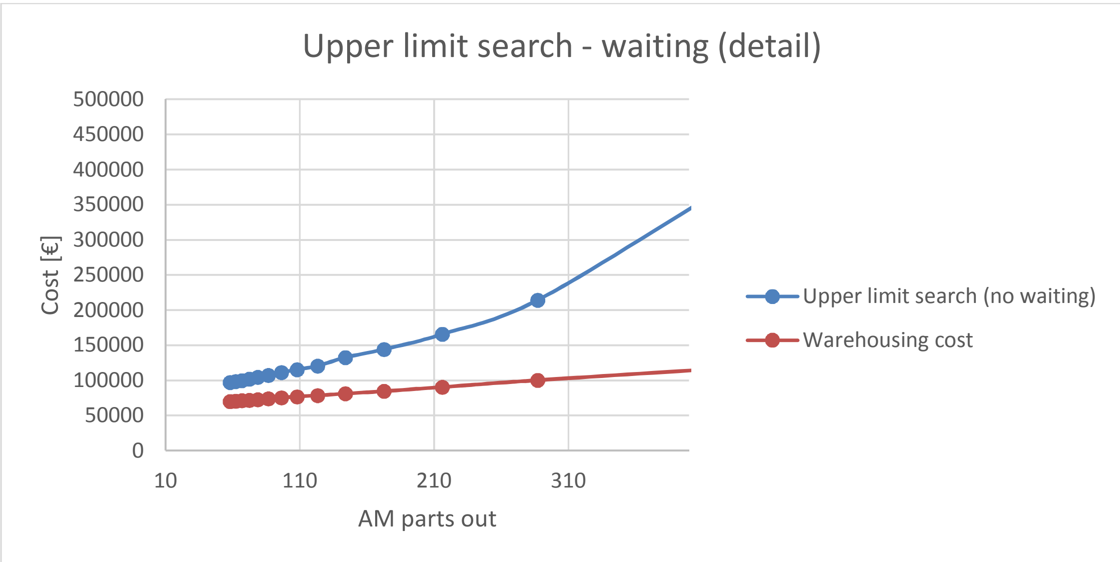


Figure 7-16: Two machines with flexible material - Upper limit search - Waiting

For the two-machine with flexible material assignment, the performance deterioration appears to be considerably more significant when the waiting mode is applied, which resulted in a near 45% reduction of the maximum system utilization as shown in Table 7-3. Comparing Table 7-1 and Table 7-3 it can be seen that under this condition the flexible strategy does not appear to add any benefits to the system when waiting. Also, in this case machine utilization decreases to 24 %, since less parts can be produced due to waiting. This seems very similar compared the two machines with the fixed material assignment, but the average number of parts in queue decreased, which is indicates a well-performing system.

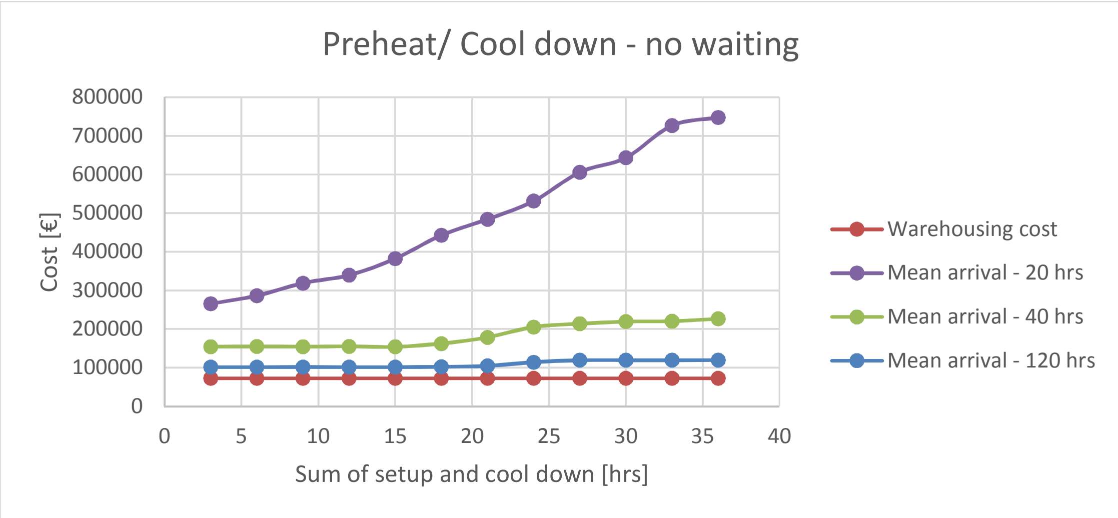


Figure 7-17: Two machines with flexible material – Preheat and cool down – No waiting

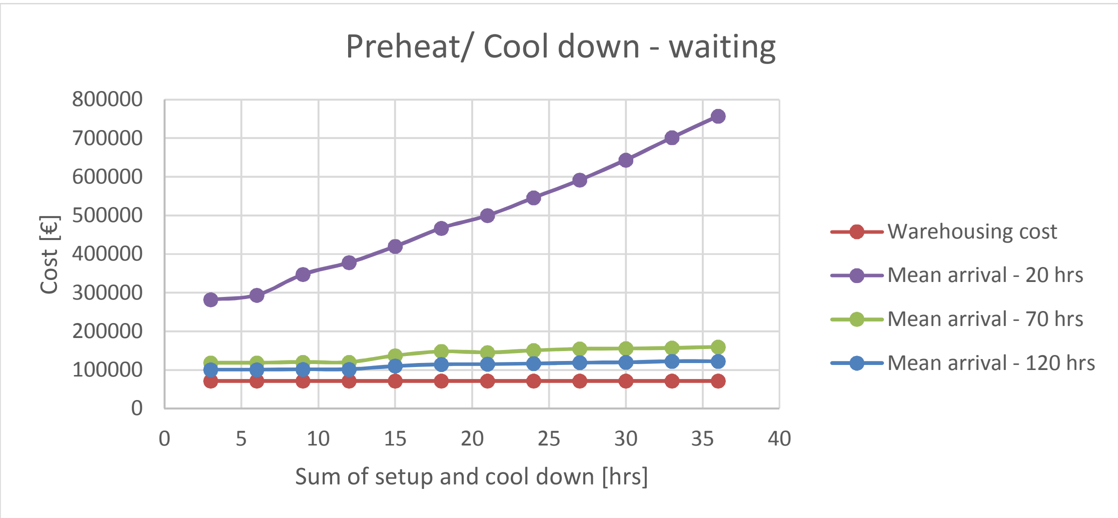


Figure 7-18: Two machines with flexible material – Preheat and cool down – Waiting

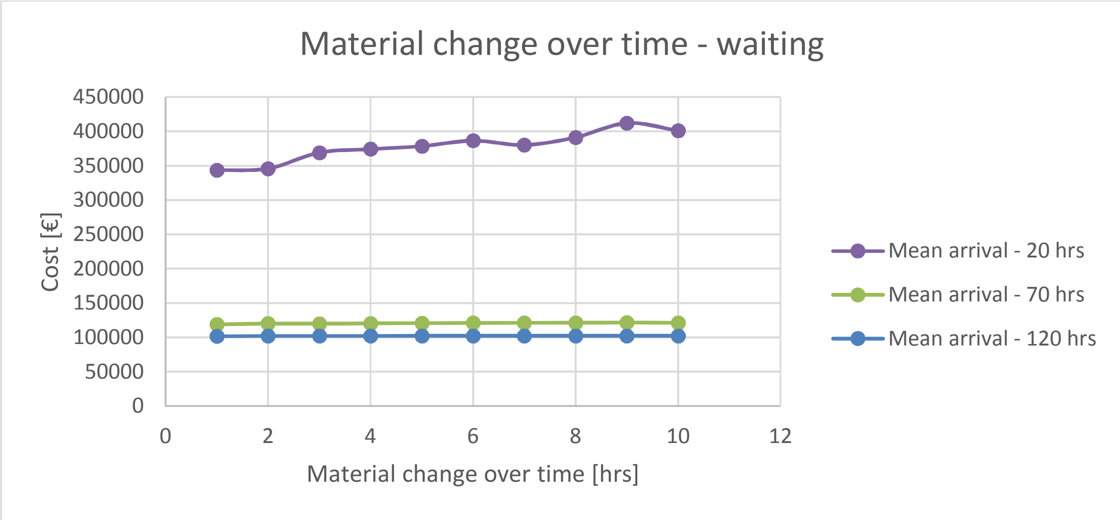


Figure 7-19: Two machines with flexible material – Material change over time – Waiting

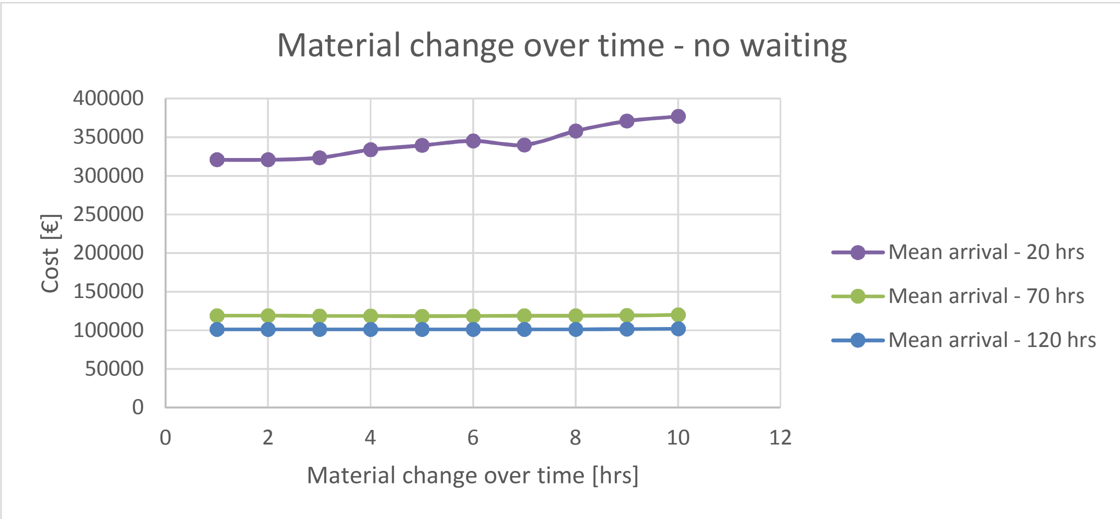


Figure 7-20: Two machines with flexible material – Material change over time – No waiting

The influences of material changeover, preheat and cool down are similar to the two-machine with fixed material assignment, with the no-waiting mode outperforming the waiting mode.

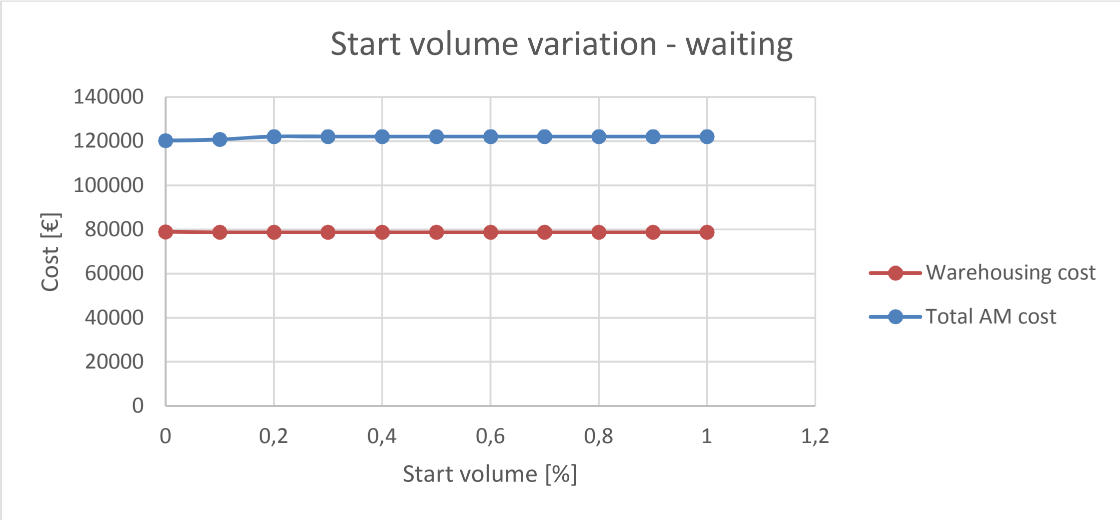


Figure 7-21: Two machines with flexible material – Start volume – Waiting

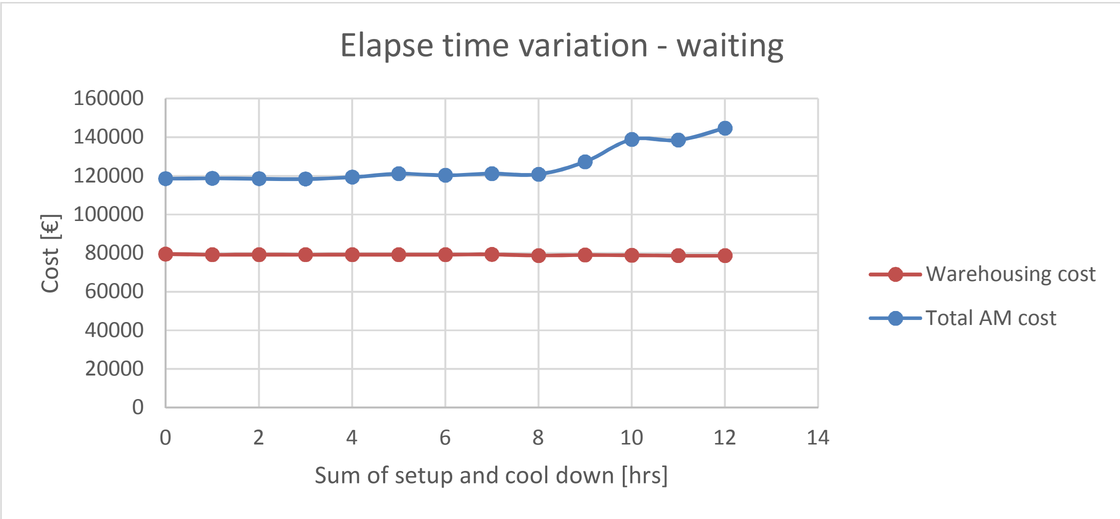


Figure 7-22: Two machines with flexible material – Elapse time – Waiting

Also, the start volume and elapse time variation show almost identical effects to the total cost compared to the fixed material strategy with the current part set designs as discussed previously.

7.2.3 THREE MACHINES WITH FIXED MATERIAL ASSIGNMENT

In this section the strategy of three-machine with fixed material assignments was modeled and analyzed. Each machine was dedicated to fabricate only one fixed type of material. One of the three possible materials was assigned to each spare part request, and the treatment of the model followed the same approach as that used in two-machine with fixed material assignment strategy. Again, changes with respect to the upper limit, setup and cool down time, elapse time and start volume were investigated.

7.2.4 MODEL ADJUSTMENT

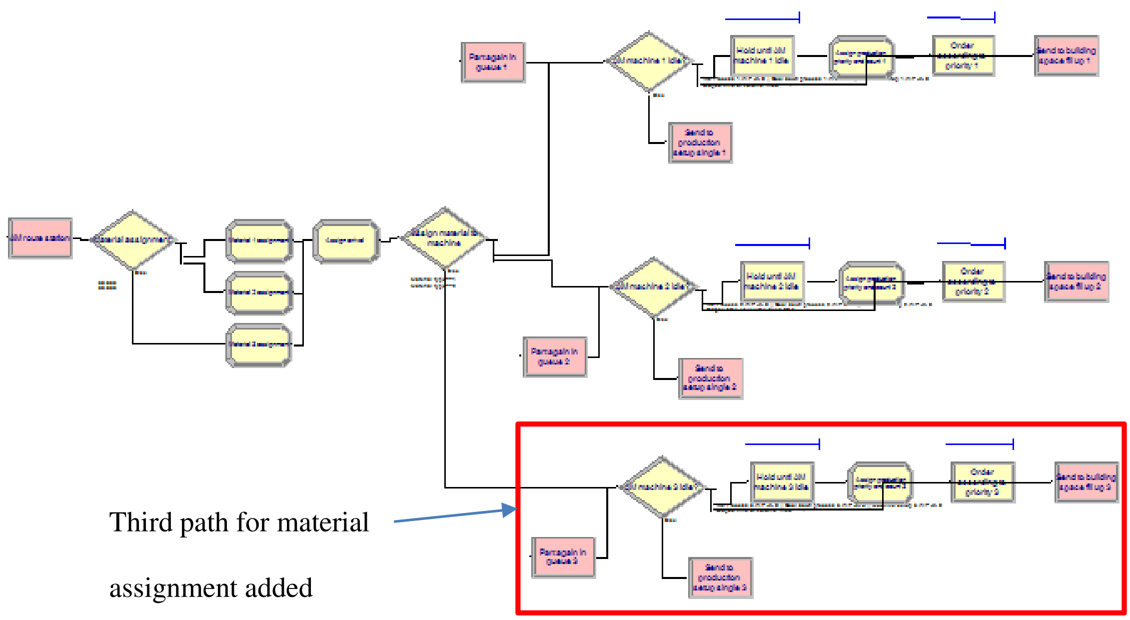


Figure 7-23: Main adjustment of the model

The Three machines with fixed material model is an extension of the two machines with fixed material model. A third path is added which allows assignment of a third material type. The rest of the model is adjusted accordingly.

7.2.5 RESULTS AND DISCUSSION

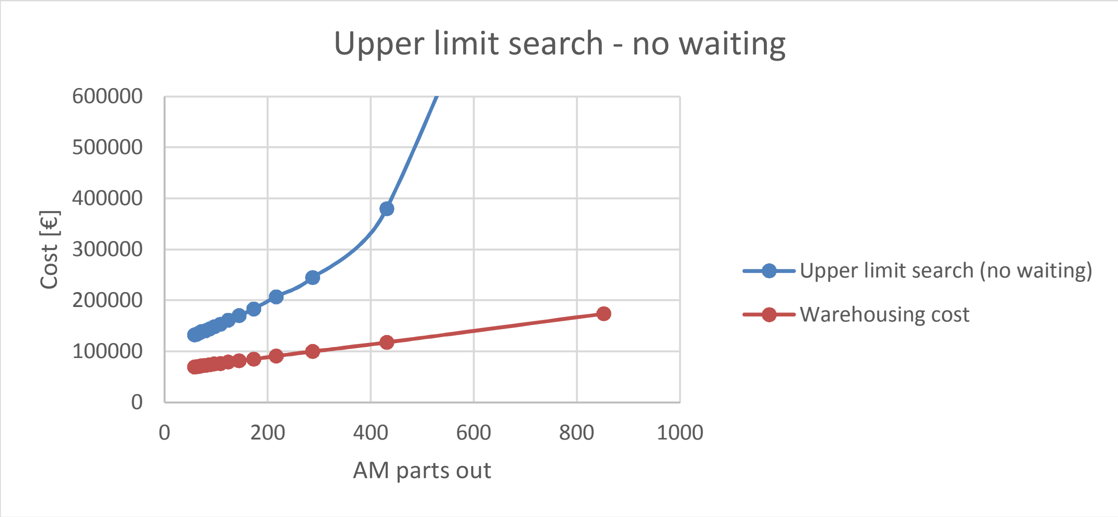
The result of the upper limit search is presented in Table 7-4

Table 7-4: Three machines with fixed material - Upper limit No waiting/ Waiting

		Base case	Three machines with fixed material assignment						Upper limit - changes compared to base case [%]	
			Mean arrival No waiting			Mean arrival Waiting				
Control		Upper limit	Low arrival rate	Upper limit	High arrival rate	Low arrival rate	Upper limit	High arrival rate	No waiting	Waiting
Mean arrival	hr	100	130	60	20	130	60	20	60%	60%
Cost related responses										
Total warehousing cost	€	55436	70873	81454	117537	70873	80950	120076	147%	146%
Total AM cost	€	73494	136044	169974	380022	136172	169690	409459	231%	231%
Consumed material cost	€	22030	15475	35687	103204	15461	35114	103328	162%	159%
Consumed energy cost	€	4210	2957	6819	19720	2954	6709	19744	162%	159%
Operator cost	€	4336	3333	7211	21558	3330	7186	21483	166%	166%
Total maintenance cost	€	29407	85584	87285	88122	85632	87228	88208	297%	297%
Total AM penalty	€	3708	166	3875	118041	250	4375	147291	105%	118%
AM process related responses										
Consumed material	kg	275	193	446	1290	193	438	1291	162%	159%
Consumed energy	kWh	70160	49284	113655	328677	49241	111829	329071	162%	159%
System setup time	%	8	2	5	12	2	5	12	58%	58%
System utilization time	%	19	4	10	29	4	10	29	53%	53%
Systen cool down time	%	8	2	5	12	2	4	11	56%	56%
Total system utilization	%	35	9	19	53	9	19	52	55%	55%
Average building volume	mm³	404530	366354	393399	90080	366389	389143	383055	97%	96%
Machine depreciation	€	30061	87485	89225	90080	87534	89166	90168	297%	297%
Average time in queue	hr	50	1,285	28,122	31,795	1,61	18,224	31,623	56%	36%
Average number of parts in queue	pcs.	0,001	0,001	0,013	0,236	0,001	0,014	0,279	1300%	1400%
Number of parts in queue total	pcs.	5	1	10	190	1	13	226	200%	260%
AM parts out	pcs.	87	67	144	431	67	144	430	166%	166%

From the previous results, the two-machine setup exhibited significantly higher total number of parts out and system utilization compared to the one-machine setup. Therefore, it would appear logical that a three-machine setup would further improve the system efficiency. However, from Table 7-4 the three-machine setup did not achieve any performance gain compared to the two-machine setup. The overall queuing is slightly reduced, but parts still has to wait in queue if two parts of the same material arrive in a row between short intervals. Therefore, with the current part set design the three-machine setup can be essentially treated as a scaled-up version of the two-machine setup. It can be reasonably concluded that the same observation can be made for four- or more-machine setups with the same part set design.

When the waiting mode was applied to the system, the upper limit is reduced slightly. However, a nearly identical system performance was observed for the three-machine strategy. On the other hand, the queuing situation for the no waiting mode is favorable.



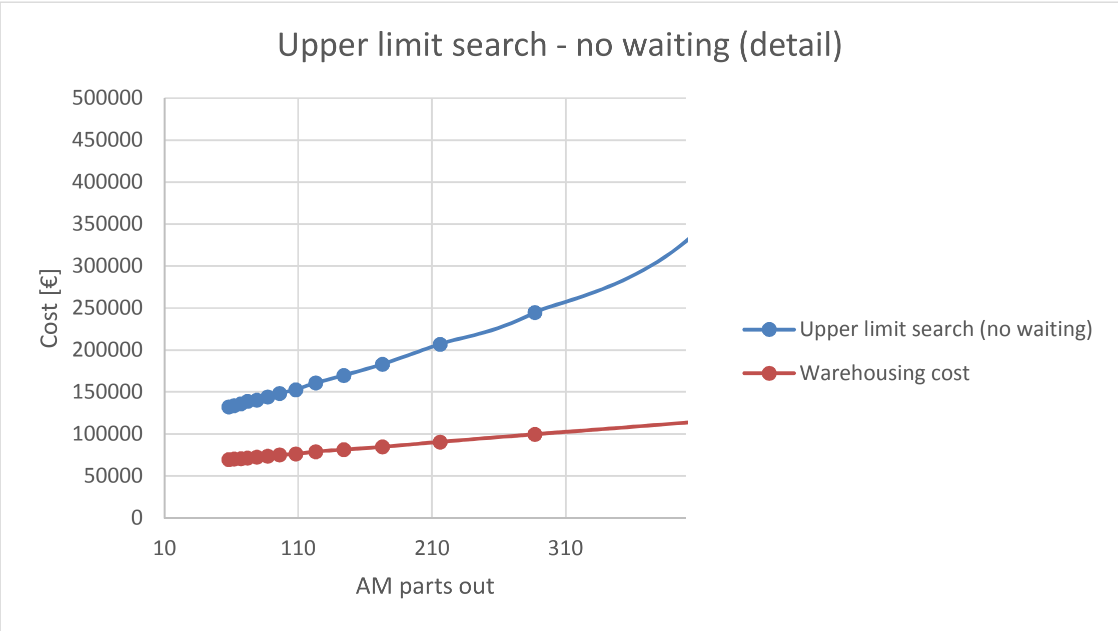
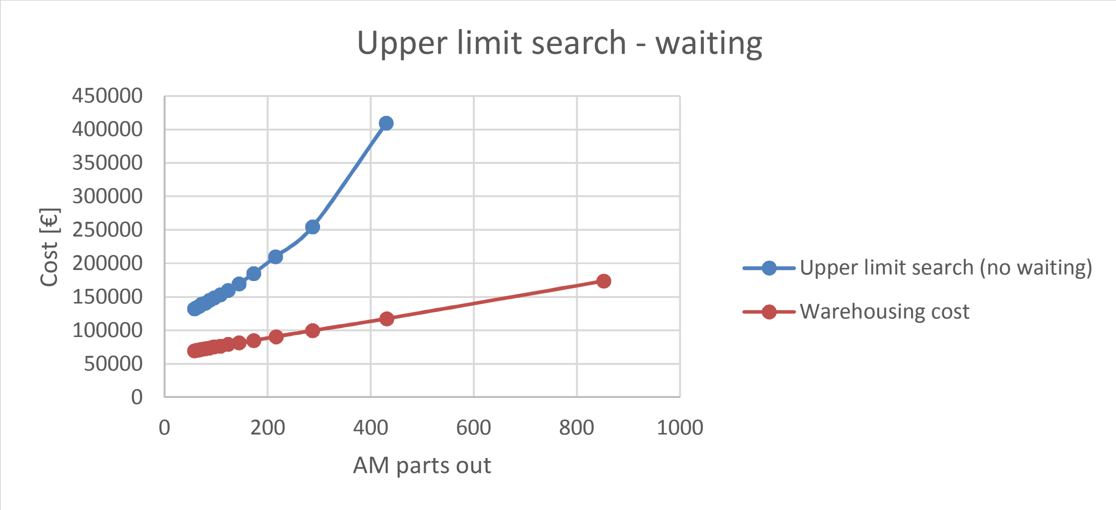


Figure 7-24: Three machines with fixed material - Upper limit search - No waiting



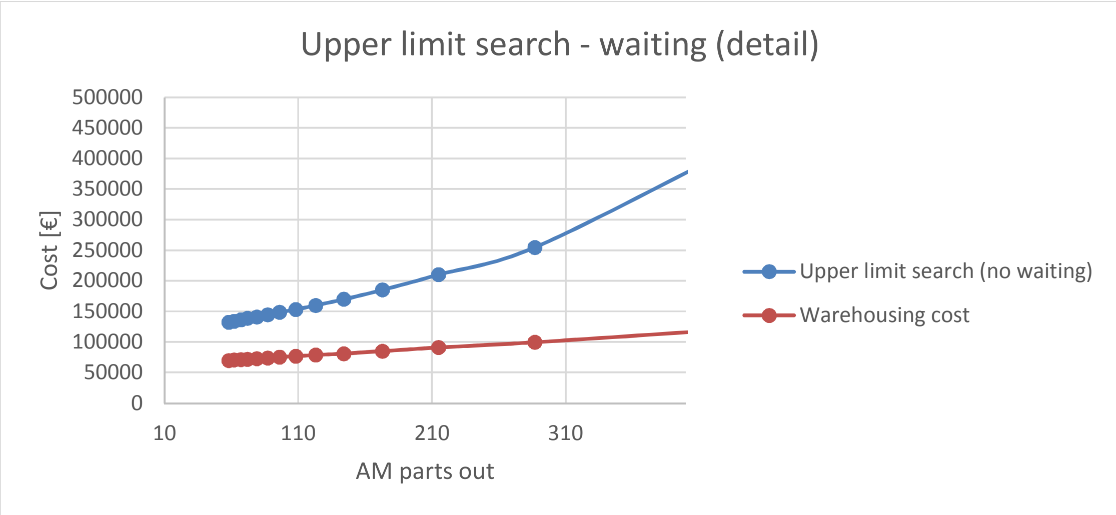


Figure 7-25: Three machines with fixed material - Upper limit search - Waiting

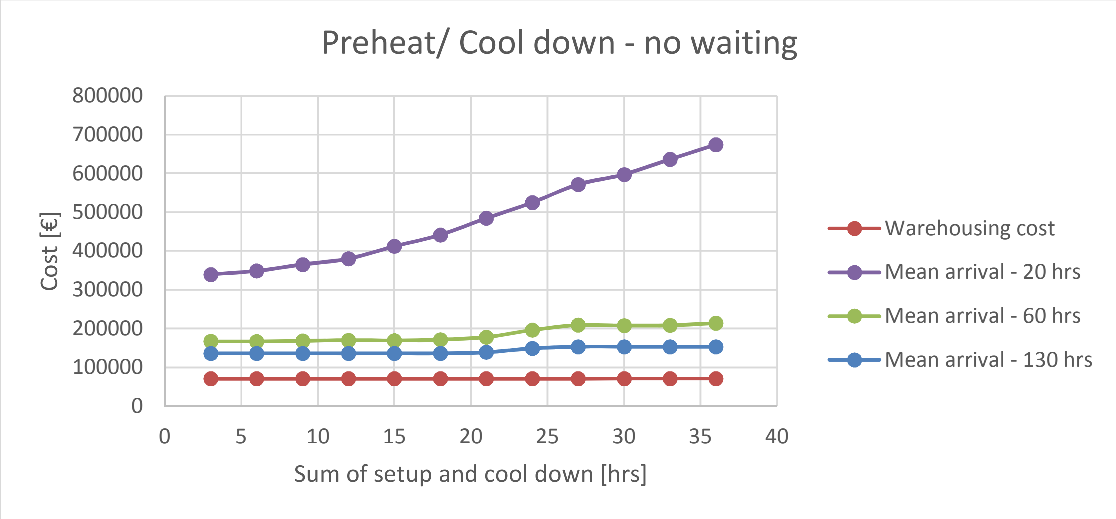


Figure 7-26: Three machines with fixed material – Preheat and cool down - No waiting

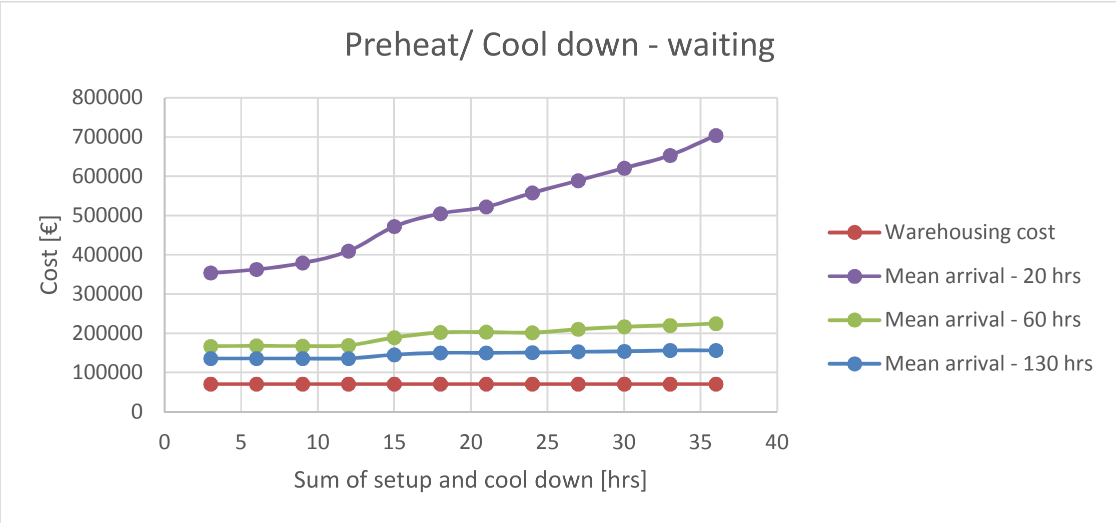


Figure 7-27: Three machines with fixed material – Preheat and cool down - Waiting

The influence of preheat and cool down is similar to the two-machine with fixed material assignment strategy. The no-waiting mode performed better compared to the waiting mode, and the start volume and elapse time variation show almost identical characteristics to the two-machine setups, which again could be readily explained by treating the three-machine system as a scaled-up two-machine system.

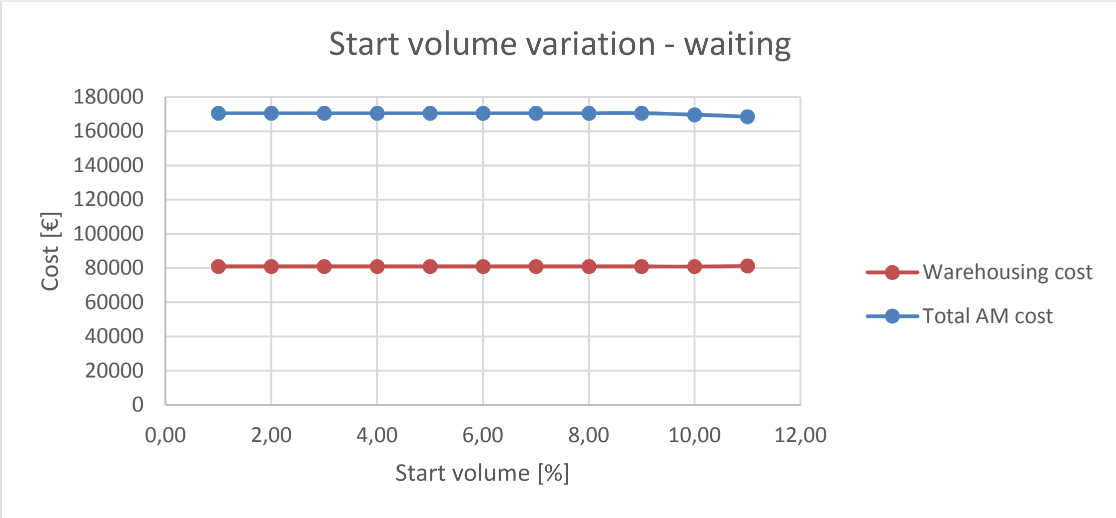


Figure 7-28: Three machines with fixed material – Start volume - Waiting

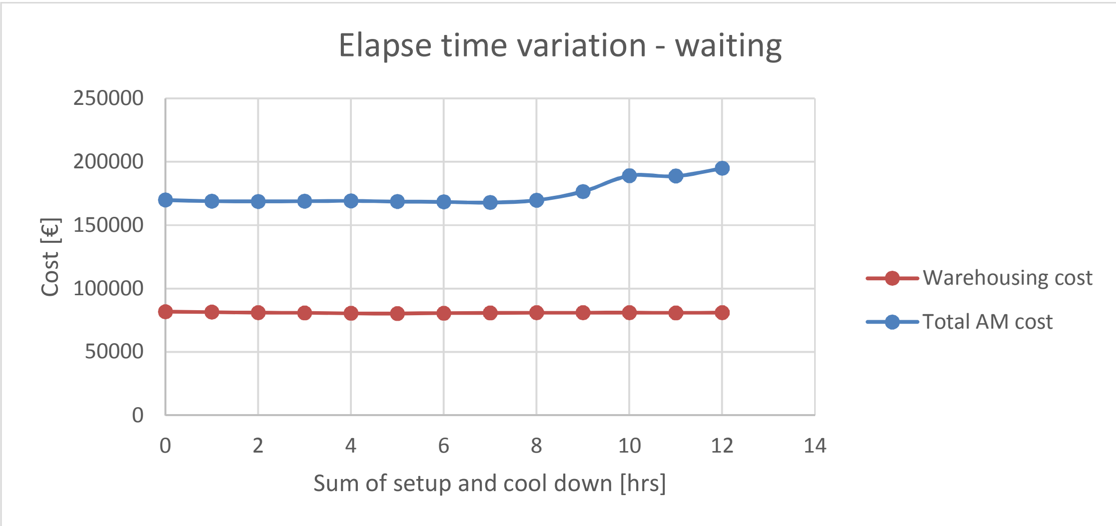


Figure 7-29: Three machines with fixed material – Elapse time – Waiting

7.3 THREE MACHINES WITH FLEXIBEL MATERIAL ASSIGNMENT

The three-machine with flexible material assignment strategy was modeled similarly to the two-machine with flexible material strategy, with the only difference being the number of material types. System performance with respect to the upper limit, setup and cool down time, elapse time, start volume and material changeover time were investigated.

7.3.1 MODEL ADJUSTMENT

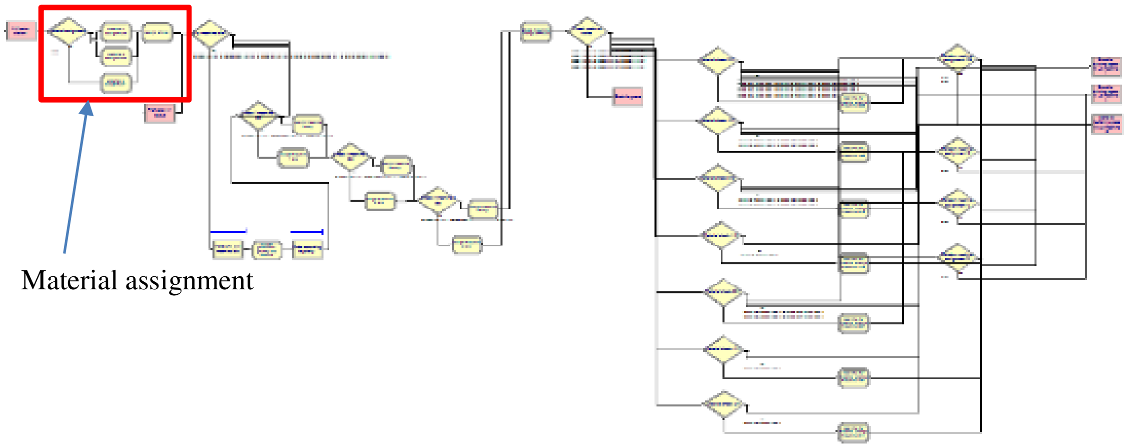


Figure 7-30: Adjusted AM route arrival and queueing logic

The model for three-machine with flexible material is a further expansion of the two-machine with flexible material model with a third machine added. Changes of the setup were made in the AM route and queueing logic. Similar to the two-machine with flexible material setup, the material assignment starts with a decide module, which forwards the part request to three material type assign modules with a 33 % chance each.

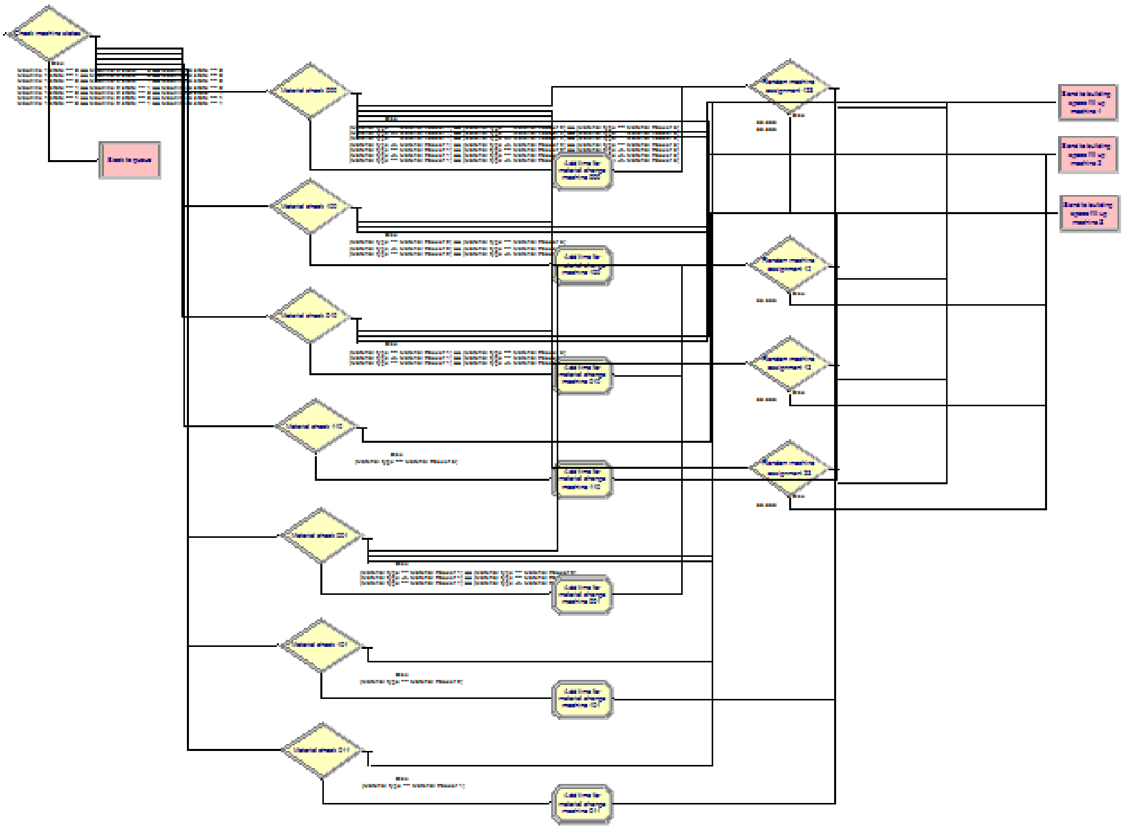


Figure 7-31: Machine assignment and material changeover logic – three machines

Similar to the two machine setup, machine assignment and material changeover setups were specified based on individual conditions of the machine status. Table 7-5 shows the overview of combinations and actions. After this step in the model an independent path is set up for each machine.

Table 7-5: Machine assignment and material changeover logic – three machines

Check for idle machines

Machine 1	Machine 2	Machine 3	Description	Action
0	0	0	All machines idle	Forward to combination 0-0-0
1	0	0	Machine 2 and 3 idle	Forward to combination 1-0-0
0	1	0	Machine 1 and 3 idle	Forward to combination 0-1-0
1	1	0	Machine 3 idle	Forward to combination 1-1-0
0	0	1	Machine 1 and 2 idle	Forward to combination 0-0-1
1	0	1	Machine 2 idle	Forward to combination 1-0-1
0	1	1	Machine 1 idle	Forward to combination 0-1-1
1	1	1	Machine 1,2 and 3 utilized.	Can not happen - Spare part requests will wait in queue until one machine is idle

Combination Material 0-0-0

Material 1	Material 2	Material 3	Description	Action
0	0	0	All machines apply required material type	Assign to machine 1, 2 or 3 randomly with a 1/3 chance
1	0	0	Machine 2 and 3 apply required material type	Assign to machine 2 or 3 randomly with a 1/2 chance
0	1	0	Machine 1 and 3 apply required material type	Assign to machine 1 or 3 randomly with a 1/2 chance
1	1	0	Machine 3 applies required material type	Assign to machine 3
0	0	1	Machine 1 and 2 apply required material type	Assign to machine 1 or 2 randomly with a 1/2 chance
1	0	1	Machine 2 applie required material type	Assign to machine 2
0	1	1	Machine 1 applies required material type	Assign to machine 1
1	1	1	No machine applies required material type	Assign to machine 1, 2 or 3 randomly with a 1/3 chance and execute material changeover

Combination Material 1-0-0

Material 1	Material 2	Material 3	Description	Action
---	0	0	Both machines apply required material type	Assign to machine 2 or 3 randomly with a 1/2 chance
---	1	0	Machine 3 applies required material type	Assign to machine 3
---	0	1	Machine 2 applies required material type	Assign to machine 2
---	1	1	No machie applies required material type	Assign to machine 2 or 3 randomly with a 1/2 chance and execute material changeover

Combination Material 0-1-0

Material 1	Material 2	Material 3	Description	Action
0	---	0	Both machines apply required material type	Assign to machine 1 or 3 randomly with a 1/2 chance
1	---	0	Machine 3 applies required material type	Assign to machine 3
0	---	1	Machine 1 applies required material type	Assign to machine 1
1	---	1	No machie applies required material type	Assign to machine 1 or 3 randomly with a 1/2 chance and execute material changeover

Combination Material 1-1-0

Material 1	Material 2	Material 3	Description	Action
---	---	0	Machine 3 applies required material type	Assign to machine 3
---	---	1	Machine 3 does not apply required material type	Assign to machine 3 and execute material changeover

Combination Material 0-0-1

Material 1	Material 2	Material 3	Description	Action
0	0	---	Both machines apply required material type	Assign to machine 1 or 2 randomly with a 1/2 chance
1	0	---	Machine 2 applies required material type	Assign to machine 2
0	1	---	Machine 1 applies required material type	Assign to machine 1
1	1	---	No machine applies required material type	Assign to machine 1 or 2 randomly with a 1/2 chance and execute material changeover

Combination Material 1-0-1

Material 1	Material 2	Material 3	Description	Action
---	0	---	Machine 2 applies required material type	Assign to machine 2
	1		Machine 2 does not apply required material type	Assign to machine 2 and execute material changeover

Combination Material 0-1-1

Material 1	Material 2	Material 3	Description	Action
0	---	---	Machine 1 applies required material type	Assign to machine 1
1	---	---	Machine 1 does not apply required material type	Assign to machine 1 and execute material changeover

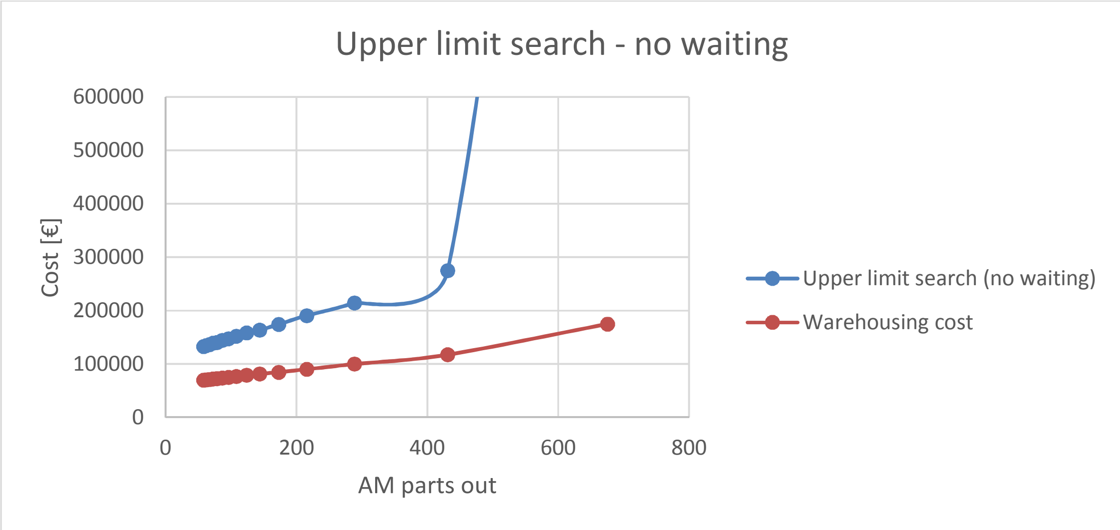
7.3.2 RESULTS AND DISCUSSION

The result of the upper limit search is presented in Table 7-6:

Table 7-6: Three machines with flexible material assignment - Upper limit No waiting/ Waiting

		Base case	Three machines with flexible material assignment						Upper limit - changes compared to base case [%]	
			Mean arrival No waiting			Mean arrival Waiting				
Control		Upper limit	Low arrival rate	Upper limit	High arrival rate	Low arrival rate	Upper limit	High arrival rate	No waiting	Waiting
Mean arrival	hr	100	40	20	10	100	60	20	20%	60%
Cost related responses										
Total warehousing cost	€	55436	90275	117594	174999	74119	81248	118375	212%	147%
Total AM cost	€	73494	190719	274890	2471954	145352	169015	313436	374%	230%
Consumed material cost	€	22030	52633	103858	164495	20851	34054	102195	471%	155%
Consumed energy cost	€	4210	10057	19845	31432	3984	6507	19527	471%	155%
Operator cost	€	4336	10775	21550	33762	4318	7186	21538	497%	166%
Total maintenance cost	€	29407	87814	88351	88448	86368	87356	88349	300%	297%
Total AM penalty	€	3708	166	11833	2124333	1041	4791	52375	319%	129%
AM process related responses										
Consumed material	kg	275	657	1298	2056	260	425	1277	472%	155%
Consumed energy	kWh	70160	167623	330758	523870	66404	108452	325464	471%	155%
System setup time	%	8	8	18	30	3	5	18	224%	65%
System utilization time	%	19	15	29	46	6	10	29	153%	51%
Systen cool down time	%	8	7	13	21	3	5	13	167%	56%
Total system utilization	%	35	29	60	97	12	19	60	173%	55%
Average building volume	mm³	404530	391011	386009	390217	386701	378199	379486	95%	93%
Machine depreciation	€	30061	89766	90315	90413	88287	89298	90313	300%	297%
Average time in queue	hr	50	---	10,62	12,45	0	0	10,744	21%	0%
Average number of parts in queue	pcs.	0,001	0,001	0,094	8,806	0	0	0,139	9400%	0%
Number of parts in queue total	pcs.	5	0	73	58618	0	0	108	1469%	0%
AM parts out	pcs.	87	216	431	675	86	144	431	495%	166%

When compared to the base case, the three-machine setup appears to bring about further improvements. The maximum parts out exhibited an approximately 400 % increase with the mean arrival rate of 20 hours. Also, the possible total system utilization increased by almost 73 %. The high system utilization is due to the fact that each machine can start production at arrival of a spare part request. No unnecessary idle times, as in the fixed material setups, must be compensated by the system. On the other hand, when the waiting mode is applied to the system, the upper limit is significantly reduced to a level similar to the two-machine setup with the same waiting mode. In addition, the total system utilization was even further lowered compared to the two-machine setup.



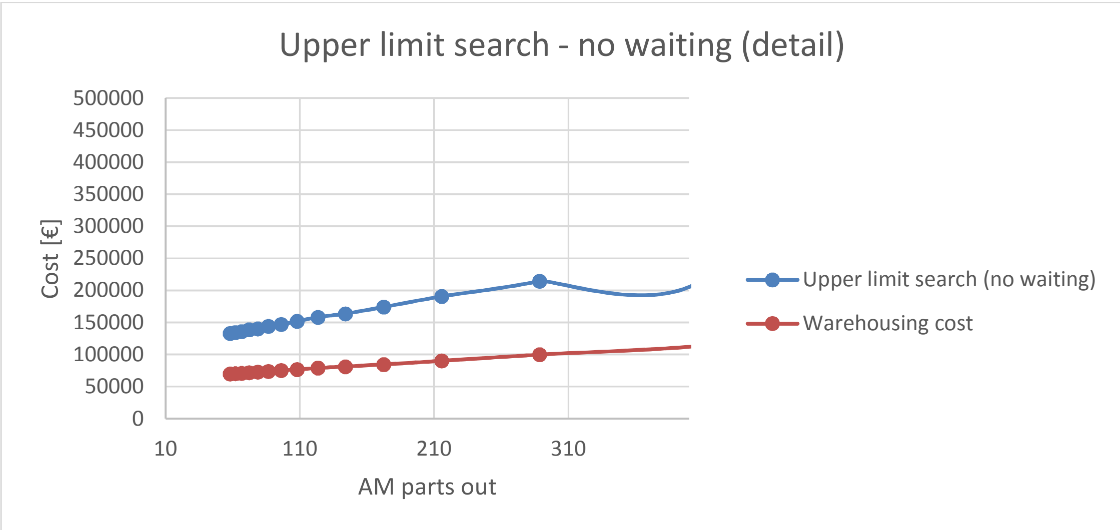


Figure 7-32: Three machines with flexible material - Upper limit search - No waiting

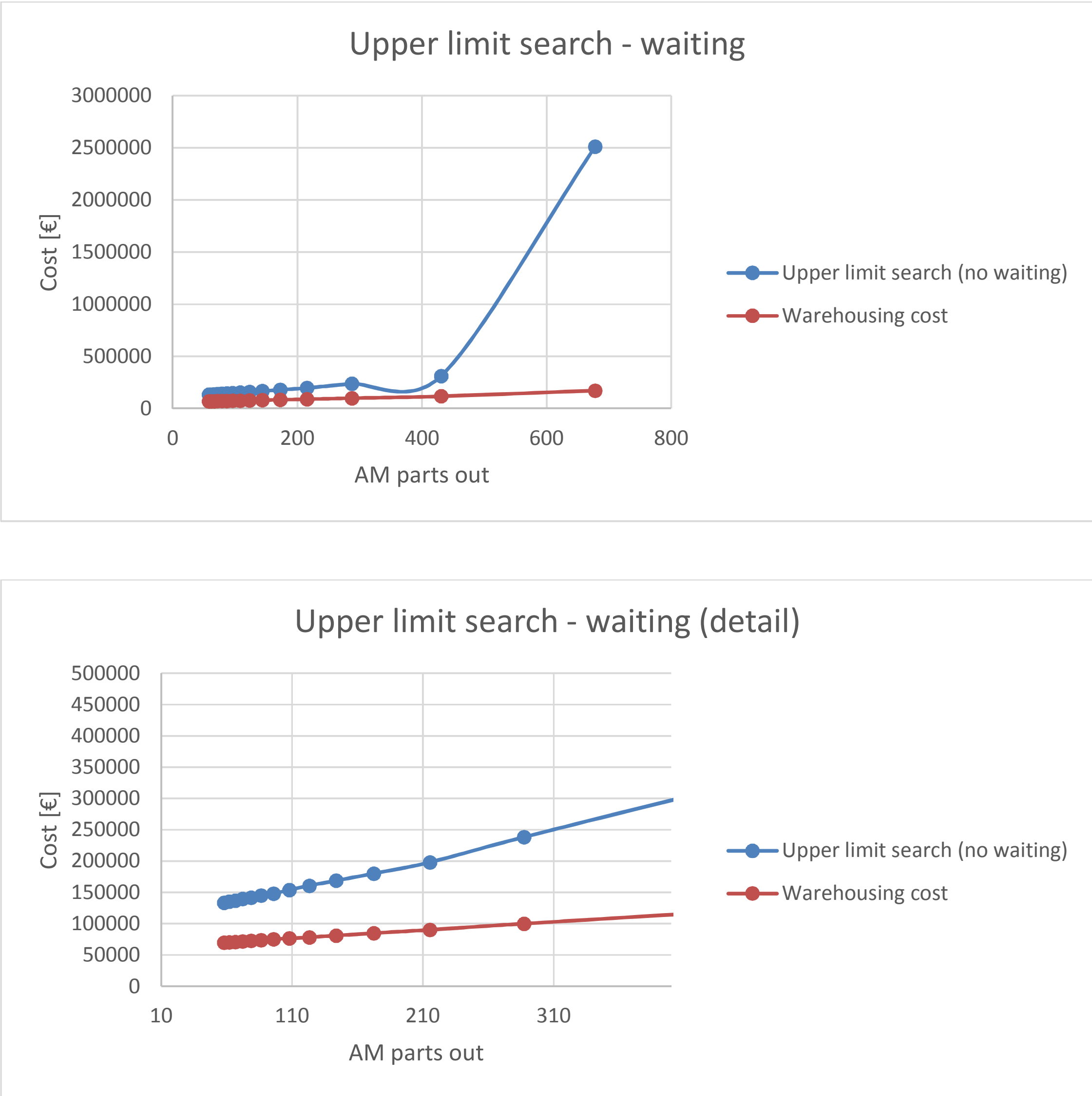


Figure 7-33: Three machines with flexible material - Upper limit search - Waiting

The influences of material changeover, preheat and cool down are similar to the two-machine with fixed material assignment strategy. Again, the no-waiting mode significantly more efficient compared to the waiting mode. The start volume and elapse time variation still show identical characteristics compared to the fixed material setup. On the other hand, the effect of preheat and cool down time on the total system cost exhibited a different pattern as shown in Figure 7-36.

When the sum of preheat and cool down time exceeds a certain level (approx. 24 hrs) the total AM cost decreases. This result is seemingly counterintuitive and is actually artificial effects due to the modelling. Cost related factors are updated when a part leaves the system. In other words, the more parts leave the system, the more cost and/ or penalties are charged. As a result, when preheat and cool down time becomes significantly elongated, the number of parts leaving the system will be largely controlled by this time delay, which contributed to the reduction of the AM costs over the fixed period of time. Therefore, after taking the artificial effects into account, the system output is actually expected to exhibit decrease due to the increasing overall process time.

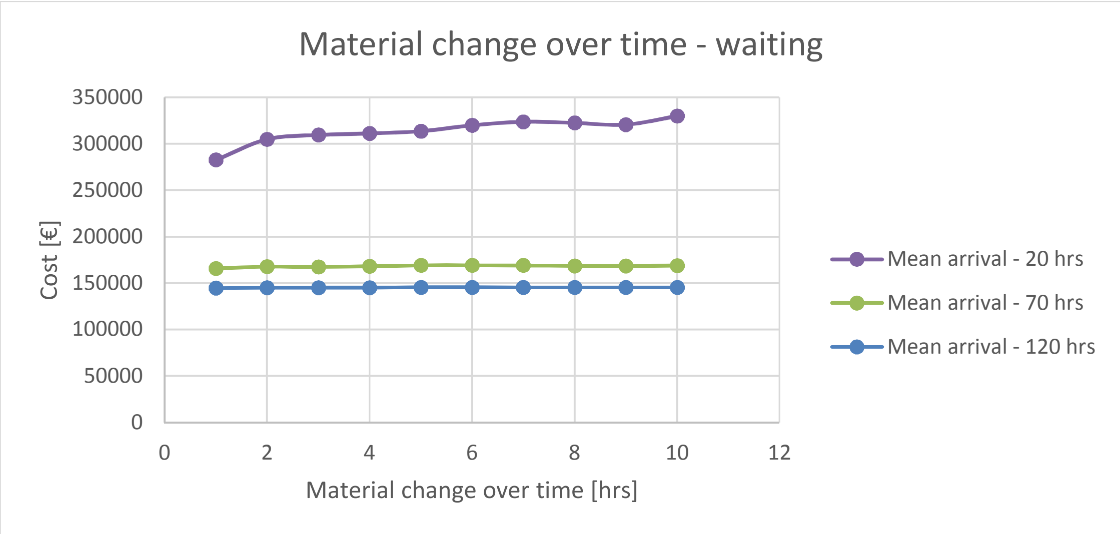


Figure 7-34: Three machines with flexible material - Material change over time - Waiting

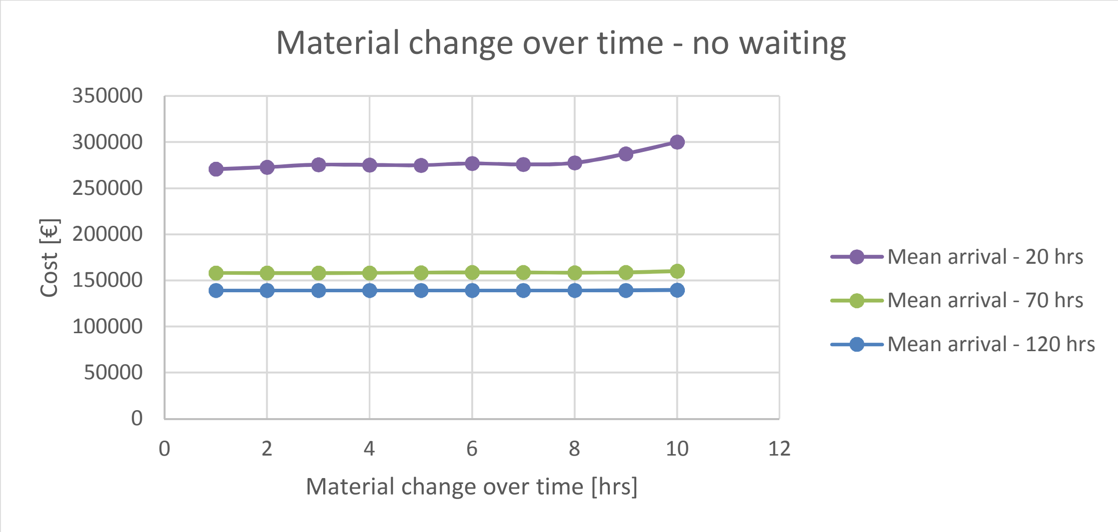


Figure 7-35: Three machines with flexible material - Start volume - No waiting

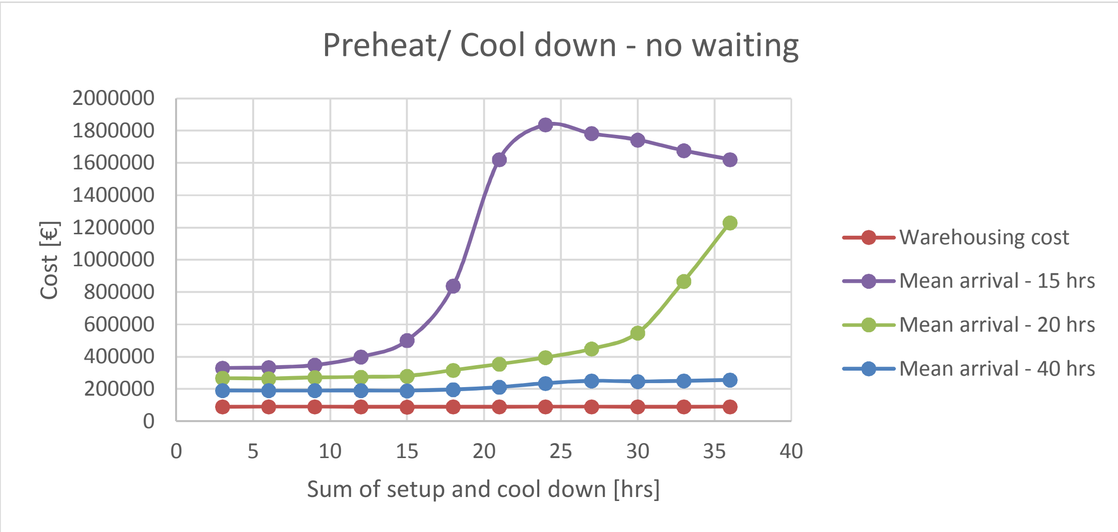


Figure 7-36: Three machines with flexible material - Preheat and cool down - No waiting

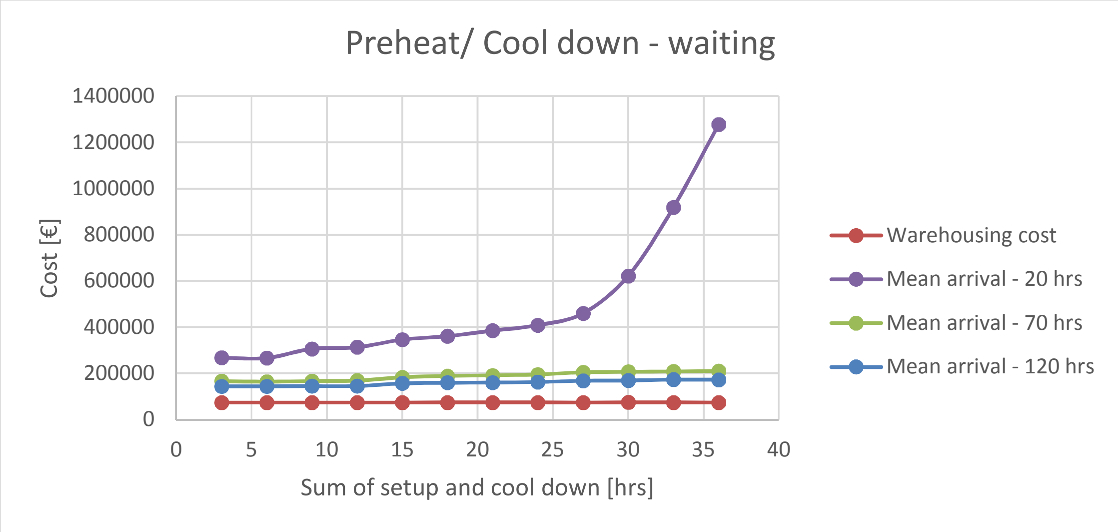


Figure 7-37: Three machines with flexible material – Preheat and cool down - Waiting

The start volume variation and elapse time shows the same properties like in the two machines with flexible material experiment.

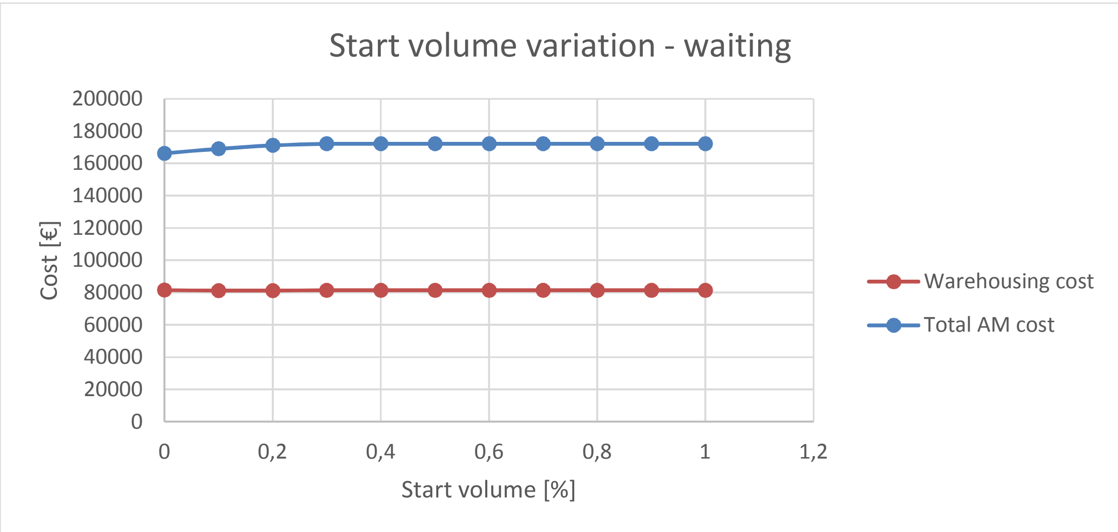


Figure 7-38: Three machines with flexible material - Start volume - Waiting

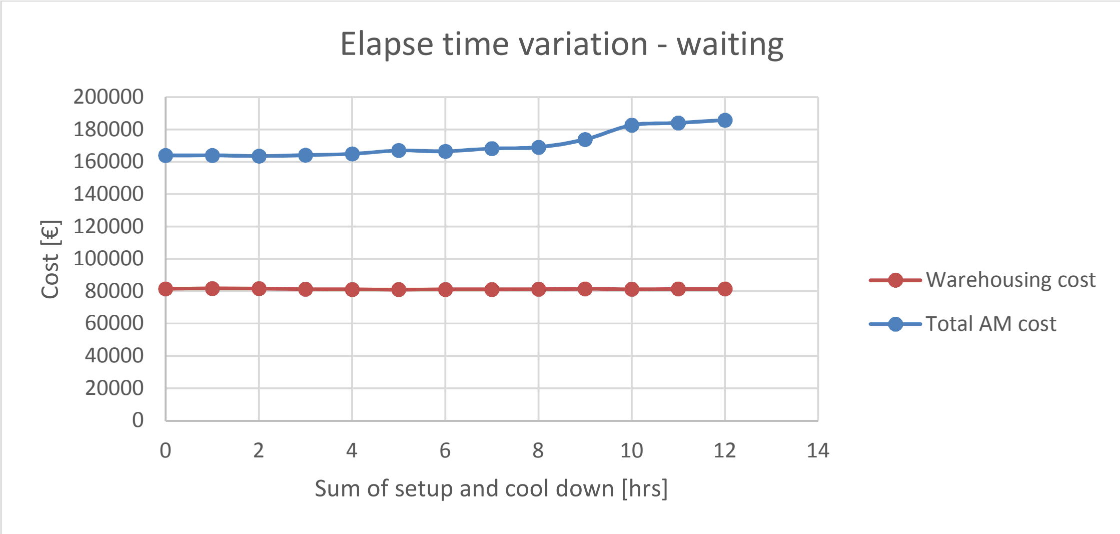


Figure 7-39: Three machines with flexible material - Elapse time - Waiting

7.4 PART SIZE DISTRIBUTION

The part size distribution setups are based on the two-machine system with flexible material assignment strategy with the part size distribution being the only variable. In this experiment the spare parts requests require only one material in order to focus the investigation on the part size effects. Several distributions of part sizes such big parts only or an equally distributed mix of small, mid and big parts were analyzed. The setup were also simulated in both a waiting and no waiting mode.

7.4.1 MODEL ADJUSTMENT

The part size simulation model was created based on the two-machine with flexible material setup. The main changes were made in the AM rout arrival and queuing logic.

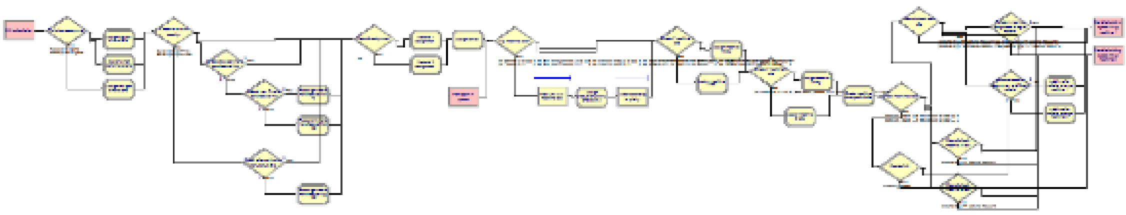


Figure 7-40: Adjusted AM rout arrival and queueing logic

Firstly, the spare part sizes attributes were re-defined (see Figure 7-41). The original spare part set consisted of 75 % small, 20 % medium size and 5 % big parts, which were modified for this study. Three new variables “Reassign small parts”, “Reassign mid parts” and “Reassign big parts” were introduced. The values represent the percentage of the occurring spare part size on random basis, with the only restriction that the sum of those three needed to equal 100. The variables were then used in a decide module to control the assignment of the spare part size.

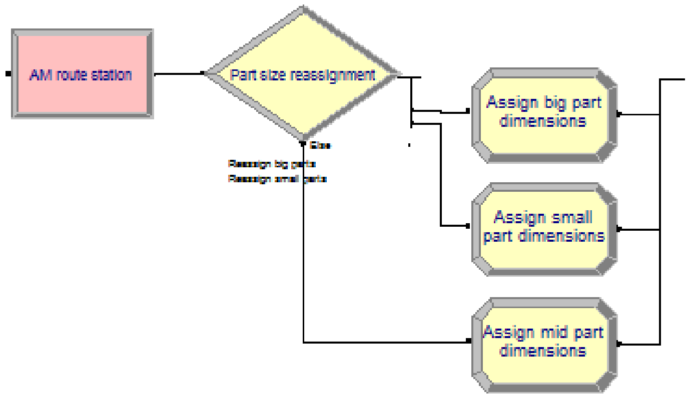


Figure 7-41: New part size assignment

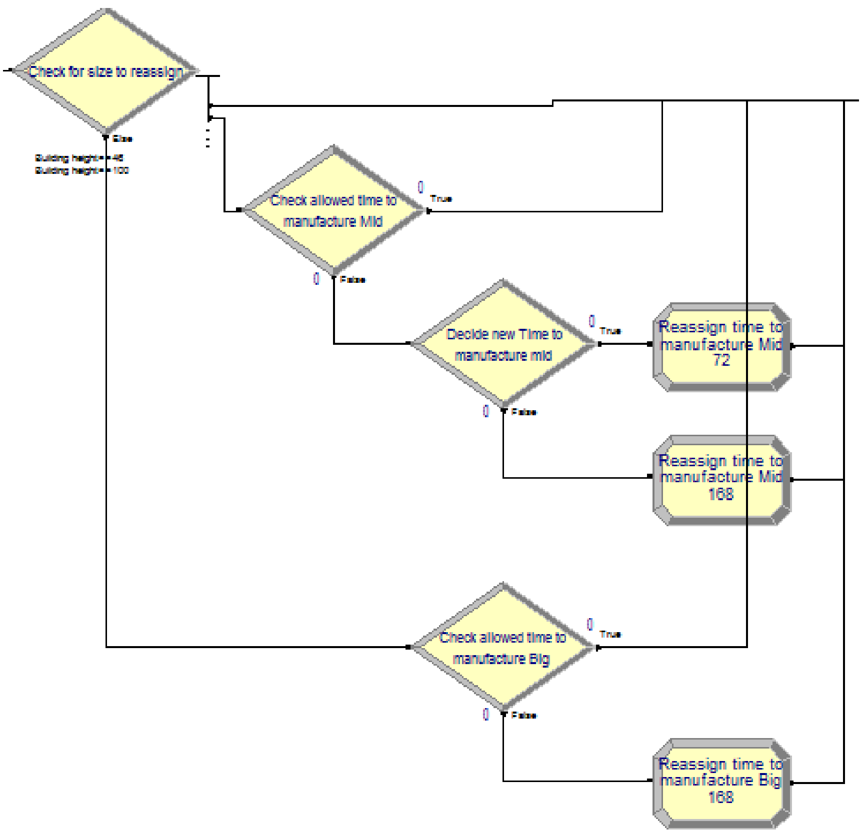


Figure 7-42: Check for allowed time to manufacture

Due to the part size reassignment it is necessary to recheck the allowed time to manufacture. For example a big part cannot be produced in the originally defined allowance time which was 46 hrs.

First, the reassigned part size was checked to ensure that it meets the following criteria:

- Small parts work with all times to manufacture.
- Medium size parts work with medium time to manufacture and long time to manufacture.
- Big parts work with the long time to manufacture only.

The parts will follow a specific path according to part size which works according to the following logics:

- Small parts are simply forwarded to the next material assignment section.
- Medium size parts are assigned with medium or long allowance time (50/50 chance)
- Large size parts are assigned with long allowed time to manufacture.

After that the parts are sent to the material assignment. The rest of the model is identical to the two-machines with flexible material setup.

7.4.2 PROCEEDING

The percentages of big, medium and small parts were varied at several levels. These variations allow for multiple combinations. In order to limit the simulations to only the most representative setups, combinations with extreme settings were selected for simulations as listed in Table 7-7. For the purpose of comparison, the basic setup was included as the baseline reference.

Table 7-7: Selected variations of part size distributions

	Selected spare part size setups		
	Big	Mid	Small
	%	%	%
Case 1	5	20	75
Case 2	33	33	33
Case 3	50	50	0
Case 4	50	0	50
Case 5	100	0	0
Case 6	0	50	50
Case 7	0	100	0
Case 8	0	0	100

The applied tool for calculation is the integrated process analyzer of Arena.

Following simulations will run in the no waiting and waiting mode:

- Upper limit search

7.4.3 RESULTS AND DISCUSSION

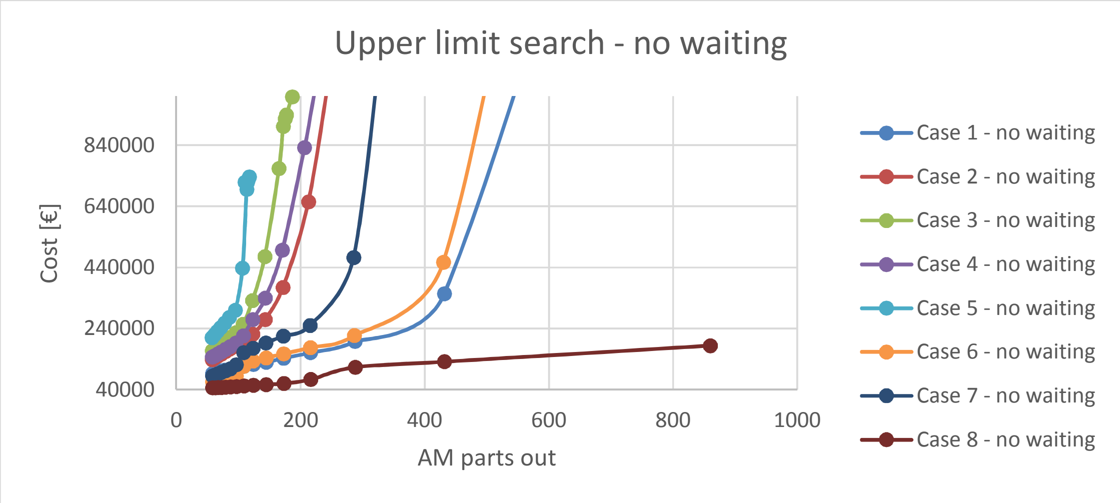


Figure 7-43: Results of part size simulations - Upper limit – No waiting

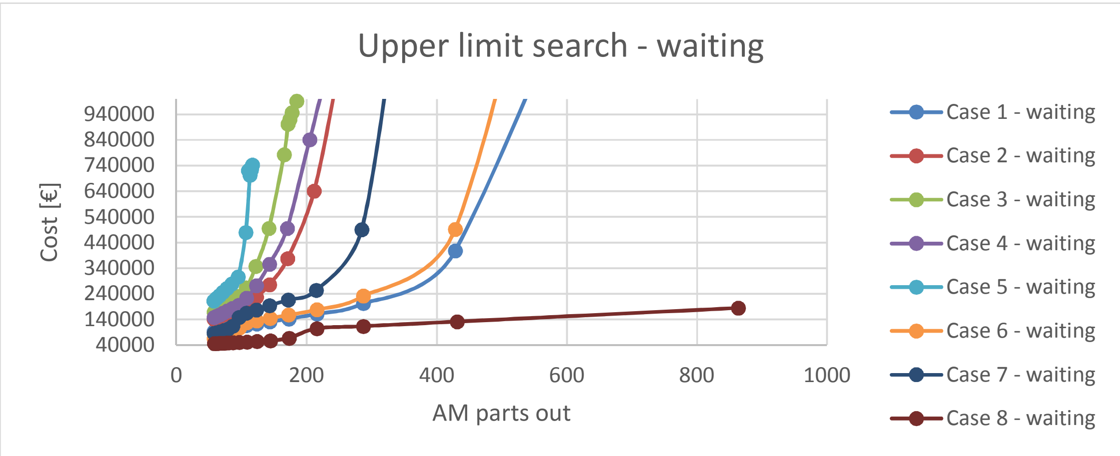


Figure 7-44: Results of part size simulations - Upper limit – Waiting

Figure 7-43 and Figure 7-44 show the results of the upper limit search for each setup in the waiting and no-waiting mode. The cases show a clear trend. The smaller the average size of the requested spare parts, the better the system can react to arriving spare part requests. This seems logical since producing small parts allows to produce more parts in the same time frame.

Table 7-8: Upper limit results of spare part size variation - No waiting and waiting

Control		Part size variation – Mean arrival - No waiting: Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Mean arrival	hr	40	80	90	90	90	40	40	8
Big parts	%	5	33	50	50	100	0	0	0
Medium parts	%	20	33	50	0	0	50	100	0
Small parts	%	75	33	0	50	0	50	0	100
Cost related responses									
Total warehousing cost	€	90275	76559	75075	75201	75056	90227	90697	201283
Total AM cost	€	161281	195676	226837	193128	300524	178079	250516	213543
Consumed material cost	€	58101	92354	120589	92386	181434	74446	135040	65914
Consumed energy cost	€	11102	17647	23042	17653	34668	14225	25804	12595
Operator cost	€	10780	5389	4781	4795	4738	10794	10751	53915
Total maintenance cost	€	58816	58433	58536	58438	58575	58897	58908	59088
Total AM penalty	€	2875	2375	375	375	1583	83	375	2333
AM process related responses									
Consumed material	kg	726	1154	1507	1154	2267	930	1688	823
Consumed energy	kWh	185036	294123	384042	294224	577816	237092	430066	209918
System setup time	%	10	5	5	5	5	10	10	34
System utilization time	%	24	39	51	39	77	31	57	28
Systen cool down time	%	10	5	4	4	4	10	10	33
Total system utilization	%				45	50	60	48	86
Average building volume	mm³	431063	1368484	2011654	1538840	3048625	550032	1000000	97336
Machine depreciation	€	60123	59731	59837	59736	59876	60206	60217	60401
Average time in queue	hr	21,271	8,648	1,988	1,823	---	1,806	3,401	8,269
Average number of parts in queue	pcs.	0,027	0,005	0,001	0	0,002	0	0,002	0,905
Number of parts in queue total	pcs.	10	5	1	1	3	1	4	945
AM parts out	pcs.	216	108	96	96	95	216	215	1078

Control		Part size variation – Mean arrival - Waiting: Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Mean arrival	hr	40	80	90	90	100	40	40	7
Big parts	%	5	33	50	50	100	0	0	0
Medium parts	%	20	33	50	0	0	50	100	0
Small parts	%	75	33	0	50	0	50	0	100
Cost related responses									
Total warehousing cost	€	90648	76489	74836	75039	73685	90860	90886	219627
Total AM cost	€	161905	198649	230666	195556	279998	178438	254449	233128
Consumed material cost	€	57149	92622	121559	92866	163182	74156	134988	75166
Consumed energy cost	€	10920	17698	23227	17745	31181	14170	25794	14363
Operator cost	€	10783	5373	4765	4784	4261	10780	10747	61484
Total maintenance cost	€	58758	58497	58429	58433	58498	58841	58907	59085
Total AM penalty	€	4708	4958	3208	2250	3375	875	4375	3333
AM process related responses									
Consumed material	kg	714	1157	1519	1160	2039	926	1687	939
Consumed energy	kWh	182003	294975	387131	295752	519688	236167	429900	239384
System setup time	%	10	5	5	5	4	10	10	30
System utilization time	%	24	39	52	39	69	31	57	32
Systen cool down time	%	10	5	4	4	4	10	10	29
Total system utilization	%	44	50	61	49	77	52	77	91
Average building volume	mm³	423489	1378738	2033402	1550195	3048625	548455	1000000	97336
Machine depreciation	€	60064	59797	59728	59731	59798	60149	60217	60398
Average time in queue	hr	19,772	8,853	4,405	3,125	---	3,968	4,591	6,974
Average number of parts in queue	pcs.	0,031	0,009	0,001	0,001	0	0,004	0,015	0,822
Number of parts in queue total	pcs.	13	8	2	2	0	8	28	1017
AM parts out	pcs.	216	107	95	96	85	216	215	1230

Even if this is an important finding it must be extenuated. The spare part size distribution has an effect on the system's performance. But if the system's overall performance is better than the required system performance there is no argument for limiting the spare part sizes to an unnecessarily small size. For example in case 7 – no waiting only medium size parts are produced and 95 spare parts can leave the system. When the actual system would require less parts to be delivered in this time the setup is sufficient to meet the demand.

Results also allow to conclude that a smaller the part size results in a higher machine utilization. For example small parts only allows for a system utilization of 94 % at an upper limit of 8 hrs, while big parts allow for a system utilization of 86 % at an upper limit of 90 hrs. A mix of two types of spare parts strongly reduces the system performance. A 50/ 50 mix of small and big size spare parts reaches a 49 % total system utilization at an upper limit of 90 hrs.

90 hrs is the upper limit for both, big parts only and the 50/50 mix of small and big parts, but the utilization is 49 % instead 86 % for the small and big size mix. To explain this gap it can be assumed that several big parts are requested in a row. Then the situation is equal to the big parts only case. In consequence, if penalties should be avoided, the system must be designed to handle big parts only. If again small parts arrive again the total system utilization must decrease, due to the fact that the total production time for small parts is shorter, while the system is designed for longer production times.

The effect is also recognizable when the upper limits of the other cases are taken into account. Small parts only have an upper limit of 8 hours, medium size parts have an upper limit of 40 hrs and big parts only 100 hrs. If other part sizes are mixed in the upper limit of the bigger spare part type decreases only slightly. For example in case 1 75 % of parts are small, 20 % are medium size and 5 % are big. The upper limit is at 40 hrs. Compared to the small only case with an upper limit of 8 hrs the system performance decreased by the factor 5. Further medium size parts are the second relevant group of requested spare parts and 40 hrs is the upper limit of the medium parts only setup. Since a certain penalty is accepted it can be created by arriving big part requests. Also the system utilization decreased by approx. 50 %. It can be assumed that the biggest part type will influence the upper limit of a system most. The utilization will be a result of the produced amount of smaller parts. Consequently for a high utilization a uniform part size is advantageous.

The waiting setup decreases the system performance in most cases. But things change at the point where only small parts are produced. Table 7-8 shows that the waiting mode performs better than the no waiting mode in case 8 (More AM parts out at an equivalent cost level). This seems logical, since setup and cool down is only applied once if one, two or more parts are placed in the building space, while the production time is relatively short and the allowed time to manufacture is relatively long. If the parts would become even smaller, waiting is assumed to become a more beneficial strategy. Consequently this means that the advantage of waiting can improve when the typical part size is decreases.

Table 7-9: Possibility of simultaneous production

Part size	Allowed time to manufac-ture	Manufac-turing	Preheat & cool down	Max waiting time	Production possible if two parts are in building space								
	Defined	Part volume/ Building speed	Preheat + cool down	(if no other part arrives)	small - 168	small - 72	small - 48	mid - 168	mid - 72	mid - 48	big - 168	big - 72	big - 48
---	hrs	hrs	hrs	hrs	hrs	hrs	hrs	hrs	hrs	hrs	hrs	hrs	hrs
small	168	4,5	12	151,5		51	27	106,5	10,5	-13,5	11,5	-84,5	-108,5
						147	147	106,5	106,5	106,5	11,5	11,5	11,5
small	72	4,5	12	55,5	147		27	106,5	10,5	-13,5	11,5	-84,5	-108,5
					51		51	10,5	10,5	10,5	-84,5	-84,5	-84,5
small	48	4,5	12	31,5	147	51		106,5	10,5	-13,5	11,5	-84,5	-108,5
					27	27		-13,5	-13,5	-13,5	-108,5	-108,5	-108,5
mid	168	45	12	111	106,5	10,5	-13,5		-30	-54	-29	-125	-149
					106,5	106,5	106,5		66	66	-29	-29	-29
mid	72	45	12	15	106,5	10,5	-13,5	66		-54	-29	-125	-149
					10,5	10,5	10,5	-30		-30	-125	-125	-125
mid	48	45	12	-9	106,5	10,5	-13,5	66	-30		-29	-125	-149
					-13,5	-13,5	-13,5	-54	-54		-149	-149	-149
big	168	140	12	16	11,5	-84,5	-108,5	-29	-125	-149		-220	-244
					11,5	11,5	11,5	-29	-29	-29		-124	-124
big	72	140	12	-80	11,5	-84,5	-108,5	-29	-125	-149	-124		-244
					-84,5	-84,5	-84,5	-125	-125	-125	-220		-220
big	48	140	12	-104	11,5	-84,5	-108,5	-29	-125	-149	-124	-220	
					-108,5	-108,5	-108,5	-149	-149	-149	-244	-244	

Table 7-9 illustrates this fact. The left part of the table lists the different part size types and their major production related characteristics. Manufacturing allowance time is the driving component from which manufacturing, setup and cool down time are subtracted. This results in the maximum waiting time (values are simplified), which describes the time a spare part request is allowed to wait in queue before a penalty is charged. A negative maximum waiting time indicates that a production of the part is not possible, since a penalty cannot be avoided. Therefore several parts are excluded from further analysis. If the maximum allowed waiting time is bigger than zero, it is checked if a second part can enter the production run without creating a penalty. The production time of the second part is then subtracted from the maximum allowed time to manufacture of the first part. If the result is positive, waiting can be beneficial. The same check is executed on the second part. The production time of the first part is subtracted from the maximum allowed time to manufacture of the second part. If the result is positive, waiting can be beneficial. If one of those two checks is negative waiting is not an option since a penalty will be charged for the part with the negative results.

The same check can be done for third part which might enter the production run, but introducing a third part would not lead to new system behaviors. But if the calculations are executed for a third part entering the production run the results represent the new maximum waiting time for the two already set parts. This allows to increase the number of parts in the building volume in some situations.

Table 7-9 now shows the possible combinations of part sizes in green and the non-possible combinations in red. This shows that waiting is only possible when small parts are produced. If medium and big parts are introduced penalties will be created. A better control of the spare part set might slightly improve the situation, since a production of exceptionally small/ medium size and small/ big combinations are possible. However, in the current setup this is not an option. For future extensions to this work this may present a new field of study. In a situation in which for no part in process a penalty is charged, adding a part to an ongoing production run might become an option to eliminate double setup and cool down times for certain part combinations. For now it is assumed that the more parts are added to a production run the longer the production will take. This can increase the chance to create a penalty if the system is not balanced accordingly.

The smaller the part size will become, the bigger the influence of setup and cool down times will be. This can lead to the conclusion that reducing setup and cool down times might again lead to further improvements. It can be assumed that the waiting mode can become less beneficial for the small parts only production if setup and cool down times decrease significantly.

8 SUMMARY OF FINDINGS

The individual findings have been presented in the previous chapters. This chapter focuses on the comparison between different strategies directly. The following tables summarize findings when parameter such as setup and cool down are varied for one-, two- or three machine setups in no waiting and waiting mode.

If relevant, the most representative results are added according to the specific purpose.

The following tables are presented:

Table 8-1: Discussion of base case simulation

Table 8-2: Discussion of AM strategy investigations

Table 8-3: Comparison of different strategies – Upper limit – No waiting

Table 8-4: Comparison of different strategies – Upper limit – Waiting

Table 8-5: Comparison of different strategies – Preheat and cool down – No waiting

Table 8-6: Comparison of different strategies – Preheat and cool down – Waiting

Table 8-7: Comparison of different part size setups - No waiting

Table 8-8: Comparison of different part size setups - Waiting

Table 8-1: Discussion of base case simulation

Controlls	Unit	Base case	Technical investigations - Verification				
			Building space volume	Building speed	Material price	Machine purchase price	Cool down time
Investigation	---	Reference case for direct comparison with other scenarios.	Increased building space volume increases processing and and delivery time.	Increased building speed will lead to faster processing and has a positive impact on the spare part supply, while increased building volumes can be compensated.	Price a company is willing to pay for material.	Influence of machine purchase price and depreciation time.	Decrease of the cool down time leads to faster processing and improved spare part supply.
Control variation	---	Arrival mean: 10 - 1500 hr	Building height: 145 - 500 mm Building depth: 145 - 650 mm Building width: 145 - 500 mm	Building speed: 10 - 100 cm³/ hr Arrival mean: 10 - 150 hr	Material price: 10 - 150 €	Machine purchase price: 100000 - 500000 € Depreciation time: 2 - 20 yr	Arrival mean: 10 - 150 hr Cool down time: 0 - 12 hr
Responses at upper limit							
Control set for results		Arrival mean: 100 hr	Building heigth: 145 mm Building depth: 145 mm Building width: 145 mm	Building speed: 40 cm³/ hr Arrival mean: 80 hr	Material price: 10 €	Machine purchase price: 450000 € Depreciation time: 8 yr	Arrival mean: 100 hr Cool down time: 11 hr
Upper limit	hr	**100**	**100**	**80**	**100**	**100**	**100**
AM parts out	pcs.	**87**	**87**	**108**	**87**	**87**	**87**
Cost related responses							
Total warehousing cost	€	**74191**	**74115**	**76796**	**74191**	**74191**	**74185**
Total AM cost	€	**73494**	**72439**	**76947**	**54217**	**73494**	**73840**
Consumed material cost	€	22030	21881	27082	2754	22030	22015
Consumed energy cost	€	4210	4181	5175	4210	4210	4207
Operator cost	€	4336	4332	5410	4336	4336	4333
Total maintenance cost	€	29407	29409	29460	29407	29407	29401
Total AM penalty	€	3708	2833	0	3708	3708	73840
AM process related responses							
Consumed material	kg	275	274	339	275	275	275
Consumed energy	kWh	70160	69685	86248	70160	70160	70112
Machine setup time	%	8	5	10	8	8	8
Machine production time	%	19	18	13	19	19	19
Machine cool down time	%	8	5	10	8	8	11
Total machine utilization time	%	35	32	33	35	35	38
Average building volume	mm³	404530	402003	398349	404530	404530	404306
Machine depreciation	€	30061	30063	30115	30061	56364	30055
Average time in queue	hr	50	48	14	50	50	52
Average number of parts in queue	pcs.	0	0	0	0	0	0
Number of parts in queue total	pcs.	5	5	4	5	5	5
Findings	---	A further increase of the machine utilization (in this case > 35 %) will lead to queuing of part requests, creating longer production runs, due to more parts in a run, what again increases the queuing issue and so forth. High penalties can be expected in this case.	It is prerable to adjust the building space volume to the maximum part size instead of generating unused building space volume with the related drawbacks. Bigger building space volume enables: - longer processing times (bigger or more parts) - longer setup and cool down times Both should be minimized to allow a fast reacting system. In general the system should be balanced that average building volume does not exceed the utilization borders of the system. In this specific case typically no more than one part should enter the production run to keep a stable system.	The positive impact on spare part supply and compensation of building space volume increase can be confirmed. Building speed strongly increases the production capacity, but production cost and service related factors need to be balanced. With increasing building speed the relevance of penalties is decreaseing compared to the production related cost. Buidling speed can be selected according to the system requirements, since at a certain limit no cost improvements can be gained by increasing the building speed further.	Price level of model is balanced due to upper limit defined in the base case. General conclusion: - The lower the price the better. A higher material price can be acceptable when the actual consumed material is lower than the consumed material at the upper limit case, since the material cost follows a linear function. The acceptable material price can be calculated on this basis.	Better to evaluate the purchase price independent of the total AM cost. Gerneral conclusion: - The lower the price the better. After 8 years the annual machine depreciation tends to "stabilize" at a certain level.	It can be confirmed that a reduced cool down time leads to faster processing and improved spare part supply. But from a cost perspective the potential is limited. The cool down time has only slight influence on the results as long as the system is in a stable state. The lower the utilization is, the smaller is the effect on the total AM cost. As for the machine setup and building speed a faster cool down supports a higher system output which can increase the variable production cost. The system needs to be balanced.

Table 8-2: Discussion of AM strategy investigations

Scenarios	Technical extensions - Alternative strategies							
	Two machines with fixed material assignment		Two machines with flexible material assignment		Three machines with fixed material assignment		Three machines with flexible material assignment	
Description	Two identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one or two, both with a 50 % chance.		Two identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.		Three identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one, two or three, all with a 33 % chance.		Three identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.	
	Investigation (For both, with and without waiting before production start):	Control variables	Investigation (For both, with and without waiting before production start):	Control variables	Investigation (For both, with and without waiting before production start):	Control variables	Investigation (For both, with and without waiting before production start):	Control variables
	Upper limit	Mean arrival	Upper limit	Mean arrival	Upper limit	Mean arrival	Upper limit	Mean arrival
	Setup and cool down time (at low, mid and high arrival rates)	Sum of setup and cool down time	Setup and cool down time (at low, mid and high arrival rates)	Sum of setup and cool down time	Setup and cool down time (at low, mid and high arrival rates)	Sum of setup and cool down time	Setup and cool down time (at low, mid and high arrival rates)	Sum of setup and cool down time
	Waiting only: Elapse time	Elapse time	Waiting only: Elapse time	Elapse time	Waiting only: Elapse time	Elapse time	Waiting only: Elapse time	Elapse time
	Waiting only: Start volume	Production start volume	Waiting only: Start volume	Production start volume	Waiting only: Start volume	Production start volume	Waiting only: Start volume	Production start volume
	---	---	Material change over time (at low, mid and high arrival rates)	Material change time	---	---	Material change over time (at low, mid and high arrival rates)	Material change time

Findings

Findings	Two machines with fixed material assignment	Two machines with flexible material assignment	Three machines with fixed material assignment	Three machines with flexible material assignment
Upper limit (No waiting)	The upper limit was reached at 60 hrs with 144 parts Machine utilization at this upper limit is 28 % The highest possible production rate was at a mean arrival of 20 hrs with 429 parts.	The upper limit was reached at 40 hrs with 215 parts Machine utilization at this upper limit is 44 % The highest possible production rate was at a mean arrival of 20 hrs with 430 parts.	The upper limit was reached at 60 hrs with 144 parts Machine utilization at this upper limit is 19 % The highest possible production rate was at a mean arrival of 20 hrs with 431 parts.	The upper limit was reached at 30 hrs with 288 parts Machine utilization at this upper limit is 39 % The highest possible production rate was at a mean arrival of 20 hrs with 431 parts. (Compared to the two machine setup the system performs better, since the number of parts in queue is lower)
Upper limit (Waiting)	The upper limit was reached at 60 hrs with 123 parts Machine utilization at this upper limit is 24 % The highest possible production rate was at a mean arrival of 20 hrs with 429 parts.	The upper limit was reached at 70 hrs with 123 parts Machine utilization at this upper limit is 44 % The highest possible production rate was at a mean arrival of 20 hrs with 429 parts.	The upper limit was reached at 60 hrs with 144 parts Machine utilization at this upper limit is 19 % The highest possible production rate was at a mean arrival of 20 hrs with 430 parts.	The upper limit was reached at 60 hrs with 144 parts Machine utilization at this upper limit is 19 % The highest possible production rate was at a mean arrival of 20 hrs with 431 parts. (Compared to the two machine setup the system performs better, since the number of parts in queue is lower)
Setup and cool down (No waiting)	A decrease in setup and cool down time increases the system performance. The sensitivity of the system is dependent on the mean arrival rate. An increased part arrival rate makes the system more sensitive changes in the setup and cool down times.			
Setup and cool down (Waiting)	Equivalent to setup and cool down with no waiting with an increased total cost, caused by more charged penalties due waiting.			
Waiting only: Elapse time	At the current setup elapse time has no influence on the system due to no further part arrival in the max. waiting time.			
Waiting only: Start volume	At the current setup start volume has no influence on the system due to no further part arrival in the max. waiting time.			
Fexible only: Material change over time	The material changeover time has a slight influence on the system performance. Similar to other increased time consumers (e.g. setup and cool down times) the system is stronger the more the system is stressed. A decrease in material changeover time will lead to an improved system performance.			

General findings	Waiting can not be better in this spare part setup. The max. part arrival rate is 20 hrs. If the waiting time does not exceed 20 hrs (what will lead to pentalties due to the allowd time for production), production will always be delayed without receiving a second part for production while the machine is idle. Waiting can become an option when the parts are relatively small and production is fast. Extra setup and cool down times can be avoided by waiting, but total production plus waiting time may not exceed the allowed time to manufacture. Otherwise penalties are charged. Also variations of the start volume and the elapse time support that waiting is not effective in the current setup, since variations show no to minor effect on the results. It can be clearly stated that waiting strategies are not efficient when no other part arrival is expected during waiting time and only reduceds the performance of the system.

Table 8-3: Comparison of different strategies – Upper limit – No waiting

Setting - No waiting	Unit	Investigation: Upper limit			
		Two machines with fixed material assignment	Two machines with flexible material assignment	Three machines with fixed material assignment	Three machines with flexible material assignment
Investigation	---	Two identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one or two, both with a 50 % chance.	Two identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.	Three identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one, two or three, all with a 33 % chance.	Three identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.
Control variation	---	Upper limit	Upper limit	Upper limit	Upper limit

Responses at upper limit

Upper limit	hr	**60**	**40**	**60**	**30**
AM parts out	pcs.	**144**	**216**	**144**	**288**

Cost related responses

Total warehousing cost	€	**81403**	**90498**	**81454**	**99982**
Total AM cost	€	**131635**	**154963**	**169974**	**214494**
Consumed material cost	€	34664	53087	35687	68923
Consumed energy cost	€	6623	10144	6819	13170
Operator cost	€	7206	10778	7211	14424
Total maintenance cost	€	58573	5877	87285	88138
Total AM penalty	€	5041	2583	3875	458

AM process related responses

Consumed material	kg	433	663	446	861
Consumed energy	kWh	110396	169069	113655	219501
System setup time	%	6,88	11,786	4,65	10,876
System utilization time	%	14,67	22,387	10,13	19,383
Systen cool down time	%	6,67	10,022	4,51	8,968
Total system utilization	%	28,22	44,194	19,3	39,226
Average building volume	mm³	382907	393624	393399	382545
Machine depreciation	€	59875	60083	89225	90097
Average time in queue	hr	30	19,264	28,123	6,191
Average number of parts in queue	pcs.	0,027	0,023	0,012	0,003
Number of parts in queue total	pcs.	15	9,3	10	3,217

Findings	The results show a clear trend with respect to system performance. The fixed material systems perform on a similar level with respect to AM parts out. The overall peformance of the three machine setup can even be evaluated as worse compared to the two machine setup, since the total system utilization is only 19 % compared to 28 % using two machines only. The flexible material systems improve significantly with respect to system perfomance. The number of AM parts out is increased by 33 % while the upper limit improved by 25 % when a third machine is added. Also the two machine setup shows clearly better results compared to the fixed material setup. With respect to a performance evaluation of fixed vs. flexible material systems, the flexible material system is preferable for the current system setup.

Table 8-4: Comparison of different strategies – Upper limit – Waiting

Setting - Waiting	**Unit**	**Investigation: Upper limit** Two machines with fixed material assignment	Two machines with flexible material assignment	Three machines with fixed material assignment	Three machines with flexible material assignment
Investigation	---	Two identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one or two, both with a 50 % chance.	Two identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.	Three identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one, two or three, all with a 33 % chance.	Three identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.
Control variation	---	Upper limit	Upper limit	Upper limit	Upper limit

Responses at upper limit

Upper limit	hr	**70**	**70**	**60**	**60**
AM parts out	pcs.	**123**	**123**	**144**	**144**

Cost related responses

Total warehousing cost	€	**78402**	**78751**	**80950**	**81248**
Total AM cost	€	**122822**	**120773**	**169690**	**169015**
Consumed material cost	€	29487	28534	35114	34054
Consumed energy cost	€	5634	5452	6709	6507
Operator cost	€	6172	6163	7186	7186
Total maintenance cost	€	58396	58498	87228	87356
Total AM penalty	€	3666	2625	4375	4791

AM process related responses

Consumed material	kg	368	356	438	425
Consumed energy	kWh	93907	90874	111829	108452
System setup time	%	5,93	6,473	4,64	5,174
System utilization time	%	12,52	12,095	9,98	9,661
Systen cool down time	%	5,74	5,773	4,49	4,508
Total system utilization	%	24,19	24,341	19,11	19,342
Average building volume	mm^3	380333	370109	389143	378199
Machine depreciation	€	59694	59798	89166	89298
Average time in queue	hr	27	---	27,336	---
Average number of parts in queue	pcs.	0,017	0,001	0,015	0
Number of parts in queue total	pcs.	10	1	13	0

Findings	The upper limit search in the "waiting" setting shows similar results to the "no waiting" setting. The flexible material setup performs better than the fixed material setup. While the upper limit and the number of parts out are equal for both setups with an equivalent penalty, the queing behaviour is different. While queueing occurs for the fixed material setup, no queuing occurs for the flexible material setup. That indicates that the system performs better.

Table 8-5: Comparison of different strategies – Preheat and cool down – No waiting

Setting - No waiting	Unit	Investigation: Preheat/ Cool down variation			
		Two machines with fixed material assignment	Two machines with flexible material assignment	Three machines with fixed material assignment	Three machines with flexible material assignment
Investigation	---	Two identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one or two, both with a 50 % chance.	Two identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.	Three identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one, two or three, all with a 33 % chance.	Three identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.
Control variation	---	Sum of setup and cool down	Sum of setup and cool down	Sum of setup and cool down	Sum of setup and cool down

Setting

Mean arrival	hr	**60**	**40**	**60**	**20**
Sum of setup and cool down	hr	**9**	**15**	**15**	**4**

Cost related responses

Total warehousing cost	€	**81203**	**90533**	**80609**	**117901**
Total AM cost	€	**131289**	**153721**	**169277**	**265106**
Consumed material cost	€	35080	51965	34289	103701
Consumed energy cost	€	6703	9929	6552	19815
Operator cost	€	7201	10772	7191	21535
Total maintenance cost	€	58478	58758	87214	88259
Total AM penalty	€	4333	2708	4958	2375

AM process related responses

Consumed material	kg	438	649	428	1296
Consumed energy	kWh	111721	165494	109202	330259
System setup time	%	6,06	13,05	5,2	13,667
System utilization time	%	14,87	21,925	9,74	29,123
Systen cool down time	%	5,01	12,51	5,62	6,685
Total system utilization	%	25,93	47,486	20,56	49,474
Average building volume	mm³	387570	386087	378971	385188
Machine depreciation	€	59777	60064	89152	90220
Average time in queue	hr	32	18,368	29,296	8,988
Average number of parts in queue	pcs.	0,025	0,024	0,013	0,038
Number of parts in queue total	pcs.	12	10,23	11	32,783
AM parts out	pcs.	144	215	144	431

Findings	With respect to setup and cool down times the flexible material systems perform better than the fixed material systems. (Results show the middle upper limit of the upper limit search. The systems where stressed by increasing the sum of setup and cool down times.) The three machine setup with flexible material very good results with respect to the mean arrival rate of part requests, but needs extremely low setup/ cool down times to perform with an acceptable penalty. This means that the more part request arrive the faster the setup and changeover should be, since the sum of setup and cool down become significant. This effect is not as significant as long as the mean arrival rate is in a more relaxed state.

Table 8-6: Comparison of different strategies – Preheat and cool down – Waiting

Setting - Waiting	**Unit**	**Investigation: Upper limit** Two machines with fixed material assignment	Two machines with flexible material assignment	Three machines with fixed material assignment	Three machines with flexible material assignment
Investigation	---	Two identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one or two, both with a 50 % chance.	Two identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.	Three identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Spare parts are either of material type one, two or three, all with a 33 % chance.	Three identical AM systems will work in parallel. Each machine can fabricate two types of material. Spare parts are either of material type one or two, both with a 50 % chance. Material change time is considered when a material change on a machine is required.
Control variation	---	Upper limit	Upper limit	Upper limit	Upper limit

Responses at upper limit

Upper limit	hr	**70**	**70**	**60**	**60**
AM parts out	pcs.	**123**	**123**	**144**	**144**

Cost related responses

Total warehousing cost	€	**78402**	**78751**	**80950**	**81248**
Total AM cost	€	**122822**	**120773**	**169690**	**169015**
Consumed material cost	€	29487	28534	35114	34054
Consumed energy cost	€	5634	5452	6709	6507
Operator cost	€	6172	6163	7186	7186
Total maintenance cost	€	58396	58498	87228	87356
Total AM penalty	€	3666	2625	4375	4791

AM process related responses

Consumed material	kg	368	356	438	425
Consumed energy	kWh	93907	90874	111829	108452
System setup time	%	5,93	6,473	4,64	5,174
System utilization time	%	12,52	12,095	9,98	9,661
Systen cool down time	%	5,74	5,773	4,49	4,508
Total system utilization	%	24,19	24,341	19,11	19,342
Average building volume	mm^3	380333	370109	389143	378199
Machine depreciation	€	59694	59798	89166	89298
Average time in queue	hr	27	---	27,336	---
Average number of parts in queue	pcs.	0,017	0,001	0,015	0
Number of parts in queue total	pcs.	10	1	13	0

Findings	The upper limit search in the "waiting" setting shows similar results to the "no waiting" setting. The flexible material setup performs better than the fixed material setup. While the upper limit and the number of parts out are equal for both setups with an equivalent penalty, the queing behaviour is different. While queueing occurs for the fixed material setup, no queuing occurs for the flexible material setup. That indicates that the system performs better.

Table 8-7: Comparison of different part size setups - No waiting

Setting - No waiting	**Unit**	**Investigation: Part size variation** Two machines producing several part size combinations
Investigation	---	Two identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Standard cases and extreme spare part size setup are investigated.
Part size - small		46 x 46 x 46 mm³
Part size - mid		100 x 100 x 100 mm³
Part size - big	---	145 x 145 x 145 mm³

Setting

Percentage small parts	%	**75**	**33**	**0**	**50**	**0**	**50**	**0**	**100**
Percentage mid parts	%	**20**	**33**	**50**	**0**	**0**	**50**	**100**	**0**
Percentage big marts	%	**5**	**33**	**50**	**50**	**100**	**0**	**0**	**0**

Cost related responses

Total warehousing cost	€	**90275**	**76559**	**75075**	**75201**	**75056**	**90227**	**90697**	**201283**
Total AM cost	€	**161281**	**195676**	**226837**	**193128**	**300524**	**178079**	**250516**	**213543**
Consumed material cost	€	58101	92354	120589	92386	181434	74446	135040	65914
Consumed energy cost	€	11102	17647	23042	17653	34668	14225	25804	12595
Operator cost	€	10780	5389	4781	4795	4738	10794	10751	53915
Total maintenance cost	€	58816	58433	58536	58438	58575	58897	58908	59088
Total AM penalty	€	2875	2375	375	375	1583	83	375	2333

AM process related responses

Consumed material	kg	726	1154	1507	1154	2267	930	1688	823
Consumed energy	kWh	185036	294123	384042	294224	577816	237092	430066	209918
System setup time	%	10,361	5,279	4,682	4,705	4,636	10,432	10,388	33,958
System utilization time	%	24,486	39,17	51,062	39,19	76,779	31,33	56,823	27,651
Systen cool down time	%	9,975	5,054	4,476	4,497	4,433	10,042	10,001	32,827
Total system utilization	%	44,822	49,503	60,22	48,391	85,848	51,804	77,212	94,437
Average building volume	mm³	431063	1368484	2011654	1538840	3048625	550032	1000000	97336
Machine depreciation	€	60123	59731	59837	59736	59876	60206	60217	60401
Average time in queue	hr	21,271	8,648	1,988	1,823	---	1,806	3,401	8,269
Average number of parts in queue	pcs.	0,027	0,005	0,001	0	0,002	0	0,002	0,905
Number of parts in queue total	pcs.	10,333	5,033	0,867	0,75	3,1	1,083	4,267	944,6
AM parts out	pcs.	215,617	107,783	95,633	95,917	94,767	215,883	215,033	1078,317

Findings	The smaller the parts in the spare part mix are, the better the system can react on part requests. But if the frequency of the real life spare part request is lower than the upper limit it should not be a problem, since the system is able to handle the spare part requests.

Table 8-8: Comparison of different part size setups - Waiting

Setting - Waiting	**Unit**	**Investigation: Part size variation** Two machines producing several part size combinations
Investigation	---	Two identical AM systems will work in parallel. Each machine is dedicated to fabricate with one fixed type of material only. Standard cases and extreme spare part size setup are investigated.
Part size - small		46 x 46 x 46 mm³
Part size - mid		100 x 100 x 100 mm³
Part size - big	---	145 x 145 x 145 mm³

Setting

Percentage small parts	%	**75**	**33**	**0**	**50**	**0**	**50**	**0**	**100**
Percentage mid parts	%	**20**	**33**	**50**	**0**	**0**	**50**	**100**	**0**
Percentage big marts	%	**5**	**33**	**50**	**50**	**100**	**0**	**0**	**0**

Cost related responses

Total warehousing cost	€	**90648**	**76489**	**74836**	**75039**	**73685**	**90860**	**90886**	**219627**
Total AM cost	€	**161905**	**198649**	**230666**	**195556**	**279998**	**178438**	**254449**	**233128**
Consumed material cost	€	57149	92622	121559	92866	163182	74156	134988	75166
Consumed energy cost	€	10920	17698	23227	17745	31181	14170	25794	14363
Operator cost	€	10783	5373	4765	4784	4261	10780	10747	61484
Total maintenance cost	€	58758	58497	58429	58433	58498	58841	58907	59085
Total AM penalty	€	4708	4958	3208	2250	3375	875	4375	3333

AM process related responses

Consumed material	kg	714	1157	1519	1160	2039	926	1687	939
Consumed energy	kWh	182003	294975	387131	295752	519688	236167	429900	239384
System setup time	%	10,362	5,256	4,673	4,692	4,181	10,42	10,381	30,124
System utilization time	%	24,107	39,241	51,564	39,397	69,146	31,238	56,801	31,534
Systen cool down time	%	9,978	5,033	4,468	4,486	3,992	10,039	9,997	29,113
Total system utilization	%	44,447	49,53	60,705	48,575	77,318	51,697	77,179	90,772
Average building volume	mm³	423489	1378738	2033402	1550195	3048625	548455	1000000	97336
Machine depreciation	€	60064	59797	59728	59731	59798	60149	60217	60398
Average time in queue	hr	19,772	8,853	4,405	3,125	---	3,968	4,591	6,974
Average number of parts in queue	pcs.	0,031	0,009	0,001	0,001	0	0,004	0,015	0,822
Number of parts in queue total	pcs.	13,233	7,75	1,9	1,517	0,25	8,267	27,817	1017,067
AM parts out	pcs.	215,667	107,467	95,3	95,683	85,233	215,617	214,95	1229,683

Findings	For most scenarios the waiting setup is worse that the no waiting setup under the given set of conditions. A deviation occurs when only small parts are produced. Here a sligth advantage of the waiting strategy occurs. A smaller part size means realtively long setup and cool down times compared to the actual production time. In consequence the smaller the part size the more interisting becomes batching of spare part request.

8.1 COMPARISON OF TOTAL AM COST

One advantage of the established model is to enable direct comparisons between various setup and strategies against certain performance criteria efficiently, such as the relationship between part arrival rate and system operating cost. The total AM cost of all strategies with various mean arrival time are listed in Table 8-9. The high arrival times, low arrival times and the upper limit of the spare part requests are marked in red, green and yellow respectively. Waiting generally results in additional costs and lower efficiencies in the current setup and is not discussed in this section.

Looking at the fixed material strategies, the system performance does not improve with the number of machines. This is due to the previously described effects. More interesting to note is the flexible material strategy. Overall the system performance of this strategy improves with increasing number of machines. Further it can be said that the higher the number of machines, the closer the lower, and higher limit shift to the upper limit. This can mean that the more machines are used the better the system can react, since more machines are sharing the jobs. For example it is more likely to have a machine idle for direct production when three machines are used compared to using one machine. Then the system does not need to compensate for this uncertainty, what allows the system to work stable when the upper or lower is not exceeded. On the other hand, due to the high arrival rate of spare part request, a queue is created fast if no machine is idle for a while since spare part requests keep arriving and will most likely create penalties. But below the upper limit the system can be operated very stable.

Table 8-9: Overview of different strategies - Upper limit search - No waiting

Mean arrival	Total AM cost				
	Base case	Two machines fixed	Two machines flexible	Three machines fixed	Three machines flexible
hrs	€				
150	59772	95.849	96146	132381	133019
140	62060	97.270	97749	133786	134876
130	63917	98.913	99234	136044	136234
120	66070	101.718	101237	138861	139073
110	68717	103.993	103396	140477	140697
100	73494	107.410	106276	144249	144310
90	78178	111.450	109770	148389	147166
80	84145	116.021	113943	152922	151932
70	90898	124.050	118266	160813	158433
60	104765	131.635	127048	169974	163877
50	133290	149.389	136911	183340	174260
40	199013	175.122	154963	207051	190719
30	356010	246.337	188196	244715	214494
20	1219129	482.313	339234	380022	274890
10	1709967	2.461.622	2537724	1405475	2471954

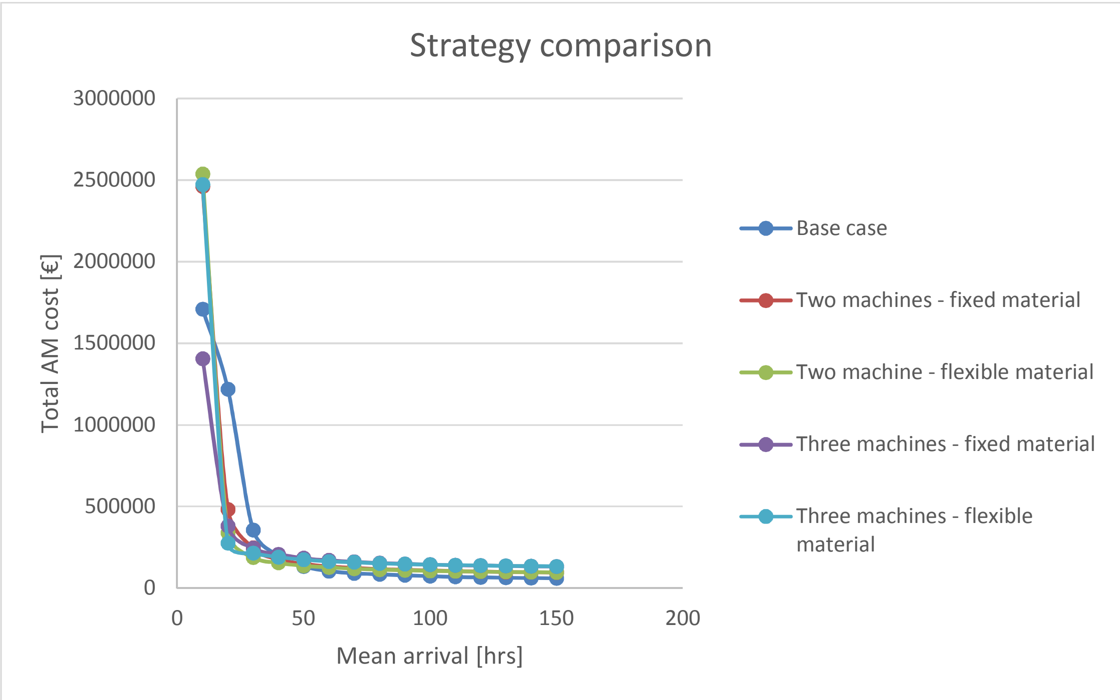


Figure 8-1: Strategy comparison

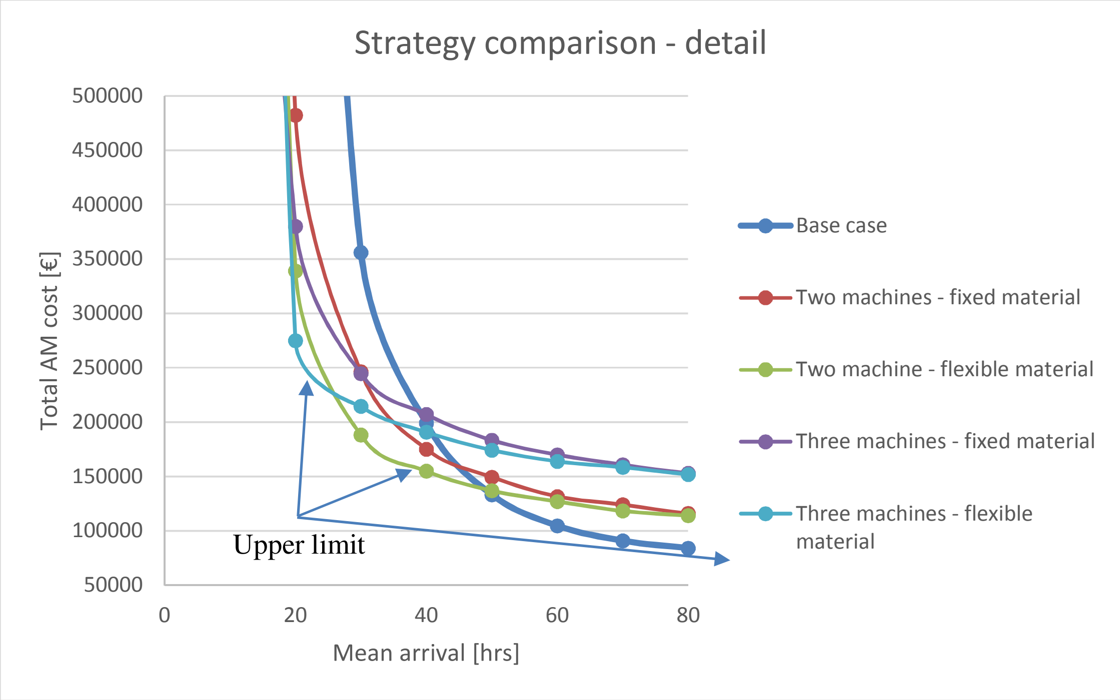


Figure 8-2: Strategy comparison - detail

Figure 8-1 and Figure 8-2 illustrate this effect. Focusing on the flexible material strategies and the base case the cost curve shows an approximately linear behavior before the upper limit is exceeded. (A lower mean arrival time results more spare part requests.) When the upper limit is exceeded the penalties become a strong cost driver the more the inter-arrival time of spare part requests increases. The base case reaches its upper limit early (100 hrs), but when the inter-arrival time of spare part requests further increases the cost increase due to penalties is relatively slow. This is due to the fact that the inter-arrival times of part requests are relatively low in the working range of a one machine setup. Since the one machine setup is the simplest approach it is logical that it works also at the lowest cost level.

If it becomes necessary the system performance can be increased by adding a second machine. This lifts the system cost to a new level and into a new working range. The illustration allows the assumption that this strategy is beneficial from a cost perspective in a working range with a mean arrival time between 28 and 50 hrs. When the upper limit is exceeded the impact of penalties is stronger than in the one machine solution. This is logical due to the higher inter-arrival times of part requests and the resulting higher number of parts in queue when queuing occurs. The equivalent principle is valid for the three machine with flexible material strategy. What can be learned from this graphic is that each strategy, one or multi machine, has its specific application and needs to be adjusted to the actual requirements. Also changing spare part parameters like part size can influence the decision for a strategy.

8.2 ADDITIONAL DISCUSSION

8.2.1 AM SPARE PART STRATEGY ANALYSIS FOR CASE STUDY

In this subsection the use of AM as a potential alternative for the spare part supply of a real-world setting was analyzed. A dataset of spare parts was provided by a manufacturing company and was analyzed as described in chapter 4. The following table presents a consumption profile of that specific spare parts set for further analysis.

A total of 3510 parts were consumed from the warehouse stock in the period of one year – neither a single AM machine is able to produce this amount of parts nor will two or three machines reach this output. The following table lists the output using the flexible material strategies and the base case. The content can also be illustrated in a graph, what enables an estimate to the required number of machines to reach a specific number of machines.

Table 8-10: Consumption profile of spare part set[10]

No. of consumption	No. of part types	Total consumption [pcs.]	Value of total consumption [€]	Current stock value [€]
0 - 1	523	50	32,530	237,212
2 - 9	76	279	59,148	34,947
10 - 49	25	687	39,427	12,499
50 - 149	6	672	13,828	4,235
150 - 1,000	3	1,822	38,723	1,463
Total	**633**	**3,510**	**183,656**	**290,356**

Applying the function ten machines are needed to cover the total demand. This results in a heavy investment, which cannot be justified by further analysis without expensive tradeoffs. A check of the consumption of the specific spare parts helps it this situation. In the presented consumption profile, all values tend to follow an ABC distribution. 3 part types are consumed 1,822 times and represent a stock value of only 1,463 €. On the other hand, there are types of 523 parts that are consumed a total of 50 times but represent a stock value of 237,212 €. These parts clearly represent the more "valuable" and "critical" part sets. When only these high value-added parts are considered, AM appears to become a reasonable option in this case. The simulation model of the base case predicted an average output of 87 parts per year with an acceptable penalty. Since only 50 parts will be consumed in the real system, already the one-machine system would be sufficient from a service level perspective. Furthermore, the comparison of the base case and the real

[10] "No. Of consumption" describes the range of consumption a specific type was consumed. Example row 1: 3 part different part types were consumed between 300 and 1000 times each. So these part types are consumed often. If the consumption of the different part types is summed up, 1822 parts are consumed in total with a value of consumption of 38,723 € and a total stock value of 1,463 €. The data represents one year of data collection.

system shows that AM is a cost attractive solution for spare part supply under appropriate circumstances.

It should also be noted that the fact that the AM system is able to produce 87 parts at its upper limit implies that the system is capable of handling temporary supply surges of up to about 150% of the original rate. The output can be increased further by applying more machines if the investment is justifiable (red line indicates the trend).

	AM parts out	# of machines
Three machines with flexible material - No waiting	431	3
Two machines with flexible material - No waiting	215	2
Base case - No waiting	87	1

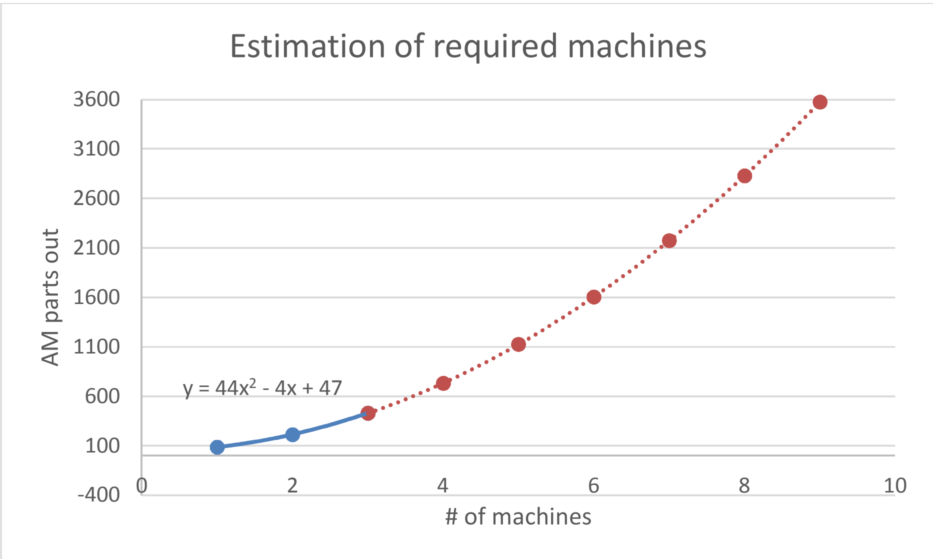


Table 8-11: AM parts out using two, three or the base case strategy with flexible material

8.2.2 INFLUENCE OF CO2 EMISSIONS

Many publications assume that AM is able to reduce CO_2 emission. This hypothesis cannot be proven by this thesis but two facts support the idea. The following results can be drawn based on the base case results for an upper limit of 150 hrs, which is a reasonable approximation of some of the actual warehouse situation with low turnover items. In this case the low turnover of parts indicates that approximation that 89 % of the part types are stored without any use. This consequently implies that the manufacturing and transport of unnecessary spare parts to the warehouse would result in unnecessary CO_2 emissions. Furthermore, these parts account for approximately 1,389 kg of materials which do not need to be manufactured in the first place. For AM strategy, both aspects would likely contribute to the reduction of CO_2 emissions compared to a warehouse. Referring to a study by the ALBA Group the CO_2 savings are estimated (ALBA Group, 2011). The study contains the following information presented in Table 8-12.

1.2 billion tons of steel were produced by primary and secondary[11] production in 2009. 13 % of the material was delivered by secondary production. When steel is recycled 0.97 ton CO_2 are produced for every ton of material. Compared to primary production processes recycling saves 64 % of the primary production process (ALBA Group, 2011). This would result in a mixed CO2 production (primary plus secondary production) of 1.45 ton for every ton of steel. Therefore, for the previously described spare part stock, approximately 2 tons of CO_2 would be produced as a result of over-stocking.

This calculation is not intended to be accurate, as it still lacks various details such as transportation and other process steps. However, it can be reasonably expected that with additional information the environmental benefits of adopting AM strategy can be further justified.

[11] Recycling

Table 8-12: Non-required part on stock

Low turnover parts only	**Unit**	**Value (AM)**	**Warehouse data**
Parts consumed (base case)	pcs.	59	
Parts types in warehouse	pcs.	0	523
Consumed parts from warehouse	%	---	11
Unnecessary parts types in storage	**pcs.**	**0**	**512**
Unnecessary parts types in storage	**%**	**0**	**89**

Averaged values

Consumed material	kg	183	180
Consumed material per consumed part[12]	kg	3	3
Total material in storage[13]	kg	40	1569
Unnecessary material in storage (average)	**kg**	**0**	**1389**

[12] Consumed material by AM divided by the parts consumed.
[13] Regarding AM - Material is assumed to be delivered in 80 kg bags and to be ordered just in time. This results in an average of 40 kg which can be assumed to always be on stock.

8.3 SPARE PARTS ON DEMAND – A SIMULATION BASED DECISION MAKING FRAMEWORK

This thesis demonstrated a practical way to analyze the application of AM for spare part supply. The following points summarize the executed steps in a general way and present a proceeding for application.

1. Analyze the spare part stock
    a. Sort for specific process related parameters such as material, building volume or other specific properties, which prescribe a specific AM-process.
    b. Define the value of each spare part type per piece.
    c. Define the allowed time to manufacture for each spare part type.
    d. Define the penalty of each spare part time if not delivered in time.
    e. Based on the previous information create a general spare part set, representing the total stock including the total stock value. (In this thesis ABC-analysis showed a good approximation to the real stock – this is assumed to be typical for spare parts).
2. Analyze the AM process information:
    a. Process related — Building space volume, buiding speed, available material, energy consumption
    b. Cost related — Material price, machine purchase price, maintenance cost, operator cost, (depreciation time)
3. Set up and apply the simulation model
    a. Identify the parameter of interest. For example Total cost of AM, Total AM penalty, "AM parts out" and the queueing behavior deliver a good performance feedback.

b. Follow the procedure by Kelton et. al (2010) for the simulation study setup. Analyze the results and draw conclusions

Execution of experiments – It is important to set limits for evaluation of the experiments. We identify in this dissertation the most important limit as a so called "upper limit." An upper limit is defined by the "accepted penalty" which should not exceed a defined value. In this work the accepted penalty is defined in the base case and represents the penalty at the breakeven point of warehousing and AM cost. It is also possible to pre-specify an "accepted penalty" that represents the monetary penalty cost paid for not being able to deliver the spare parts on time. In practice, the accepted penalty may vary depending on specific cases at hand, but it should remain as an important input parameter in the decision making framework. The point at which a system works at its upper limit defines the best strategy or system performance in the specific setup. Different strategies or setups will have different upper limits. Therefore the upper limit can be used as reference point to compare several strategies or setups against each other.

Analyzing the results - will be different for each case, depending on the issue of interest. For example for the base case it was appropriate to compare the Total AM cost against the Total warehousing cost over the utilization of the system. During technical investigations, it was better to compare the different strategies by the Total AM cost. The next section introduces several factor of interest helping to analyze the system.

Figure 8-3 illustrates the described process.

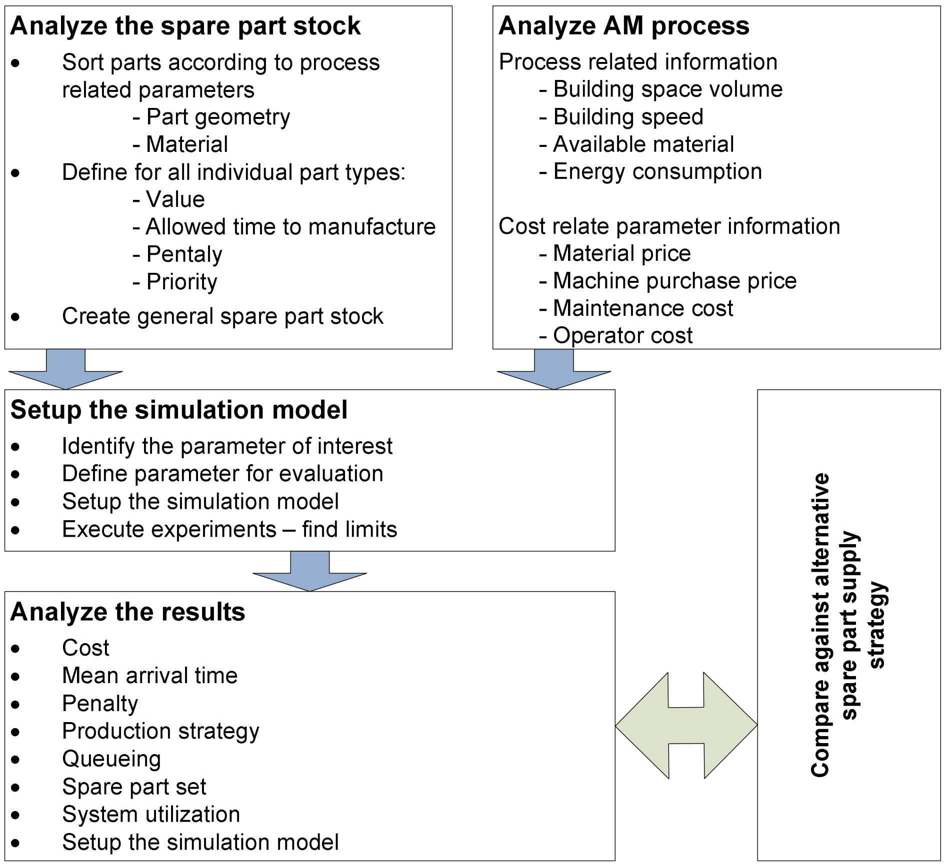


Figure 8-3: Spare parts on demand - a simulation based decision framework

8.4 FACTORS FOR EVALUATION

During simulation and analysis, the following factors are of major interest for the system performance:

Cost – Cost is the overall result of the simulation. It allows comparing different strategies to each other and a comparison of completely different concepts such as warehousing. One exception to this is that the cost of AM may only be a secondary factor in certain situations. For example on an air craft carrier storage space is very limited and therefore to be evaluated as extremely valuable. In consequence, only the parameters relating to system performance may be considered.

Mean arrival time – The mean arrival time between spare part requests is the direct input to the system and the most important control variable of the system. Additionally, the distribution type of the part arrivals is a factor, which can be considered here.

Penalty – Penalty is a cost driver and indicates the performance level of the system. Therefore, the accepted penalty, represented by the sum of charged penalties, is used to control the system. For spare part supply in particular, the penalty should be minimized to the accepted level, since a missing spare part might create unwanted or extended downtimes of facilities, machines or equipment.

Production strategy – The selected strategy is the key input for the overall service level of the entire system. It describes the setup of machines, for example two machines with a fixed material assignment operating in a waiting mode. Special care should be taken on this issue.

Queuing – Is a good indicator of system stress. When queuing occurs, manufacturing time increases rapidly and additive manufacturing is no longer an option for spare part supply due to increased penalties**.**

Spare parts set – The spare part size, the allowed time to manufacture and the actual mean arrival time of spare part requests may decide if a spare part set is interesting for the application. Knowledge about the spare part stock properties is the first important step for a good evaluation. Chapter 8.2.1 demonstrates an option to fit the spare part stock to the system properties and make AM work.

System utilization – Indicates at which level the system is able to operate in a stable state and how the system can be utilized with respect to the lower, upper and highest limit.

8.5 ADJUSTMENT OF DISTRIBUTION OF SPARE PARTS PROCUREMENT

Referring back to the model by Pérès and Noyes (2006) for illustrational reasons several things can be learned from the applied simulation:

1. In the “rapid spare part manufacturing” a “Time in queue” (h) should be considered before the actual production can start (This is an addition to the model by Pérès and Noyes (2006)). For a regular spare part production the waiting time in queue is essential for the success of a system. It should be the target to reach a waiting time in queue of zero for spare part on supply application. This will lead back to the original optimized assumption by Pérès and Noyes (2006).
2. To eliminate waiting time “Detection & diagnosis” (a) is a good starting point. The earlier the need for a spare part is known, the better the production run can be planned, since the allowed time to manufacture is extended by the prediction of failure. A well thought-out setup of maintenance strategies may help to reach this goal (preventive repairs, regular inspections or condition monitoring).

3. "Manufacturing" (f) provides further potential for improvement. It can be considered to apply postponement strategies (for example form, assembly or manufacturing postponement).

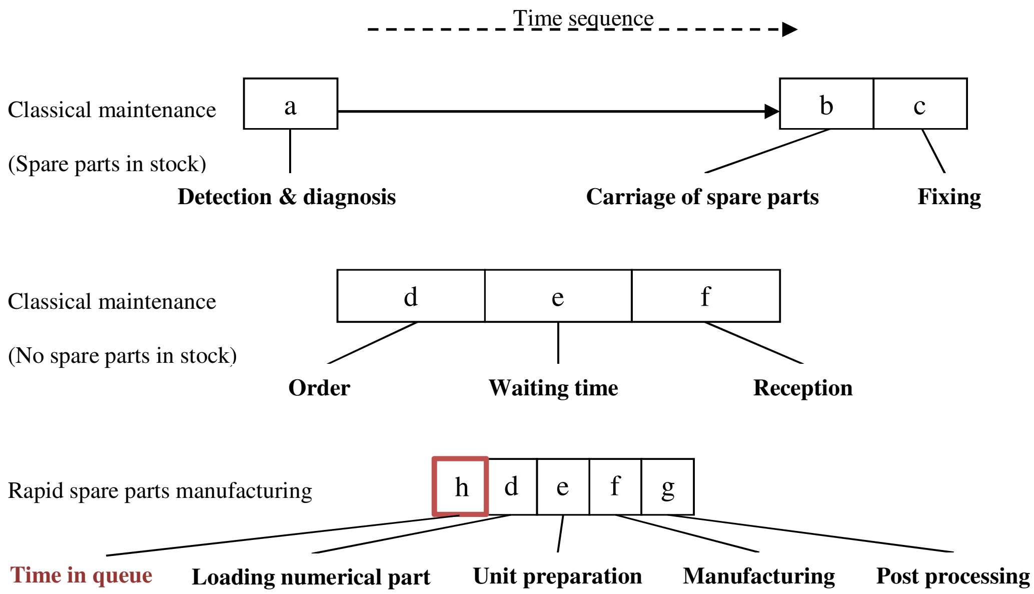


Figure 8-4. Comparison of time distribution for various strategies of spare parts procurement (Pérès & Noyes, 2006) – Waiting time added

9 CONCLUSION

This thesis analyzed some fundamental AM issues with respect to spare parts on demand. More importantly, it addresses the cost effective evaluation of using AM to make spare parts, compared to conventional warehousing, through the development of a simulation-based decision making framework. Although specific recommendations depend on particular scenarios where AM is an option, this thesis does offer some findings that are different from previously assumed deficits. In Chapter 2.2.2 several limitations were described. In respect to spare parts on demand the statements for AM process performance and cost can be modified.

AM process performance - It is stated that only a limited object size can be manufactured by AM. This can be an issue for regular production, but not for spare parts. It appears that the building space volume should be selected according to the biggest potential spare part since it will minimize the setup time. Therefore, in the spare part case, the performance of the system is not necessarily limited by the building space volume, but by the allowed time to manufacture. To meet the allowed time to manufacture, building speed, spare part size, system setup and cool down time are limiting, as already known, have potential to improve the process performance. Findings demonstrate that these parameters have a straightforward influence on the results. Further analysis of the available warehouse data did not show issues regarding part size. However, this needs to be evaluated individually for each spare part stock. For the presented simulation, the AM process performance was already performing equal to or better with the basic one machine solution than the actual warehouse, even without improving one of the process parameters.

Cost – It is expensive to buy and maintain an AM machine. The same is true for a warehouse or workshop. The machine purchase price is therefore not as relevant a decision variable as considered by for example Neef et al (2005) from a spare part perspective. Also the material price is not necessarily too high. A cheaper price of machine and material will attract more customers, but the simulation model shows that the simulated AM process can already perform better than a warehouse under the given set of conditions, both from a cost and a performance perspective.

While the AM process performance parameters and cost issues are already in focus, the production strategy is not. As the results show the applied strategy of how and how many AM-machines will react on arriving spare part request has the most important impact. The selected strategy moves the total AM cost and the system performance to different levels. For further research, it can be of interest to focus more on the influence of several production strategies. As can be seen in the spare part size variation simulation, there is a correlation between the properties of the spare part stock and the selected production strategy. Consequently, more research in the area of spare part stock properties may allow to create smarter production strategies for a more efficient utilization of the AM machine.

As an example for a smarter production strategy, it is considered that adding parts to a production run might be beneficial. Adding parts to a production run can also be combined with a good building space packing strategy for parts, which is also an independent production strategy. Referring back to the waiting mode, waiting makes sense for a limited number of part combinations under the given set of conditions only. This is because the allowed time to manufacture can be exceeded for one or all parts in production, due to the longer production time. This can be equivalent to the adding part setup. But as it was shown for the waiting strategy for smaller parts this strategy can be beneficial. Another interesting strategy can be a machine with two building space volumes in which one is preparing the next production run while production is running in the other (similar to a two machine setup, but maintenance cost can reduce to a one machine setup). Also multi-material application in one production run (similar to the base case) can be of interest. Creative investigations might lead to further concepts.

As mentioned before the spare part stock takes a key role. When the target is making AM take part in spare part supply, it is important to take the whole set of aspects into consideration. This thesis starts to look at the process performance of AM with the spare part request arrival. This is a good stopping point for this simulation approach, since in a real life application the first point of interest would be maintenance. Well-considered and executed maintenance strategies reduce the number of unplanned arriving spare part requests. This means production becomes more plannable which in turn improves the AM system performance in terms of a possibly higher machine utilization.

Also spare part supply strategies can contribute to improving the system performance. One interesting topic is the issue of postponement strategies, such as form or assembly postponement. Also combinations with other supply strategies can improve the situation. For example when typically 5 parts of one type are stored due to their availability this number can be reduced. One part is stored and a new one will be produced if it is consumed. This could increase the allowed time to manufacture to a much more comfortable level, since the allowed time to manufacture is the most critical part attribute since it defines when the penalty is due.

In comparison to a classical warehousing of spare parts, AM for spare parts on demand is more complex. Due to the required production, the knowledge of the required parts must be more detailed than it is necessary when the parts are already available on stock. This makes it difficult to apply AM in every situation.

Already now AM is an option to reduce spare part stocks in an efficient way. It must be evaluated on an individual basis if the efforts are worth it to gain the spare part information and sufficient production strategy is available.

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APPENDIX

1 INTRRODUCTION TO APPLIED ARENA SIMULATION MODULES

Arena is a fully hierarchical high level simulation software which allows the user to use predefined modules and constructs. When necessary, it is possible to break the programming down to a low level where alternative programming languages such as Microsoft Visual Basic, C or other alternatives can be applied, which allows individual setups of a model. The work done in this study will use Arena as modeling tool and tries to use the predefined modules to keep a high programming level and provide transparency for the reader. To have an idea about the concept and the functionality of Arena this section provides an overview about the concepts and functions of the software. For more detail, refer to literature, which holds detailed information.[14]

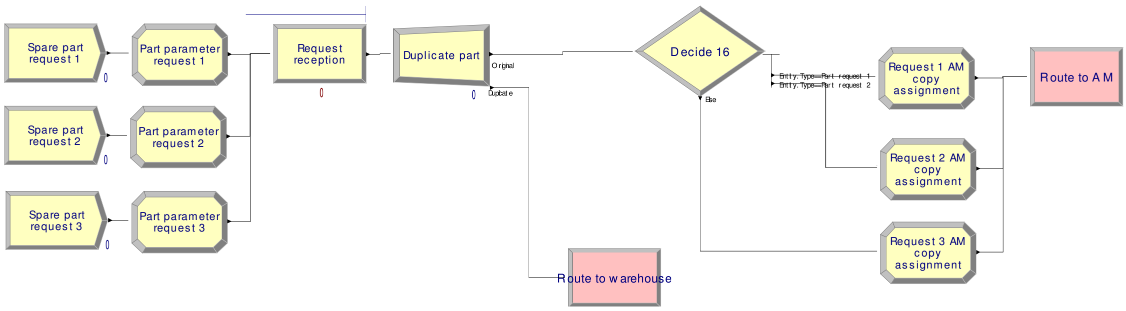

Figure 9-1: Graphical display of connected Arena modules

Figure 9-1 shows an extract of an Arena simulation model. It has great resemblance to a process flow chart and works very similarly. Entities, in this case spare part requests, are generated, enter the system, move through the process and leave the system when the process is finished. Arena allows to describe the way of an entity through a process in detail by use of attributes, variables, queues, resources and modules simulating logical actions. The following will introduce the most

[14] "Simulation with Arena" Kelton et al. (2010)

important Arena information to enable the reader to understand further explanations in the scope of this work. It will start with the basic modules.

Create module - The first thing which happens in a simulation model is the creation of an entity. In the create module the name and type of an entity is defined by the user. Also the time between arrivals and number of arrivals can be edited by changing the settings. Different types of entities can be created by several create modules in one simulation model.

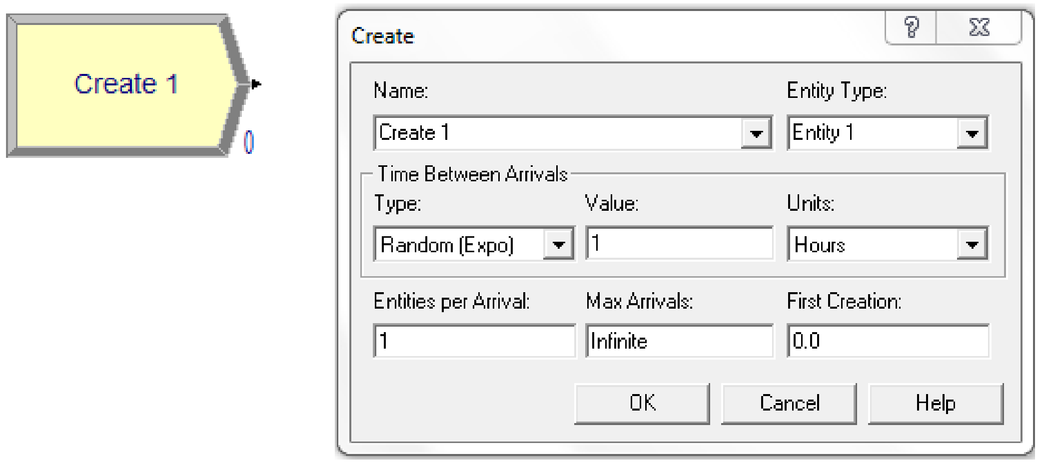

Figure 9-2: Create module

Assign module - The assign module allows to assign variables and attributes to an entity when it enters the module. It is also possible to change the entity type itself. The difference between variables and attributes must be explained. Both can be assigned to an entity and contain a specific value. A variable can be understood as a global variable that can be used or changed at every position in the model. An attribute is to understand as a local variable which is directly linked to an entity. While discussing variables it is important to know that there are two types of variables in Arena. The first type are user defined variables such as service time, building space, etc.. The other variables are Arena build-in variables which are automatically followed like number in queue, WIP, current simulation clock, etc.. According to Kelton et al (2010) variables can be used as trigger changing values over time and they can be useful to collect user defined statistics and metrics.

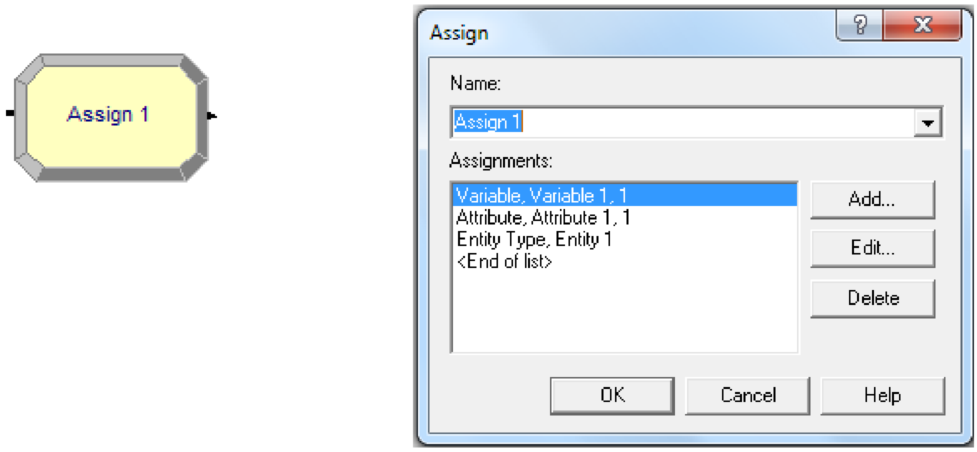

Figure 9-3: Assign module

Process module - The process module allows to simulate a process. In the following model the process module is typically used in the setting "Seize Delay Release". When an entity enters the module a resource is seized, for example a person, machine or something else that is required to perform the task. The time the process takes is defined by delay, which can be set in the module directly, and can follow various distributions or a mathematical expression. When the process is finished, the resource is released again and is available for the next process.

Due to the delay of processing it is logical that queuing occurs when the entities have to wait for processing. Therefore a symbol for the queue is shown above the process module, where the entities are displayed while waiting.

It is possible to set rules for the queue. The predefined rules are First in first out, Last in first out, Lowest attribute value and Highest attribute value. The preset for each queue is First in first out, which can be changed when required. Queues can also appear on other modules, for example the hold module.

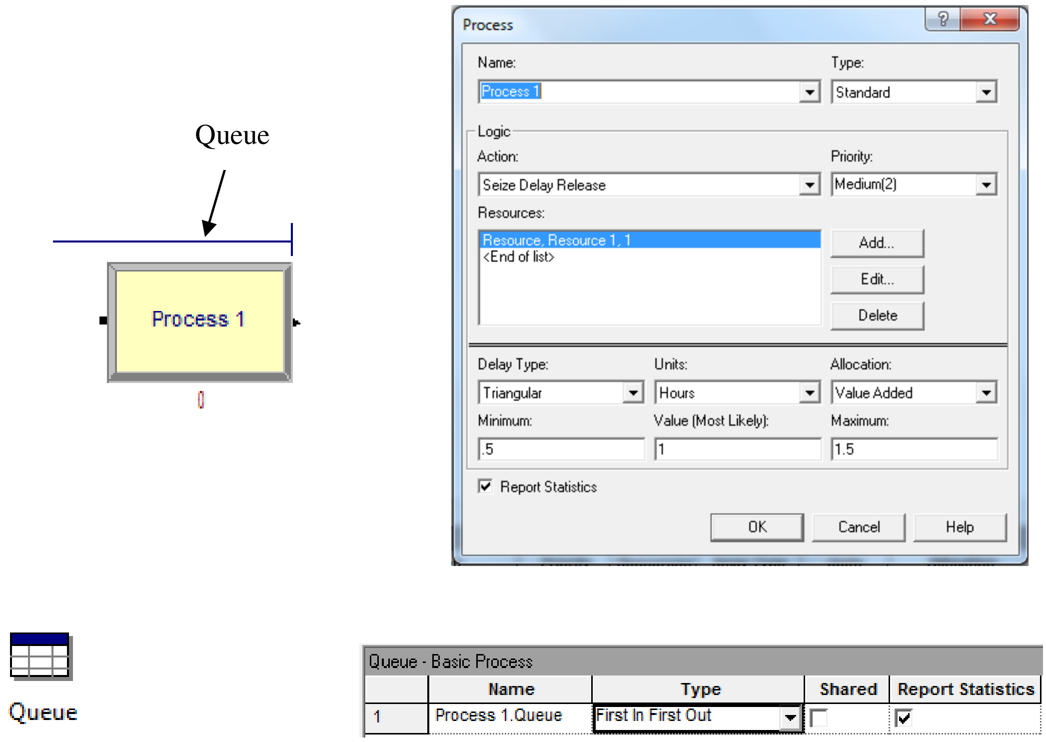

Figure 9-4: Process module and queue

Decide module - The decide module allows to direct entities by chance or condition to different paths through the process. For both, the decision can be 2-way or n-way.

The setup by chance follows assigned probabilities in percent. The proceeding is the same for n-ways. Figure 9-5 shows a fifty percent chance that the entity will follow the true path, as opposed to following the false path. The decide module is also very interesting in the condition based setup, since it can analyze variables or attributes of entities and direct the entity accordingly.

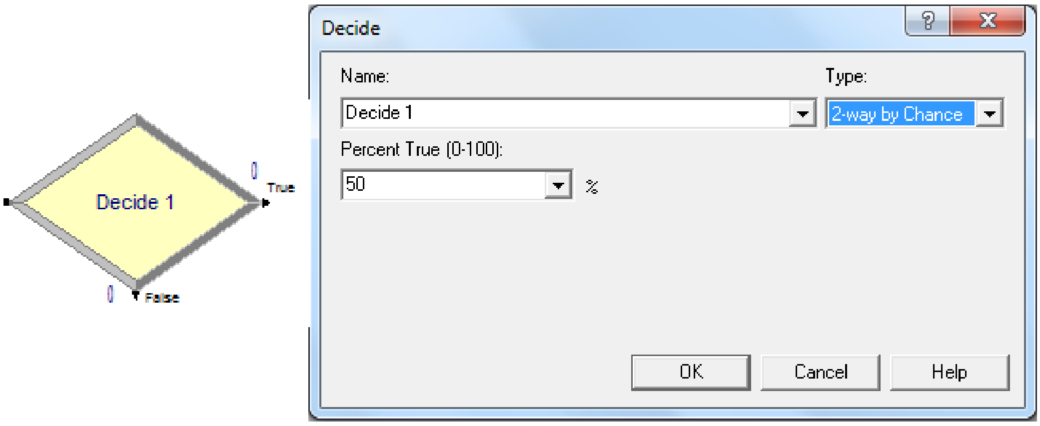

Figure 9-5: Decide module

Separate module - The separate module creates duplicates of entities or splits up arriving batches. The original entity will then follow the original path, while the duplicate will follow the duplicate path.

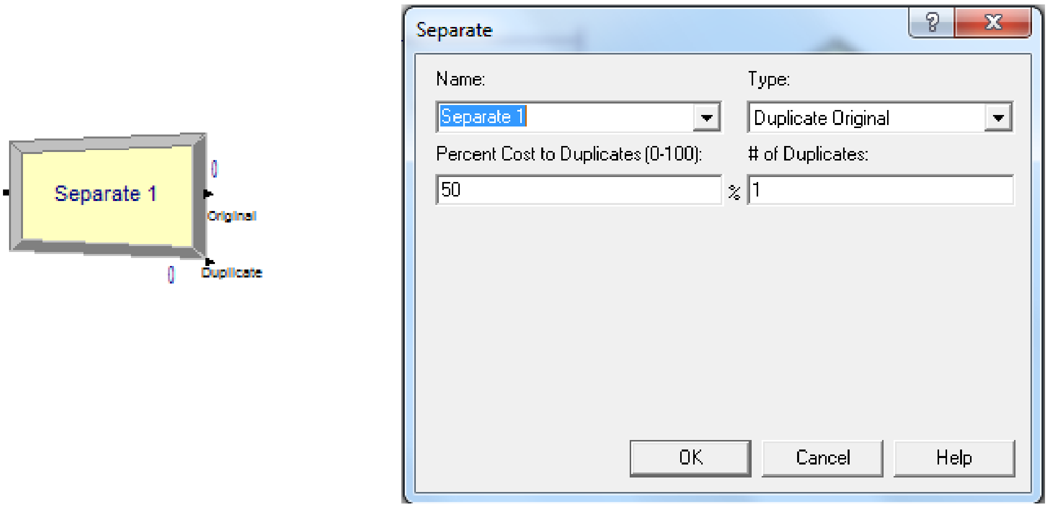

Figure 9-6: Separate module

Hold module - The hold module is able to hold entities in a queue until a specific condition or a signal occurs. Then the entities in queue can pass the hold module. The next arriving entities will then again be held until a condition or signal is set. When the setup is condition based, the module scans for example process or queue parameters like "number in queue equals zero". The signal setup waits for an arriving signal. When the signal occurs the hold module allows the entities to pass. A signal is generated by a signal module.

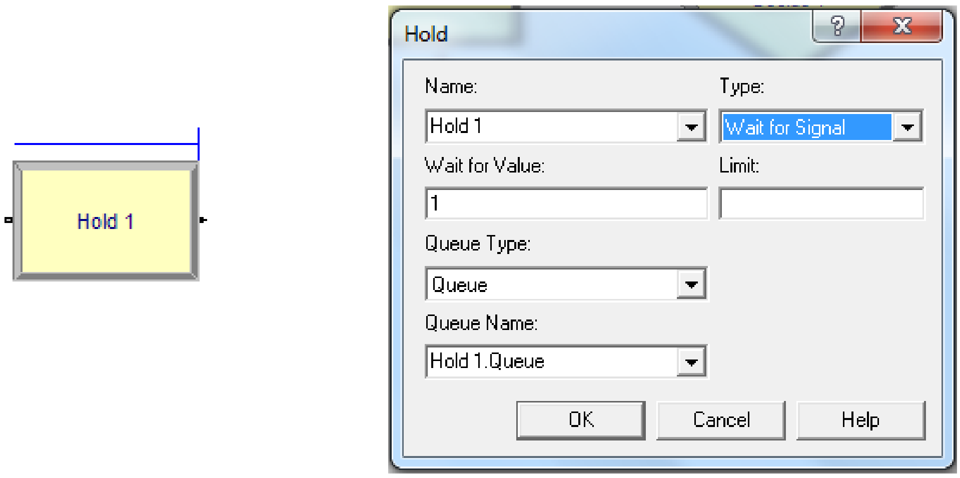

Figure 9-7: Hold module

Signal module - The signal module sends a signal to the whole model when an entity enters the module. In Figure 9-8 Signal 1 sends the value 1 as a signal. When for example a hold module, which waits for the signal 1, receives the signal, it will allow the queued entities to pass. The signal activates all modules which are waiting for signal 1.

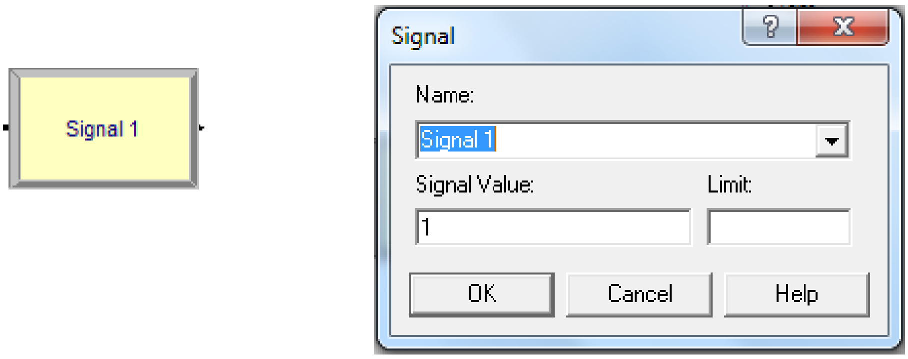

Figure 9-8: Signal module

Route and Station module - The route and station module typically appear together. The route module allows to send entities to a station without having the modules connected directly. This is beneficial when modules become complex and a direct connection is messing the view. It should be said that modules are always connected to each other, to guide the entity through the process. This can be avoided by the route and station idea. In Figure 9-9 the Route 1 module will send an entity to Station 1.

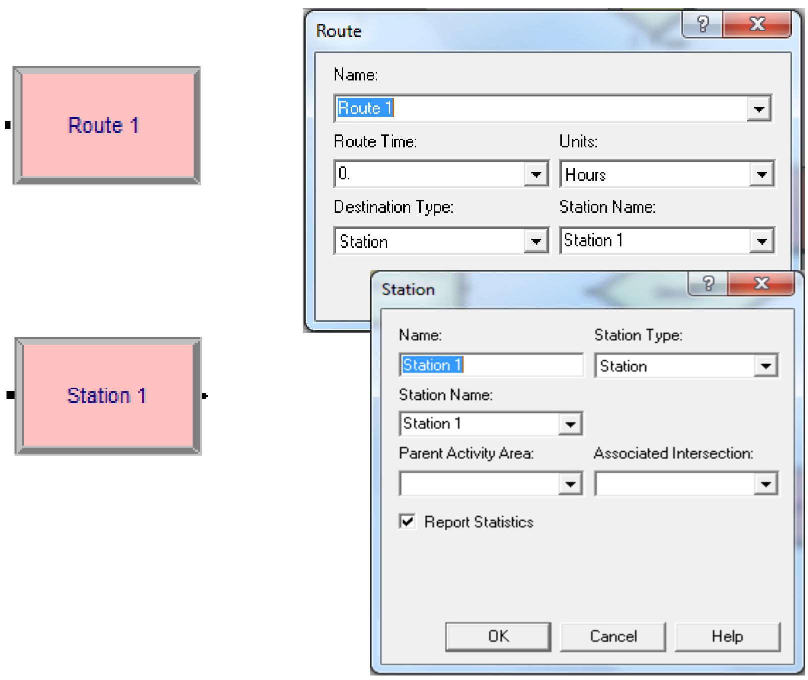

Figure 9-9: Route and Station module

Dispose module - Every created entity must leave the system. This happens by use of the dispose module. When an entity enters the module it is removed from the system.

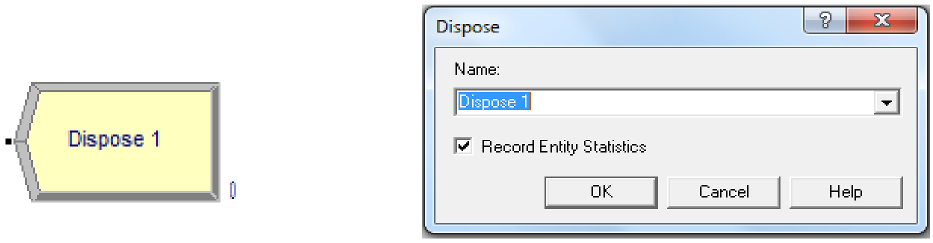

Figure 9-10: Dispose module

Data modules - Data modules are not placed in the model window and no entity will run through them. The data modules contain additional information to queues, entities etc. and allow to describe details on a lower level. The data modules are organized as lists and can be edited by the user. They allow direct access to objects, variables and attributes.

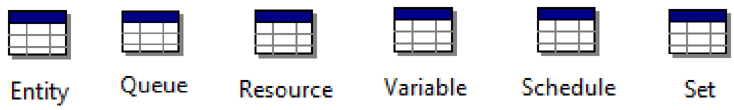

Figure 9-11: Data modules

By arranging the explained modules and data modules, it is possible to set up a simulation model. When the model is ready the simulation can start. But before the model can run the "run setup" should take place. Arena offers a context menu to set the replication parameters. The most important settings are the number of replications, warm up period, replication length. and the time units. Number of replications is important for statistical reasons. The more replications of the simulation are run, the more accurate will be the result. (For each replication a new set of random numbers is selected, which is the basis for the setup of the event calendar and generates randomized results.) A useful number of replication will be defined later. A warm up period is to apply when a system needs to be followed under continuous conditions. When an empty system begins to operate, processes and queues are all idle. The warm up period should be set until the system is in "balance". This assures a better accuracy of the results without the effect of an idle system. The replication length defines the time frame the system will actually simulate and record statistics. The base time unit is also an important setting which should be carefully followed throughout the whole model. Mistakes with this unit may lead to significant errors. After the run setup the model can run.

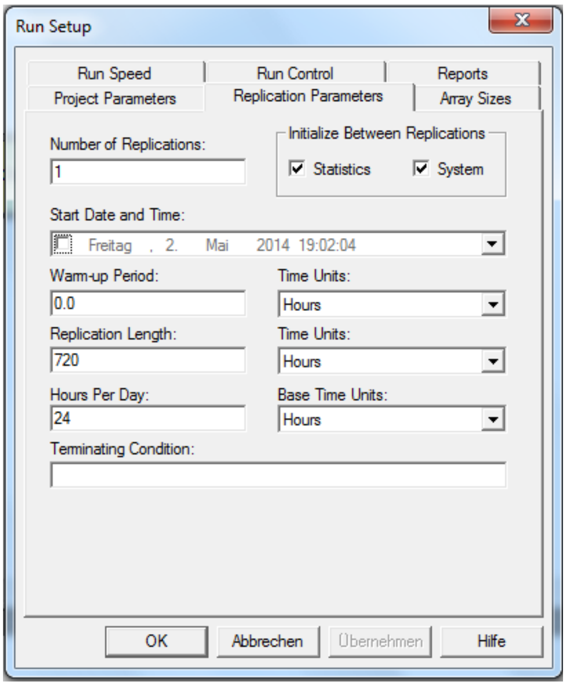

Figure 9-12: Run setup

When the model starts to run it is important to be aware of the simulation clock and event calendar, which interact together. The simulation clock is a variable keeping track of time during simulation. Since Arena is an event driven simulation keeping track of time means keeping track of events happening at times planned in the event calendar. This is due to the fact that between events nothing happens, so there is no need to follow this time.

Event is a key word in Arena. "An event is something that happens at an instant of (simulated) time that might change attributes, variables, or statistical accumulators." (Kelton et al, 2010). These events are planned in an event calendar to keep track of the simulation. Kelton et al describe the idea: "When the logic of the simulation calls for it, a record of information for a future event is placed on the event calendar. This event record contains identification of the entity involved, the event time, and the kind of event it will be. Arena places each newly scheduled event on the calendar so that the next (soonest) event is always at the top of the calendar. [...] When it is time to execute the next event, the top record is removed from the calendar and the information in this record used to execute the appropriate logic" (Kelton et al, 2010).

With this basic information it should be possible to follow the setup of the simulation model presented in this work.

.

2 RESULTS OF ADDITIVE STRATEGY INVESTIGATIONS

2.1 RESULTS OF TWO MACHINES WITH FIXED MATERIAL

Table 9-1: Results of two machines with fixed material - Upper limit - No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs		%	hrs	€	kg	kWh	€	€	€	€	€	€
Upper limit 1.1	0	150	4	8	12	0,10	8	69.652	170	43.315	13.601	2.598	2.891	57.506	83	95.849
Upper limit 1.2	0	140	4	8	12	0,10	8	70.277	179	45.693	14.347	2.741	3.094	57.752	83	97.270
Upper limit 1.3	0	130	4	8	12	0,10	8	70.873	193	49.251	15.465	2.955	3.332	57.745	166	98.913
Upper limit 1.4	0	120	4	8	12	0,10	8	71.634	213	54.274	17.042	3.256	3.615	58.103	333	101.718
Upper limit 1.5	0	110	4	8	12	0,10	8	72.555	233	59.431	18.661	3.565	3.933	57.968	541	103.993
Upper limit 1.6	0	100	4	8	12	0,10	8	73.843	258	65.945	20.706	3.956	4.327	58.064	1.000	107.410
Upper limit 1.7	0	90	4	8	12	0,10	8	75.146	289	73.701	23.142	4.422	4.812	58.180	1.500	111.450
Upper limit 1.8	0	80	4	8	12	0,10	8	76.042	321	81.875	25.708	4.912	5.404	58.340	2.208	116.021
Upper limit 1.9	0	70	4	8	12	0,10	8	78.610	377	96.298	30.237	5.777	6.173	58.427	3.958	124.050
Upper limit 1.10	0	60	4	8	12	0,10	8	81.403	433	110.396	34.664	6.623	7.206	58.573	5.041	131.635
Upper limit 1.11	0	50	4	8	12	0,10	8	84.866	519	132.435	41.584	7.946	8.635	58.636	13.041	149.389
Upper limit 1.12	0	40	4	8	12	0,10	8	90.625	635	161.905	50.838	9.714	10.753	58.675	25.583	175.122
Upper limit 1.13	0	30	4	8	12	0,10	8	100.013	883	225.074	70.673	13.504	14.348	58.827	69.375	246.337
Upper limit 1.14	0	20	4	8	12	0,10	8	117.856	1.313	334.693	105.093	20.081	21.470	58.907	257.125	482.313
Upper limit 1.15	0	10	4	8	12	0,10	8	174.351	2.484	632.895	198.729	37.973	40.336	57.811	2.107.500	2.461.622

Name	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.	mm³	€	pcs.	pcs.
Upper limit 1.1	2,82	5,74	2,74	2,86	5,98	2,77	2,84	5,86	2,76	11,46	---	0,001	---	0,001	374.601	58.784	1	58
Upper limit 1.2	3,01	5,99	2,92	3,05	6,33	2,95	3,03	6,16	2,94	12,13	---	0,001	---	0,001	369.158	59.036	1	62
Upper limit 1.3	3,25	6,43	3,14	3,29	6,85	3,18	3,27	6,64	3,16	13,07	---	0,002	---	0,002	369.511	59.028	1	67
Upper limit 1.4	3,52	7,16	3,41	3,52	7,38	3,41	3,52	7,27	3,41	14,20	---	0,003	---	0,003	374.322	59.394	1	72
Upper limit 1.5	3,86	7,85	3,74	3,82	8,11	3,70	3,84	7,98	3,72	15,54	---	0,004	---	0,005	376.865	59.256	2	79
Upper limit 1.6	4,27	8,80	4,13	4,17	8,88	4,04	4,22	8,84	4,08	17,14	---	0,005	---	0,006	380.669	59.355	2	87
Upper limit 1.7	4,69	9,68	4,54	4,67	10,05	4,52	4,68	9,86	4,53	19,07	---	0,008	---	0,008	381.689	59.473	2	96
Upper limit 1.8	5,17	10,73	5,01	5,27	11,13	5,10	5,22	10,93	5,05	21,20	43	0,010	38	0,013	378.145	59.637	4	108
Upper limit 1.9	5,87	13,07	5,68	5,95	12,59	5,76	5,91	12,83	5,72	24,46	39	0,018	36	0,015	389.874	59.725	7	123
Upper limit 1.10	6,85	14,36	6,63	6,92	14,99	6,70	6,88	14,67	6,67	28,22	30	0,024	30	0,030	382.907	59.875	15	144
Upper limit 1.11	8,07	17,08	7,82	8,25	18,08	7,99	8,16	17,58	7,90	33,64	30	0,045	32	0,055	384.530	59.939	27	173
Upper limit 1.12	9,92	21,20	9,60	10,05	21,76	9,73	9,98	21,48	9,67	41,12	35	0,087	37	0,097	375.995	59.979	43	215
Upper limit 1.13	12,31	29,15	11,92	12,35	30,41	11,95	12,33	29,78	11,93	54,04	38	0,207	38	0,224	392.026	60.134	96	287
Upper limit 1.14	15,25	42,40	14,76	15,09	46,05	14,60	15,17	44,23	14,68	74,08	37	0,594	39	0,690	389.408	60.216	285	429
Upper limit 1.15	6,58	85,18	6,32	6,58	85,31	6,34	6,58	85,24	6,33	98,15	147	7,300	152	7,731	393.417	59.096	832	807

Table 9-2: Results of two machines with fixed material - Upper limit - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs		%	hrs	€	kg	kWh	€	€	€	€	€	€
Upper limit 2.1	1	150	4	8	12	0,10	8	69.601	168	43.037	13.513	2.582	2.888	57.504	83	95.740
Upper limit 2.2	1	140	4	8	12	0,10	8	70.291	179	45.724	14.357	2.743	3.092	57.774	125	97.350
Upper limit 2.3	1	130	4	8	12	0,10	8	70.873	193	49.208	15.451	2.952	3.329	57.705	333	99.006
Upper limit 2.4	1	120	4	8	12	0,10	8	71.635	213	54.304	17.051	3.258	3.615	58.156	375	101.841
Upper limit 2.5	1	110	4	8	12	0,10	8	72.555	232	59.226	18.597	3.553	3.929	57.975	666	104.047
Upper limit 2.6	1	100	4	8	12	0,10	8	73.831	260	66.387	20.845	3.983	4.326	58.106	1.000	107.631
Upper limit 2.7	1	90	4	8	12	0,10	8	75.193	287	73.134	22.964	4.388	4.806	58.227	1.583	111.379
Upper limit 2.8	1	80	4	8	12	0,10	8	76.578	331	84.414	26.506	5.064	5.402	58.335	2.833	117.586
Upper limit 2.9	1	70	4	8	12	0,10	8	78.402	368	93.907	29.487	5.634	6.172	58.396	3.666	122.822
Upper limit 2.10	1	60	4	8	12	0,10	8	80.856	442	112.688	35.384	6.761	7.183	58.502	8.291	135.623
Upper limit 2.11	1	50	4	8	12	0,10	8	85.257	523	133.250	41.840	7.995	8.642	58.586	16.458	153.051
Upper limit 2.12	1	40	4	8	12	0,10	8	90.594	656	167.288	52.528	10.037	10.775	58.730	33.458	185.107
Upper limit 2.13	1	30	4	8	12	0,10	8	100.068	879	224.105	70.368	13.446	14.340	58.791	74.166	250.711
Upper limit 2.14	1	20	4	8	12	0,10	8	117.891	1.313	334.720	105.102	20.083	21.489	58.825	283.833	508.942
Upper limit 2.15	1	10	4	8	12	0,10	8	---	---	---	---	---	---	---	---	---

Name	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.	mm³	€	pcs.	pcs.
Upper limit 2.1	2,83	5,71	2,74	2,86	5,94	2,77	2,84	5,83	2,75	11,42	---	0,001	---	0,001	372.155	58.782	1	58
Upper limit 2.2	3,02	6,01	2,92	3,04	6,31	2,94	3,03	6,16	2,93	12,12	---	0,001	---	0,002	369.663	59.058	1	62
Upper limit 2.3	3,24	6,43	3,14	3,29	6,85	3,19	3,26	6,64	3,16	13,07	---	0,002	---	0,003	369.507	58.987	1	67
Upper limit 2.4	3,52	7,16	3,41	3,52	7,37	3,40	3,52	7,27	3,41	14,19	---	0,003	---	0,004	374.508	59.448	1	72
Upper limit 2.5	3,87	7,84	3,75	3,80	8,07	3,68	3,83	7,95	3,71	15,50	---	0,004	---	0,005	376.204	59.264	2	79
Upper limit 2.6	4,27	8,91	4,14	4,15	8,88	4,02	4,21	8,90	4,08	17,18	---	0,006	---	0,007	383.505	59.397	2	87
Upper limit 2.7	4,67	9,64	4,53	4,66	9,91	4,51	4,67	9,78	4,52	18,96	39	0,008	40	0,009	379.094	59.521	3	96
Upper limit 2.8	5,13	11,06	4,97	5,29	11,47	5,12	5,21	11,27	5,04	21,52	34	0,011	35	0,013	390.463	59.631	5	108
Upper limit 2.9	6,02	12,57	5,83	5,84	12,46	5,65	5,93	12,52	5,74	24,19	25	0,015	28	0,018	380.333	59.694	10	123
Upper limit 2.10	6,85	14,41	6,63	6,89	15,57	6,67	6,87	14,99	6,65	28,51	28	0,029	29	0,038	391.798	59.802	19	144
Upper limit 2.11	8,05	17,18	7,80	8,22	18,23	7,96	8,14	17,70	7,88	33,72	34	0,057	35	0,066	385.031	59.888	30	173
Upper limit 2.12	9,73	21,81	9,42	9,97	22,53	9,65	9,85	22,17	9,54	41,55	35	0,105	39	0,125	388.179	60.035	52	216
Upper limit 2.13	12,31	29,79	11,92	12,19	29,54	11,80	12,25	29,67	11,86	53,77	31	0,238	32	0,237	391.046	60.098	127	287
Upper limit 2.14	14,70	43,78	14,22	14,62	44,80	14,15	14,66	44,29	14,18	73,13	38	0,710	38	0,725	389.230	60.133	317	430
Upper limit 2.15	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

Table 9-3: Results of two machines with fixed material - Preheat and cool down - No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs		%	hrs	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.	mm³	€	pcs.	pcs.
0-Preheat-Cooldown 1.1	0	130	12	24	36	0,10	8	70.958	192	49.156	15.435	2.949	3.320	57.698	17.541	116.177	6,40	6,44	9,45	6,42	6,83	9,48	6,41	6,63	9,47	22,51	---	0,003	---	0,004	369.616	58.980	1	66
0-Preheat-Cooldown 1.2	0	130	11	22	33	0,10	8	70.932	193	49.254	15.466	2.955	3.320	57.690	17.666	116.329	6,00	6,45	8,64	6,04	6,84	8,72	6,02	6,65	8,68	21,35	---	0,003	---	0,004	370.158	58.972	1	66
0-Preheat-Cooldown 1.3	0	130	10	20	30	0,10	8	70.915	193	49.354	15.497	2.961	3.323	57.689	17.791	116.492	5,60	6,45	7,85	5,66	6,88	7,94	5,63	6,66	7,90	20,19	---	0,003	---	0,004	371.097	58.971	1	66
0-Preheat-Cooldown 1.4	0	130	9	18	27	0,10	8	70.891	193	49.386	15.507	2.963	3.325	57.694	17.666	116.388	5,20	6,43	7,06	5,27	6,90	7,16	5,24	6,67	7,11	19,02	---	0,003	---	0,003	370.908	58.976	1	67
0-Preheat-Cooldown 1.5	0	130	8	16	24	0,10	8	70.873	192	49.103	15.418	2.946	3.327	57.710	12.750	111.389	4,81	6,43	6,28	4,88	6,83	6,37	4,84	6,63	6,32	17,79	---	0,002	---	0,003	368.927	58.993	1	67
0-Preheat-Cooldown 1.6	0	130	7	14	21	0,10	8	70.873	192	49.106	15.419	2.946	3.328	57.704	3.041	101.675	4,42	6,43	5,49	4,48	6,83	5,57	4,45	6,63	5,53	16,61	---	0,002	---	0,003	368.890	58.986	1	67
0-Preheat-Cooldown 1.7	0	130	6	12	18	0,10	8	70.873	193	49.245	15.462	2.954	3.330	57.734	333	99.061	4,03	6,43	4,71	4,08	6,86	4,78	4,06	6,64	4,74	15,44	---	0,002	---	0,002	369.636	59.017	1	67
0-Preheat-Cooldown 1.8	0	130	5	10	15	0,10	8	70.873	193	49.245	15.462	2.954	3.330	57.713	291	98.991	3,64	6,43	3,93	3,69	6,86	3,98	3,66	6,65	3,96	14,26	---	0,002	---	0,002	369.636	58.995	1	67
0-Preheat-Cooldown 1.9	0	130	4	8	12	0,10	8	70.873	193	49.251	15.465	2.955	3.332	57.745	166	98.913	3,25	6,43	3,14	3,29	6,85	3,18	3,27	6,64	3,16	13,07	---	0,002	---	0,002	369.511	59.028	1	67
0-Preheat-Cooldown 1.10	0	130	3	6	9	0,10	8	70.840	194	49.428	15.520	2.965	3.335	57.769	166	99.013	2,86	6,42	2,36	2,89	6,91	2,39	2,87	6,66	2,37	11,91	---	0,002	---	0,002	370.283	59.053	1	67
0-Preheat-Cooldown 1.11	0	130	2	4	6	0,10	8	70.845	195	49.871	15.659	2.992	3.336	57.762	125	99.130	2,46	6,45	1,57	2,49	7,00	1,59	2,48	6,72	1,58	10,78	---	0,001	---	0,002	373.226	59.046	1	67
0-Preheat-Cooldown 1.12	0	130	1	2	3	0,10	8	70.877	194	49.453	15.528	2.967	3.335	57.768	83	98.939	2,07	6,46	0,79	2,09	6,88	0,80	2,08	6,67	0,79	9,54	---	0,001	---	0,001	370.328	59.052	1	67
0-Preheat-Cooldown 2.1	0	60	12	24	36	0,10	8	81.262	432	110.093	34.569	6.605	7.171	58.570	56.458	182.898	13,34	14,61	19,69	13,42	14,66	19,81	13,38	14,63	19,75	47,76	36	0,065	35	0,061	384.320	59.871	30	143
0-Preheat-Cooldown 2.2	0	60	11	22	33	0,10	8	81.282	430	109.716	34.450	6.582	7.171	58.567	52.000	178.295	12,59	14,54	18,15	12,53	14,62	18,06	12,56	14,58	18,11	45,25	35	0,056	36	0,057	382.398	59.868	27	143
0-Preheat-Cooldown 2.3	0	60	10	20	30	0,10	8	81.219	427	108.795	34.161	6.527	7.177	58.521	47.458	173.354	11,74	14,28	16,46	11,80	14,67	16,55	11,77	14,47	16,51	42,75	36	0,051	33	0,052	378.831	59.822	25	144
0-Preheat-Cooldown 2.4	0	60	9	18	27	0,10	8	80.833	424	108.262	33.994	6.495	7.175	58.518	47.375	173.065	10,79	14,07	14,65	11,15	14,74	15,13	10,97	14,40	14,89	40,27	34	0,046	33	0,047	377.154	59.818	24	144
0-Preheat-Cooldown 2.5	0	60	8	16	24	0,10	8	81.175	431	109.960	34.527	6.597	7.182	58.528	37.625	163.971	10,00	14,28	13,05	10,30	14,96	13,44	10,15	14,62	13,25	38,02	32	0,040	31	0,043	382.323	59.829	22	144
0-Preheat-Cooldown 2.6	0	60	7	14	21	0,10	8	81.101	425	108.337	34.017	6.500	7.189	58.575	17.291	143.099	9,18	13,85	11,41	9,51	14,94	11,81	9,34	14,39	11,61	35,34	30	0,033	30	0,039	376.987	59.877	20	144
0-Preheat-Cooldown 2.7	0	60	6	12	18	0,10	8	81.290	439	111.976	35.160	6.718	7.195	58.514	11.708	138.801	8,43	14,50	9,86	8,60	15,30	10,06	8,51	14,90	9,96	33,37	31	0,036	30	0,037	389.392	59.814	19	144
0-Preheat-Cooldown 2.8	0	60	5	10	15	0,10	8	80.946	434	110.611	34.732	6.636	7.201	58.553	7.750	134.391	7,67	14,65	8,29	7,74	14,76	8,36	7,71	14,71	8,32	30,73	31	0,032	27	0,031	384.200	59.854	17	144
0-Preheat-Cooldown 2.9	0	60	4	8	12	0,10	8	81.403	433	110.396	34.664	6.623	7.206	58.573	5.041	131.635	6,85	14,36	6,63	6,92	14,99	6,70	6,88	14,67	6,67	28,22	30	0,024	30	0,030	382.907	59.875	15	144
0-Preheat-Cooldown 2.10	0	60	3	6	9	0,10	8	81.203	438	111.721	35.080	6.703	7.201	58.478	4.333	131.289	6,06	14,79	5,01	6,05	14,95	5,00	6,06	14,87	5,01	25,93	31	0,025	33	0,025	387.570	59.777	12	144
0-Preheat-Cooldown 2.11	0	60	2	4	6	0,10	8	81.290	434	110.809	34.794	6.648	7.194	58.466	4.000	130.592	5,18	14,76	3,31	5,26	14,74	3,36	5,22	14,75	3,33	23,31	34	0,022	32	0,022	385.319	59.765	11	144
0-Preheat-Cooldown 2.12	0	60	1	2	3	0,10	8	81.069	442	112.771	35.410	6.766	7.216	58.500	4.458	131.852	4,34	14,72	1,65	4,44	15,29	1,69	4,39	15,00	1,67	21,06	39	0,022	36	0,022	390.728	59.800	9	144
0-Preheat-Cooldown 3.1	0	20	12	24	36	0,10	8	118.133	1.288	328.297	103.085	19.697	21.249	58.778	609.583	831.986	19,77	43,08	29,13	19,54	43,86	28,79	19,66	43,47	28,96	92,09	53	1,220	55	1,276	386.274	60.084	393	425
0-Preheat-Cooldown 3.2	0	20	11	22	33	0,10	8	118.378	1.290	328.868	103.264	19.732	21.280	58.801	560.125	782.804	19,31	44,35	27,79	19,85	42,73	28,57	19,58	43,54	28,18	91,30	53	1,216	50	1,122	386.353	60.108	387	426
0-Preheat-Cooldown 3.3	0	20	10	20	30	0,10	8	118.017	1.307	333.231	104.634	19.993	21.335	58.853	536.458	760.893	18,94	44,31	26,52	19,13	43,83	26,79	19,04	44,07	26,66	89,76	51	1,138	49	1,096	390.392	60.161	380	427
0-Preheat-Cooldown 3.4	0	20	9	18	27	0,10	8	118.326	1.278	325.759	102.288	19.545	21.299	58.797	466.333	687.863	18,95	43,14	25,69	18,93	43,11	25,66	18,94	43,12	25,67	87,74	47	1,026	47	0,999	382.641	60.104	368	426
0-Preheat-Cooldown 3.5	0	20	8	16	24	0,10	8	117.869	1.319	336.295	105.596	20.177	21.307	58.850	442.666	668.215	18,01	44,80	23,48	18,40	44,16	23,98	18,21	44,48	23,73	86,42	48	1,006	45	0,942	394.896	60.158	360	426
0-Preheat-Cooldown 3.6	0	20	7	14	21	0,10	8	117.343	1.308	333.386	104.683	20.003	21.413	58.845	395.250	619.810	17,79	43,82	22,10	17,72	44,37	22,00	17,76	44,10	22,05	83,90	44	0,900	43	0,885	389.324	60.152	348	428
0-Preheat-Cooldown 3.7	0	20	6	12	18	0,10	8	118.404	1.281	326.503	102.522	19.590	21.416	58.880	343.375	565.411	17,40	42,66	20,33	17,21	43,66	20,10	17,30	43,16	20,22	80,68	40	0,769	41	0,803	381.254	60.188	331	428
0-Preheat-Cooldown 3.8	0	20	5	10	15	0,10	8	119.268	1.286	327.804	102.930	19.668	21.470	58.860	280.583	503.133	16,56	43,43	17,86	16,55	43,27	17,85	16,56	43,35	17,86	77,76	38	0,690	37	0,678	381.805	60.168	310	429
0-Preheat-Cooldown 3.9	0	20	4	8	12	0,10	8	117.856	1.313	334.693	105.093	20.081	21.470	58.907	257.125	482.313	15,25	42,40	14,76	15,09	46,05	14,60	15,17	44,23	14,68	74,08	37	0,594	39	0,690	389.408	60.216	285	429
0-Preheat-Cooldown 3.10	0	20	3	6	9	0,10	8	118.240	1.285	327.438	102.815	19.646	21.496	58.862	199.708	422.150	14,10	42,73	11,65	13,95	43,86	11,52	14,02	43,30	11,58	68,90	37	0,515	38	0,552	380.614	60.170	241	430
0-Preheat-Cooldown 3.11	0	20	2	4	6	0,10	8	118.861	1.309	333.533	104.729	20.012	21.543	58.893	182.958	407.768	12,27	44,23	7,83	12,32	43,93	7,87	12,30	44,08	7,85	64,22	41	0,511	42	0,532	387.065	60.202	213	431
0-Preheat-Cooldown 3.12	0	20	1	2	3	0,10	8	118.647	1.304	332.359	104.361	19.941	21.526	58.949	157.250	381.678	10,54	44,38	4,00	10,62	43,38	4,04	10,58	43,88	4,02	58,48	42	0,468	40	0,435	385.849	60.259	186	431

Table 9-4: Results of two machines with fixed material - Preheat and cool down - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs		%	hrs	€	kg	kWh	€	€	€	€	€	€
1-Preheat-Cooldown 1.1	1	130	12	24	36	0,10	8	70.967	193	49.380	15.505	2.962	3.320	57.743	21.208	119.987
1-Preheat-Cooldown 1.2	1	130	11	22	33	0,10	8	70.958	192	49.123	15.424	2.947	3.320	57.714	21.041	119.686
1-Preheat-Cooldown 1.3	1	130	10	20	30	0,10	8	70.914	193	49.284	15.475	2.957	3.320	57.718	19.000	117.711
1-Preheat-Cooldown 1.4	1	130	9	18	27	0,10	8	70.914	193	49.284	15.475	2.957	3.320	57.697	17.666	116.350
1-Preheat-Cooldown 1.5	1	130	8	16	24	0,10	8	70.858	193	49.262	15.468	2.955	3.323	57.688	14.791	113.457
1-Preheat-Cooldown 1.6	1	130	7	14	21	0,10	8	70.876	192	49.097	15.416	2.945	3.325	57.714	13.416	112.057
1-Preheat-Cooldown 1.7	1	130	6	12	18	0,10	8	70.873	192	49.100	15.417	2.946	3.326	57.700	13.375	111.999
1-Preheat-Cooldown 1.8	1	130	5	10	15	0,10	8	70.873	193	49.205	15.450	2.952	3.328	57.711	9.958	108.638
1-Preheat-Cooldown 1.9	1	130	4	8	12	0,10	8	70.873	193	49.208	15.451	2.952	3.329	57.705	333	99.006
1-Preheat-Cooldown 1.10	1	130	3	6	9	0,10	8	70.833	193	49.313	15.484	2.958	3.330	57.731	208	98.958
1-Preheat-Cooldown 1.11	1	130	2	4	6	0,10	8	70.836	193	49.286	15.475	2.957	3.331	57.758	166	98.943
1-Preheat-Cooldown 1.12	1	130	1	2	3	0,10	8	70.826	193	49.346	15.494	2.960	3.331	57.743	125	98.904
1-Preheat-Cooldown 2.1	1	60	12	24	36	0,10	8	80.873	429	109.366	34.341	6.561	7.175	58.511	64.458	190.552
1-Preheat-Cooldown 2.2	1	60	11	22	33	0,10	8	80.902	448	114.241	35.871	6.854	7.175	58.495	64.041	191.936
1-Preheat-Cooldown 2.3	1	60	10	20	30	0,10	8	81.761	436	111.173	34.908	6.670	7.196	58.524	54.125	180.932
1-Preheat-Cooldown 2.4	1	60	9	18	27	0,10	8	81.483	425	108.386	34.033	6.503	7.166	58.545	46.916	172.680
1-Preheat-Cooldown 2.5	1	60	8	16	24	0,10	8	80.852	431	109.913	34.512	6.594	7.178	58.506	45.000	171.294
1-Preheat-Cooldown 2.6	1	60	7	14	21	0,10	8	80.739	433	110.489	34.693	6.629	7.173	58.548	37.541	164.102
1-Preheat-Cooldown 2.7	1	60	6	12	18	0,10	8	81.035	446	113.797	35.732	6.827	7.179	58.537	38.750	166.539
1-Preheat-Cooldown 2.8	1	60	5	10	15	0,10	8	80.982	436	111.129	34.894	6.667	7.181	58.501	28.125	154.870
1-Preheat-Cooldown 2.9	1	60	4	8	12	0,10	8	80.856	442	112.688	35.384	6.761	7.183	58.502	8.291	135.623
1-Preheat-Cooldown 2.10	1	60	3	6	9	0,10	8	80.924	427	108.955	34.212	6.537	7.196	58.522	5.708	131.684
1-Preheat-Cooldown 2.11	1	60	2	4	6	0,10	8	81.313	433	110.443	34.679	6.626	7.211	58.545	4.333	130.911
1-Preheat-Cooldown 2.12	1	60	1	2	3	0,10	8	80.926	431	109.944	34.522	6.596	7.215	58.490	3.875	130.196
1-Preheat-Cooldown 3.1	1	20	12	24	36	0,10	8	117.092	1.284	327.383	102.798	19.643	21.251	58.799	620.666	842.758
1-Preheat-Cooldown 3.2	1	20	11	22	33	0,10	8	118.452	1.282	326.725	102.591	19.603	21.304	58.800	564.416	786.316
1-Preheat-Cooldown 3.3	1	20	10	20	30	0,10	8	118.834	1.285	327.487	102.831	19.649	21.279	58.803	526.875	749.039
1-Preheat-Cooldown 3.4	1	20	9	18	27	0,10	8	116.921	1.298	330.826	103.879	19.849	21.318	58.832	493.041	716.533
1-Preheat-Cooldown 3.5	1	20	8	16	24	0,10	8	118.312	1.309	333.505	104.720	20.010	21.345	58.841	464.916	689.448
1-Preheat-Cooldown 3.6	1	20	7	14	21	0,10	8	117.647	1.299	331.134	103.976	19.868	21.387	58.810	408.666	632.312
1-Preheat-Cooldown 3.7	1	20	6	12	18	0,10	8	118.504	1.284	327.238	102.752	19.634	21.329	58.833	379.666	601.827
1-Preheat-Cooldown 3.8	1	20	5	10	15	0,10	8	118.273	1.293	329.536	103.474	19.772	21.395	58.879	328.500	551.648
1-Preheat-Cooldown 3.9	1	20	4	8	12	0,10	8	117.891	1.313	334.720	105.102	20.083	21.489	58.825	283.833	508.942
1-Preheat-Cooldown 3.10	1	20	3	6	9	0,10	8	117.972	1.288	328.194	103.053	19.691	21.424	58.914	222.791	445.512
1-Preheat-Cooldown 3.11	1	20	2	4	6	0,10	8	119.585	1.318	335.974	105.495	20.158	21.488	58.889	201.916	427.579
1-Preheat-Cooldown 3.12	1	20	1	2	3	0,10	8	118.392	1.280	326.152	102.411	19.569	21.473	58.876	161.208	383.164

Name	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.	mm³	€	pcs.	pcs.
1-Preheat-Cooldown 1.1	6,40	6,48	9,44	6,42	6,84	9,47	6,41	6,66	9,46	22,52	---	0,003	---	0,005	371.550	59.026	1	66
1-Preheat-Cooldown 1.2	6,00	6,43	8,66	6,03	6,83	8,69	6,01	6,63	8,67	21,31	---	0,003	---	0,004	369.419	58.996	1	66
1-Preheat-Cooldown 1.3	5,59	6,43	7,84	5,65	6,87	7,93	5,62	6,65	7,89	20,16	---	0,003	---	0,004	370.764	59.001	1	66
1-Preheat-Cooldown 1.4	5,20	6,43	7,06	5,26	6,87	7,14	5,23	6,65	7,10	18,98	---	0,003	---	0,004	370.780	58.979	1	66
1-Preheat-Cooldown 1.5	4,81	6,46	6,28	4,87	6,84	6,36	4,84	6,65	6,32	17,80	---	0,002	---	0,003	370.470	58.970	1	66
1-Preheat-Cooldown 1.6	4,41	6,42	5,49	4,48	6,83	5,57	4,45	6,62	5,53	16,60	---	0,002	---	0,003	369.021	58.996	1	67
1-Preheat-Cooldown 1.7	4,02	6,42	4,71	4,08	6,83	4,78	4,05	6,63	4,74	15,42	---	0,002	---	0,003	368.957	58.982	1	67
1-Preheat-Cooldown 1.8	3,63	6,43	3,92	3,69	6,85	3,98	3,66	6,64	3,95	14,25	---	0,002	---	0,003	369.544	58.993	1	67
1-Preheat-Cooldown 1.9	3,24	6,43	3,14	3,29	6,85	3,19	3,26	6,64	3,16	13,07	---	0,002	---	0,003	369.507	58.987	1	67
1-Preheat-Cooldown 1.10	2,85	6,42	2,36	2,89	6,89	2,39	2,87	6,65	2,37	11,89	---	0,002	---	0,002	370.104	59.014	1	67
1-Preheat-Cooldown 1.11	2,46	6,42	1,57	2,49	6,88	1,59	2,47	6,65	1,58	10,70	---	0,001	---	0,002	369.823	59.042	1	67
1-Preheat-Cooldown 1.12	2,07	6,45	0.,788	2,09	6,87	0.,793	2,08	6,66	0.,791	9,53	---	0,001	---	0,002	370.342	59.027	1	67
1-Preheat-Cooldown 2.1	13,52	14,80	19,95	13,16	14,32	19,43	13,34	14,56	19,69	47,59	33	0,074	34	0,075	381.438	59.811	38	144
1-Preheat-Cooldown 2.2	12,39	15,24	17,87	12,63	15,15	18,20	12,51	15,19	18,03	45,74	36	0,069	37	0,076	397.926	59.794	34	144
1-Preheat-Cooldown 2.3	11,62	14,95	16,30	11,91	14,63	16,69	11,76	14,79	16,49	43,05	36	0,065	35	0,063	385.038	59.824	30	144
1-Preheat-Cooldown 2.4	10,95	14,15	14,86	10,90	14,67	14,79	10,92	14,41	14,83	40,15	36	0,054	37	0,058	377.175	59.846	26	143
1-Preheat-Cooldown 2.5	10,05	14,57	13,12	10,21	14,67	13,32	10,13	14,62	13,22	37,97	36	0,050	34	0,051	383.311	59.806	24	144
1-Preheat-Cooldown 2.6	9,19	14,52	11,43	9,42	14,86	11,70	9,31	14,69	11,56	35,56	34	0,045	35	0,045	385.218	59.849	22	143
1-Preheat-Cooldown 2.7	8,38	14,89	9,81	8,59	15,37	10,04	8,49	15,13	9,92	33,54	32	0,041	35	0,047	395.551	59.838	22	144
1-Preheat-Cooldown 2.8	7,59	14,17	8,20	7,77	15,40	8,39	7,68	14,79	8,29	30,76	29	0,033	30	0,043	385.735	59.801	21	144
1-Preheat-Cooldown 2.9	6,85	14,41	6,63	6,89	15,57	6,67	6,87	14,99	6,65	28,51	28	0,029	29	0,038	391.798	59.802	19	144
1-Preheat-Cooldown 2.10	5,99	14,15	4,95	6,11	14,82	5,05	6,05	14,49	5,00	25,54	29	0,027	28	0,032	378.121	59.822	17	144
1-Preheat-Cooldown 2.11	5,29	14,65	3,38	5,16	14,72	3,30	5,22	14,68	3,34	23,24	26	0,025	30	0,028	383.640	59.846	16	144
1-Preheat-Cooldown 2.12	4,39	14,44	1,67	4,41	14,81	1,68	4,40	14,63	1,67	20,70	26	0,020	30	0,026	380.692	59.790	13	144
1-Preheat-Cooldown 3.1	19,59	42,41	28,86	19,08	44,27	28,11	19,33	43,34	28,49	91,16	53	1,221	56	1,303	385.156	60.106	397	425
1-Preheat-Cooldown 3.2	19,10	43,23	27,48	19,20	43,27	27,64	19,15	43,25	27,56	89,96	52	1,184	52	1,194	383.574	60.106	392	426
1-Preheat-Cooldown 3.3	18,91	42,95	26,49	18,71	43,75	26,20	18,81	43,35	26,34	88,50	49	1,101	50	1,126	384.953	60.110	385	426
1-Preheat-Cooldown 3.4	18,34	43,64	24,85	18,23	43,89	24,72	18,29	43,77	24,78	86,84	48	1,056	48	1,054	388.096	60.140	378	426
1-Preheat-Cooldown 3.5	17,72	43,58	23,10	17,56	44,66	22,88	17,64	44,12	22,99	84,75	47	1,003	47	1,013	390.682	60.148	369	427
1-Preheat-Cooldown 3.6	17,25	43,93	21,41	17,18	43,72	21,34	17,21	43,82	21,38	82,41	44	0,932	44	0,908	387.166	60.117	357	428
1-Preheat-Cooldown 3.7	16,57	43,18	19,37	16,58	43,40	19,37	16,57	43,29	19,37	79,23	41	0,813	42	0,843	384.042	60.140	340	427
1-Preheat-Cooldown 3.8	15,66	43,88	16,90	15,97	43,24	17,23	15,82	43,56	17,07	76,44	39	0,751	39	0,759	385.270	60.188	328	428
1-Preheat-Cooldown 3.9	14,70	43,78	14,22	14,62	44,80	14,15	14,66	44,29	14,18	73,13	38	0,710	38	0,725	389.230	60.133	317	430
1-Preheat-Cooldown 3.10	13,57	43,13	11,21	13,53	43,59	11,17	13,55	43,36	11,19	68,10	35	0,589	35	0,618	383.123	60.223	294	428
1-Preheat-Cooldown 3.11	11,85	44,47	7,57	11,93	44,34	7,61	11,89	44,40	7,59	63,88	35	0,566	35	0,567	390.960	60.198	276	430
1-Preheat-Cooldown 3.12	10,53	42,86	4,00	10,39	43,38	3,94	10,46	43,12	3,97	57,55	35	0,481	35	0,496	379.641	60.184	237	429

Table 9-5: Results of two machines with fixed material - Start volume - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs		%	hrs	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.	mm³	€	pcs.	pcs.
Start volume 1.1	1	60	4	8	12	1,00	8	81.118	437	111.557	35.029	6.693	7.184	58.516	8.833	135.762	6,83	14,10	6,62	6,89	15,57	6,67	6,86	14,83	6,64	28,34	29	0,031	30	0,039	387.930	59.816	19	144
Start volume 1.2	1	60	4	8	12	0,90	8	81.118	437	111.557	35.029	6.693	7.184	58.516	8.833	135.762	6,83	14,10	6,62	6,89	15,57	6,67	6,86	14,83	6,64	28,34	29	0,031	30	0,039	387.930	59.816	19	144
Start volume 1.3	1	60	4	8	12	0,80	8	81.118	437	111.557	35.029	6.693	7.184	58.516	8.833	135.762	6,83	14,10	6,62	6,89	15,57	6,67	6,86	14,83	6,64	28,34	29	0,031	30	0,039	387.930	59.816	19	144
Start volume 1.4	1	60	4	8	12	0,70	8	81.118	437	111.557	35.029	6.693	7.184	58.516	8.833	135.762	6,83	14,10	6,62	6,89	15,57	6,67	6,86	14,83	6,64	28,34	29	0,031	30	0,039	387.930	59.816	19	144
Start volume 1.5	1	60	4	8	12	0,60	8	81.118	437	111.557	35.029	6.693	7.184	58.516	8.833	135.762	6,83	14,10	6,62	6,89	15,57	6,67	6,86	14,83	6,64	28,34	29	0,031	30	0,039	387.930	59.816	19	144
Start volume 1.6	1	60	4	8	12	0,50	8	81.118	437	111.557	35.029	6.693	7.184	58.516	8.833	135.762	6,83	14,10	6,62	6,89	15,57	6,67	6,86	14,83	6,64	28,34	29	0,031	30	0,039	387.930	59.816	19	144
Start volume 1.7	1	60	4	8	12	0,40	8	81.118	437	111.557	35.029	6.693	7.184	58.516	8.833	135.762	6,83	14,10	6,62	6,89	15,57	6,67	6,86	14,83	6,64	28,34	29	0,031	30	0,039	387.930	59.816	19	144
Start volume 1.8	1	60	4	8	12	0,30	8	81.118	437	111.557	35.029	6.693	7.184	58.516	8.833	135.762	6,83	14,10	6,62	6,89	15,57	6,67	6,86	14,83	6,64	28,34	29	0,031	30	0,039	387.930	59.816	19	144
Start volume 1.9	1	60	4	8	12	0,20	8	81.118	437	111.557	35.029	6.693	7.184	58.516	8.833	135.762	6,83	14,10	6,62	6,89	15,57	6,67	6,86	14,83	6,64	28,34	29	0,031	30	0,039	387.930	59.816	19	144
Start volume 1.10	1	60	4	8	12	0,10	8	80.856	442	112.688	35.384	6.761	7.183	58.502	8.291	135.623	6,85	14,41	6,63	6,89	15,57	6,67	6,87	14,99	6,65	28,51	28	0,029	29	0,038	391.798	59.802	19	144
Start volume 1.11	1	60	4	8	12	0,00	8	80.996	442	112.624	35.364	6.757	7.189	58.558	6.916	134.305	6,81	14,56	6,59	6,93	15,38	6,71	6,87	14,97	6,65	28,49	29	0,026	29	0,037	391.545	59.860	18	144

Table 9-6: Results of two machines with fixed material - Elapse time - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs		%	hrs	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.	mm³	€	pcs.	pcs.
Elapse time 1.1	1	60	4	8	12	0,10	12	80.657	448	114.369	35.911	6.862	7.174	58.508	31.833	159.792	6,74	14,49	6,53	6,95	15,93	6,73	6,84	15,21	6,63	28,68	30	0,034	31	0,046	398.556	59.808	21	143
Elapse time 1.2	1	60	4	8	12	0,10	11	80.809	447	113.891	35.761	6.833	7.176	58.508	28.000	155.783	6,77	14,44	6,55	6,93	15,85	6,71	6,85	15,15	6,63	28,63	31	0,033	31	0,044	397.223	59.808	21	144
Elapse time 1.3	1	60	4	8	12	0,10	10	80.547	447	113.925	35.772	6.835	7.174	58.470	26.875	154.618	6,79	14,42	6,57	6,93	15,90	6,71	6,86	15,16	6,64	28,66	30	0,032	30	0,042	397.557	59.770	20	143
Elapse time 1.4	1	60	4	8	12	0,10	9	80.743	444	113.236	35.556	6.794	7.189	58.533	15.000	142.583	6,78	14,42	6,57	6,96	15,69	6,74	6,87	15,05	6,65	28,58	28	0,029	29	0,039	393.581	59.833	20	144
Elapse time 1.5	1	60	4	8	12	0,10	8	80.856	442	112.688	35.384	6.761	7.183	58.502	8.291	135.623	6,85	14,41	6,63	6,89	15,57	6,67	6,87	14,99	6,65	28,51	28	0,029	29	0,038	391.798	59.802	19	144
Elapse time 1.6	1	60	4	8	12	0,10	7	81.231	438	111.697	35.073	6.701	7.200	58.538	8.625	135.650	6,88	14,55	6,66	6,86	15,14	6,64	6,87	14,85	6,65	28,37	29	0,032	29	0,036	387.751	59.838	19	144
Elapse time 1.7	1	60	4	8	12	0,10	6	81.203	439	112.070	35.190	6.724	7.205	58.539	8.000	135.172	6,87	14,56	6,66	6,87	15,23	6,65	6,87	14,90	6,65	28,42	30	0,032	30	0,036	388.737	59.840	18	144
Elapse time 1.8	1	60	4	8	12	0,10	5	80.838	431	109.914	34.513	6.594	7.205	58.516	6.708	133.043	6,82	14,16	6,60	6,94	15,07	6,72	6,88	14,62	6,66	28,16	29	0,030	29	0,034	380.984	59.817	18	144
Elapse time 1.9	1	60	4	8	12	0,10	4	80.968	431	109.815	34.481	6.588	7.190	58.567	7.083	133.434	6,91	14,36	6,70	6,83	14,83	6,61	6,87	14,59	6,65	28,12	30	0,029	27	0,032	381.344	59.868	17	144
Elapse time 1.10	1	60	4	8	12	0,10	3	81.051	429	109.466	34.372	6.567	7.200	58.541	6.250	132.446	6,87	14,23	6,66	6,90	14,88	6,67	6,88	14,56	6,66	28,10	30	0,029	28	0,031	380.384	59.842	17	144
Elapse time 1.11	1	60	4	8	12	0,10	2	81.451	429	109.384	34.346	6.563	7.205	58.565	5.708	131.911	6,90	14,42	6,69	6,86	14,64	6,64	6,88	14,53	6,67	28,08	29	0,028	29	0,029	379.740	59.866	16	144
Elapse time 1.12	1	60	4	8	12	0,10	1	81.644	426	108.692	34.129	6.521	7.204	58.493	5.125	130.971	6,84	14,36	6,62	6,94	14,57	6,72	6,89	14,46	6,67	28,03	30	0,027	29	0,027	377.303	59.793	15	144
Elapse time 1.13	1	60	4	8	12	0,10	0	81.370	430	109.665	34.434	6.579	7.205	58.500	5.166	131.387	6,86	14,23	6,64	6,92	14,95	6,70	6,89	14,59	6,67	28,16	28	0,024	30	0,029	381.039	59.800	15	144

2.2 RESULTS OF TWO MACHINES WITH FLEXIBLE MATERIAL

Table 9-7: Results of two machines with flexible material - Upper limit - No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Material change time	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue	Number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs		%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Upper limit 1.1	0	150	4	8	12	5	0,10	8	70168	170	43532	13669	2611	2900	57723	0	96146	2,983	5,743	2,781	2,925	5,999	2,728	2,954	5,871	2,755	11,579	---	0	378652	59006	0	58,02
Upper limit 1.2	0	140	4	8	12	5	0,10	8	70644	184	46892	14724	2813	3105	57829	0	97749	3,171	6,105	2,936	3,178	6,505	2,949	3,175	6,305	2,943	12,423	---	0	377894	59114	0	62,12
Upper limit 1.3	0	130	4	8	12	5	0,10	8	71356	197	50196	15761	3011	3344	57837	0	99234	3,371	6,6	3,116	3,459	6,904	3,217	3,415	6,752	3,167	13,334	---	0	377660	59122	0	66,88
Upper limit 1.4	0	120	4	8	12	5	0,10	8	72062	213	54339	17062	3260	3618	57971	0	101237	3,623	7,036	3,349	3,75	7,555	3,492	3,687	7,296	3,421	14,403	---	0	377345	59260	0	72,37
Upper limit 1.5	0	110	4	8	12	5	0,10	8	73008	231	59053	18542	3543	3940	58028	0	103396	3,958	7,693	3,665	4,049	8,153	3,775	4,004	7,923	3,72	15,647	---	0	376304	59317	0	78,8
Upper limit 1.6	0	100	4	8	12	5	0,10	8	74108	255	64984	20405	3899	4332	58230	0	106276	4,349	8,506	4,039	4,408	8,858	4,115	4,378	8,682	4,077	17,137	---	0	376168	59524	0	86,65
Upper limit 1.7	0	90	4	8	12	5	0,10	8	75354	285	72710	22830	4362	4813	58322	0	109770	4,831	9,47	4,494	4,869	9,935	4,547	4,85	9,703	4,521	19,073	---	0	378985	59618	0	96,27
Upper limit 1.8	0	80	4	8	12	5	0,10	8	76697	321	81925	25724	4915	5409	58420	0	113943	5,434	10,483	5,038	5,482	11,347	5,109	5,458	10,915	5,073	21,446	---	0	379653	59718	0	108,2
Upper limit 1.9	0	70	4	8	12	5	0,10	8	79230	359	91508	28733	5490	6176	58399	0	118266	6,277	11,893	5,721	6,427	12,497	5,868	6,352	12,195	5,794	24,341	---	0	372004	59697	0	123,5
Upper limit 1.10	0	60	4	8	12	5	0,10	8	81601	433	110473	34688	6628	7208	58673	291	127048	7,679	14,462	6,756	7,635	14,845	6,707	7,657	14,654	6,732	29,042	---	0,002	384452	59977	1,217	144,2
Upper limit 1.11	0	50	4	8	12	5	0,10	8	85260	518	132223	41518	7933	8647	58671	583	136911	9,327	17,198	7,977	9,497	17,888	8,172	9,412	17,543	8,074	35,029	---	0,005	384379	59975	3,017	173
Upper limit 1.12	0	40	4	8	12	5	0,10	8	90498	663	169069	53087	10144	10778	58777	2583	154963	11,857	22,179	10,048	11,715	22,594	9,995	11,786	22,386	10,022	44,194	19,264	0,023	393624	60083	9,3	215,6
Upper limit 1.13	0	30	4	8	12	5	0,10	8	100304	868	221375	69512	13282	14370	58866	12541	188196	16,021	29,491	13,108	16,067	29,045	13,181	16,044	29,268	13,145	58,457	14,907	0,085	386703	60175	46,25	287,4
Upper limit 1.14	0	20	4	8	12	5	0,10	8	117911	1295	330027	103628	19801	21503	58913	115750	339234	23,085	43,996	17,247	23,25	43,203	17,375	23,168	43,599	17,311	84,078	17,687	0,598	384850	60222	288,8	430,1
Upper limit 1.15	0	10	4	8	12	5	0,10	8	173380	2513	640346	201068	38420	41495	58304	2179000	2537724	8,052	85,572	5,819	8,138	85,395	5,916	8,095	85,483	5,868	99,446	78,027	1,566	386716	59600	1268,4	829,9

Table 9-8: Results of two machines with flexible material - Upper limit - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Material change time	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue	Number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs		%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Upper limit 2.1	1	150	4	8	12	5	0,10	8	70158	172	44054	13833	2643	2897	57656	750	96998	2,996	5,755	2,775	2,938	6,149	2,736	2,967	5,952	2,755	11,674	---	0	382405	58937	0	57,95
Upper limit 2.2	1	140	4	8	12	5	0,10	8	70598	184	47005	14759	2820	3103	57794	833	98576	3,175	6,238	2,934	3,18	6,42	2,95	3,177	6,329	2,942	12,448	---	0	381125	59079	0	62,07
Upper limit 2.3	1	130	4	8	12	5	0,10	8	71306	196	50168	15752	3010	3339	57824	875	100077	3,366	6,59	3,11	3,455	6,907	3,216	3,411	6,749	3,163	13,322	---	0	378000	59109	0	66,78
Upper limit 2.4	1	120	4	8	12	5	0,10	8	72062	213	54326	17058	3259	3615	57990	1041	102295	3,62	7,034	3,345	3,744	7,55	3,488	3,682	7,292	3,416	14,39	---	0	377651	59279	0	72,3
Upper limit 2.5	1	110	4	8	12	5	0,10	8	73008	231	59004	18527	3540	3935	58001	1208	104546	3,958	7,692	3,665	4,04	8,14	3,769	3,999	7,916	3,717	15,632	---	0	376382	59290	0	78,7
Upper limit 2.6	1	100	4	8	12	5	0,10	8	74108	254	64964	20398	3897	4327	58214	1208	107452	4,345	8,501	4,034	4,402	8,863	4,112	4,374	8,682	4,073	17,129	---	0	376490	59508	0	86,55
Upper limit 2.7	1	90	4	8	12	5	0,10	8	75355	288	73391	23044	4403	4810	58316	1500	111514	4,883	9,73	4,529	4,848	9,862	4,51	4,866	9,796	4,519	19,181	---	0	383020	59612	0	96,22
Upper limit 2.8	1	80	4	8	12	5	0,10	8	77027	321	81817	25690	4909	5391	58408	1583	115453	5,436	10,684	4,97	5,608	11,115	5,145	5,522	10,9	5,058	21,479	---	0	381270	59706	0	107,8
Upper limit 2.9	1	70	4	8	12	5	0,10	8	78751	356	90874	28534	5452	6163	58498	2625	120773	6,436	12,143	5,732	6,511	12,047	5,813	6,473	12,095	5,773	24,341	---	0,001	370109	59798	1	123,3
Upper limit 2.10	1	60	4	8	12	5	0,10	8	81296	437	111398	34979	6683	7195	58634	5666	132704	7,771	14,523	6,674	7,849	15,048	6,774	7,81	14,786	6,724	29,32	---	0,003	388278	59937	1,617	143,9
Upper limit 2.11	1	50	4	8	12	5	0,10	8	84755	520	132634	41647	7958	8632	58680	7875	144353	9,495	17,531	8,09	9,393	17,654	8,024	9,444	17,593	8,057	35,094	17,171	0,008	385994	59984	3,6	172,7
Upper limit 2.12	1	40	4	8	12	5	0,10	8	90621	658	167890	52717	10073	10797	58795	13875	165857	11,878	22,401	9,904	12,091	22,055	10,133	11,985	22,228	10,018	44,231	15,902	0,03	389858	60101	15,2	216
Upper limit 2.13	1	30	4	8	12	5	0,10	8	100403	857	218358	68564	13101	14358	58869	39916	214434	17,181	28,795	13,219	16,794	28,944	12,947	16,988	28,87	13,083	58,94	13,753	0,126	382057	60178	77,217	287,2
Upper limit 2.14	1	20	4	8	12	5	0,10	8	117681	1285	327590	102863	19655	21474	58931	155791	378359	22,818	43,2	16,839	22,572	43,331	16,697	22,695	43,265	16,768	82,728	18,353	0,718	382680	60240	335,13	429,5
Upper limit 2.15	1	10	4	8	12	5	0,10	8	173816	2471	629789	197753	37787	41138	58107	2073625	2427780	8,763	84,119	6,339	8,465	84,685	6,105	8,614	84,402	6,222	99,238	71,231	1,525	384103	59398	1261,5	822,8

Table 9-9: Results of two machines with flexible material - Preheat and cool down - No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Material change time	Produc-tion start volume	Elapse time	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total mainte-nance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utilization	Waiting time in queue	Number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs		%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
0-Preheat-Cooldown 1.1	0	120	12	24	36	5	0,10	8	72062	213	54270	17041	3256	3608	58029	18041	119319	6,942	7,018	10,003	7,219	7,542	10,443	7,081	7,28	10,223	24,584	---	0	378027	59318	0	72,17
0-Preheat-Cooldown 1.2	0	120	11	22	33	5	0,10	8	72062	213	54277	17043	3256	3610	58021	17875	119146	6,53	7,02	9,175	6,788	7,543	9,579	6,659	7,282	9,377	23,318	---	0	377842	59310	0	72,2
0-Preheat-Cooldown 1.3	0	120	10	20	30	5	0,10	8	72062	213	54280	17044	3256	3610	58019	17833	119103	6,115	7,023	8,344	6,354	7,543	8,709	6,234	7,283	8,527	22,043	---	0	377804	59308	0	72,22
0-Preheat-Cooldown 1.4	0	120	9	18	27	5	0,10	8	72062	213	54280	17044	3256	3610	57998	17833	119076	5,699	7,025	7,512	5,92	7,545	7,841	5,81	7,285	7,677	20,772	---	0	377804	59287	0	72,22
0-Preheat-Cooldown 1.5	0	120	8	16	24	5	0,10	8	72062	213	54313	17054	3258	3611	57988	12666	113909	5,284	7,033	6,681	5,487	7,548	6,972	5,385	7,29	6,826	19,502	---	0	377896	59276	0	72,23
0-Preheat-Cooldown 1.6	0	120	7	14	21	5	0,10	8	72062	213	54323	17057	3259	3614	57991	3333	104586	4,871	7,034	5,851	5,053	7,549	6,103	4,962	7,291	5,977	18,23	---	0	377678	59280	0	72,28
0-Preheat-Cooldown 1.7	0	120	6	12	18	5	0,10	8	72062	213	54330	17059	3259	3615	57983	791	102037	4,457	7,035	5,019	4,618	7,552	5,233	4,538	7,293	5,126	16,957	---	0	377567	59271	0	72,32
0-Preheat-Cooldown 1.8	0	120	5	10	15	5	0,10	8	72062	213	54336	17061	3260	3617	57985	0	101252	4,041	7,034	4,185	4,184	7,554	4,362	4,112	7,294	4,274	15,68	---	0	377424	59273	0	72,35
0-Preheat-Cooldown 1.9	0	120	4	8	12	5	0,10	8	72062	213	54339	17062	3260	3618	57971	0	101237	3,623	7,036	3,349	3,75	7,555	3,492	3,687	7,296	3,421	14,403	---	0	377345	59260	0	72,37
0-Preheat-Cooldown 1.10	0	120	3	6	9	5	0,10	8	72059	213	54379	17075	3262	3620	57995	0	101285	3,206	7,037	2,513	3,314	7,561	2,62	3,26	7,299	2,566	13,125	---	0	377342	59283	0	72,42
0-Preheat-Cooldown 1.11	0	120	2	4	6	5	0,10	8	72059	213	54379	17075	3262	3620	57974	0	101258	2,788	7,039	1,676	2,879	7,564	1,747	2,833	7,301	1,711	11,846	---	0	377342	59262	0	72,42
0-Preheat-Cooldown 1.12	0	120	1	2	3	5	0,10	8	72120	213	54302	17050	3258	3624	57968	0	101224	2,371	7,039	0,84	2,444	7,546	0,87	2,407	7,293	0,86	10,557	---	0	376410	59256	0	72,48
0-Preheat-Cooldown 2.1	0	40	12	24	36	5	0,10	8	90639	645	164562	51672	9873	10740	58862	75375	226145	23,128	21,215	29,67	22,811	22,306	29,334	22,969	21,76	29,502	74,232	16,589	0,125	384394	60170	63,133	214,8
0-Preheat-Cooldown 2.2	0	40	11	22	33	5	0,10	8	90727	645	164578	51677	9874	10753	58857	69333	220115	21,497	22,196	26,925	21,815	21,331	27,483	21,656	21,764	27,204	70,624	15,21	0,093	384013	60165	52,283	215,1
0-Preheat-Cooldown 2.3	0	40	10	20	30	5	0,10	8	91382	654	166723	52351	10003	10769	58841	67375	218954	20,202	22,387	24,668	20,333	21,717	24,909	20,267	22,052	24,788	67,108	13,843	0,075	388582	60149	44,483	215,4
0-Preheat-Cooldown 2.4	0	40	9	18	27	5	0,10	8	90863	650	165851	52077	9951	10749	58827	62291	213505	18,71	21,741	22,38	18,701	22,143	22,302	18,705	21,942	22,341	62,988	13,658	0,054	387634	60134	32,617	215
0-Preheat-Cooldown 2.5	0	40	8	16	24	5	0,10	8	90832	665	169572	53245	10174	10769	58839	52416	205058	17,113	22,746	19,794	17,255	22,12	19,986	17,184	22,433	19,89	59,507	14,99	0,047	395419	60147	25,8	215,4
0-Preheat-Cooldown 2.6	0	40	7	14	21	5	0,10	8	90450	652	166115	52160	9966	10766	58767	27041	178291	15,647	22,294	17,374	15,852	21,714	17,582	15,749	22,004	17,478	55,231	16,282	0,033	387215	60073	16,417	215,3
0-Preheat-Cooldown 2.7	0	40	6	12	18	5	0,10	8	90856	643	163835	51444	9830	10759	58802	11833	162269	14,356	21,929	14,978	14,287	21,445	14,973	14,322	21,687	14,975	50,984	19,327	0,029	382003	60108	12,7	215,2
0-Preheat-Cooldown 2.8	0	40	5	10	15	5	0,10	8	90533	649	165494	51965	9929	10772	58758	2708	153721	12,997	22,001	12,433	13,1	21,848	12,592	13,049	21,925	12,513	47,486	18,368	0,024	386087	60064	10,233	215,5
0-Preheat-Cooldown 2.9	0	40	4	8	12	5	0,10	8	90498	663	169069	53087	10144	10778	58777	2583	154963	11,857	22,179	10,048	11,715	22,594	9,995	11,786	22,386	10,022	44,194	19,264	0,023	393624	60083	9,3	215,6
0-Preheat-Cooldown 2.10	0	40	3	6	9	5	0,10	8	91065	658	167844	52703	10070	10789	58733	2333	154208	10,595	22,079	7,534	10,552	22,406	7,543	10,573	22,243	7,539	40,355	16,009	0,015	390166	60039	7,433	215,8
0-Preheat-Cooldown 2.11	0	40	2	4	6	5	0,10	8	91289	667	170177	53435	10210	10810	58781	1875	154708	9,327	22,387	5,024	9,266	22,677	5,034	9,297	22,532	5,029	36,857	18,394	0,016	394871	60088	7,05	216,2
0-Preheat-Cooldown 2.12	0	40	1	2	3	5	0,10	8	91075	669	170557	53554	10233	10821	58771	1041	154014	7,99	22,634	2,495	8,095	22,539	2,543	8,042	22,587	2,519	33,148	16,868	0,012	395626	60077	5,65	216,4
0-Preheat-Cooldown 3.1	0	20	12	24	36	5	0,10	8	117791	1284	327333	102782	19639	21313	58808	525250	747396	24,219	43,321	30,932	24,216	43,323	30,938	24,218	43,322	30,935	98,474	30,04	2,017	385016	60114	577,08	426,3
0-Preheat-Cooldown 3.2	0	20	11	22	33	5	0,10	8	118680	1317	335699	105409	20141	21355	58803	501041	726354	24,269	44,107	29,987	23,954	44,761	29,586	24,112	44,434	29,787	98,332	28,918	1,909	394151	60110	567,62	427,1
0-Preheat-Cooldown 3.3	0	20	10	20	30	5	0,10	8	118588	1291	329064	103326	19743	21390	58843	420250	643167	24,693	43,927	29,403	25,079	43,123	29,865	24,886	43,525	29,634	98,045	26,204	1,679	385719	60150	550,82	427,8
0-Preheat-Cooldown 3.4	0	20	9	18	27	5	0,10	8	118547	1325	337758	106056	20265	21409	58876	379291	605524	24,63	44,991	28,027	24,989	44,309	28,386	24,809	44,65	28,206	97,665	25,255	1,561	395469	60185	531,17	428,2
0-Preheat-Cooldown 3.5	0	20	8	16	24	5	0,10	8	118499	1300	331246	104011	19874	21415	58877	307083	530889	25,555	43,663	27,512	25,396	43,953	27,414	25,476	43,808	27,463	96,747	22,815	1,299	388344	60186	488,97	428,3
0-Preheat-Cooldown 3.6	0	20	7	14	21	5	0,10	8	118625	1295	330076	103643	19804	21460	58944	260458	483960	25,416	43,735	25,72	25,578	43,431	25,906	25,497	43,583	25,813	94,894	21,429	1,103	385779	60254	441,87	429,2
0-Preheat-Cooldown 3.7	0	20	6	12	18	5	0,10	8	118142	1317	335616	105383	20136	21512	58901	216916	442485	25,045	44,443	23,415	25,01	44,252	23,423	25,028	44,347	23,419	92,794	20,34	0,953	391132	60210	401,12	430,3
0-Preheat-Cooldown 3.8	0	20	5	10	15	5	0,10	8	118088	1303	332222	104317	19933	21428	58875	157916	382097	24,354	43,895	20,614	24,275	43,947	20,635	24,315	43,921	20,625	88,86	18,873	0,753	388784	60184	342,1	428,6
0-Preheat-Cooldown 3.9	0	20	4	8	12	5	0,10	8	117911	1295	330027	103628	19801	21503	58913	115750	339234	23,085	43,996	17,247	23,25	43,203	17,375	23,168	43,599	17,311	84,078	17,687	0,598	384850	60222	288,8	430,1
0-Preheat-Cooldown 3.10	0	20	3	6	9	5	0,10	8	118968	1309	333575	104742	20014	21477	58955	93833	318674	21,045	43,874	13,336	20,888	44,207	13,229	20,967	44,04	13,283	78,29	17,991	0,506	389825	60265	239,05	429,6
0-Preheat-Cooldown 3.11	0	20	2	4	6	5	0,10	8	118682	1316	335291	105281	20117	21521	58966	60500	286042	18,884	44,071	9,13	18,848	44,441	9,186	18,866	44,256	9,158	72,28	16,752	0,374	391150	60276	188,73	430,4
0-Preheat-Cooldown 3.12	0	20	1	2	3	5	0,10	8	118309	1304	332351	104358	19941	21612	58916	40875	265341	16,349	44,117	4,656	16,472	43,699	4,721	16,411	43,908	4,688	65,007	17,135	0,295	385899	60225	145,43	432,3

Table 9-10: Results of two machines with flexible material - Preheat and cool down - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Material change time	Produc-tion start volume	Elapse time	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total mainte-nance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs	hrs		%	hrs	€	kg	kg	€	€	€	€	€	€
1-Preheat-Cooldown 1.1	1	120	12	24	36	5	0,10	8	72066	212	54022	16963	3241	3605	58067	21541	122774
1-Preheat-Cooldown 1.2	1	120	11	22	33	5	0,10	8	72051	212	54229	17028	3253	3607	58052	21666	122959
1-Preheat-Cooldown 1.3	1	120	10	20	30	5	0,10	8	72062	213	54270	17041	3256	3608	58042	18916	120212
1-Preheat-Cooldown 1.4	1	120	9	18	27	5	0,10	8	72062	213	54274	17042	3256	3609	58027	18041	119319
1-Preheat-Cooldown 1.5	1	120	8	16	24	5	0,10	8	72062	213	54277	17043	3256	3610	58014	15625	116887
1-Preheat-Cooldown 1.6	1	120	7	14	21	5	0,10	8	72062	213	54280	17044	3256	3610	58011	14166	115427
1-Preheat-Cooldown 1.7	1	120	6	12	18	5	0,10	8	72062	213	54280	17044	3256	3610	57991	13791	115025
1-Preheat-Cooldown 1.8	1	120	5	10	15	5	0,10	8	72062	213	54317	17055	3259	3612	57988	9291	110536
1-Preheat-Cooldown 1.9	1	120	4	8	12	5	0,10	8	72062	213	54326	17058	3259	3615	57990	1041	102295
1-Preheat-Cooldown 1.10	1	120	3	6	9	5	0,10	8	72059	213	54336	17061	3260	3617	57998	791	102062
1-Preheat-Cooldown 1.11	1	120	2	4	6	5	0,10	8	72059	213	54336	17061	3260	3617	57978	0	101243
1-Preheat-Cooldown 1.12	1	120	1	2	3	5	0,10	8	72059	213	54373	17073	3262	3619	57982	0	101265
1-Preheat-Cooldown 2.1	1	70	12	24	36	5	0,10	8	78424	371	94626	29712	5677	6151	58564	40416	160045
1-Preheat-Cooldown 2.2	1	70	11	22	33	5	0,10	8	78831	364	92931	29180	5575	6167	58581	38375	157407
1-Preheat-Cooldown 2.3	1	70	10	20	30	5	0,10	8	78959	375	95652	30034	5739	6157	58535	36041	156020
1-Preheat-Cooldown 2.4	1	70	9	18	27	5	0,10	8	78870	373	95183	29887	5711	6164	58548	35375	155201
1-Preheat-Cooldown 2.5	1	70	8	16	24	5	0,10	8	78703	373	95221	29899	5713	6164	58538	31125	150953
1-Preheat-Cooldown 2.6	1	70	7	14	21	5	0,10	8	78845	362	92273	28973	5536	6152	58479	27208	145844
1-Preheat-Cooldown 2.7	1	70	6	12	18	5	0,10	8	78450	386	98395	30896	5903	6158	58477	27416	148344
1-Preheat-Cooldown 2.8	1	70	5	10	15	5	0,10	8	78493	368	93936	29496	5636	6160	58551	18250	137610
1-Preheat-Cooldown 2.9	1	70	4	8	12	5	0,10	8	78751	356	90874	28534	5452	6163	58498	2625	120773
1-Preheat-Cooldown 2.10	1	70	3	6	9	5	0,10	8	79147	366	93279	29289	5596	6158	58456	1875	120861
1-Preheat-Cooldown 2.11	1	70	2	4	6	5	0,10	8	79284	365	93034	29212	5582	6174	58526	0	119005
1-Preheat-Cooldown 2.12	1	70	1	2	3	5	0,10	8	79038	365	93210	29268	5592	6167	58496	0	119023
1-Preheat-Cooldown 3.1	1	20	12	24	36	5	0,10	8	118625	1298	330780	103865	19846	21310	58844	533958	757439
1-Preheat-Cooldown 3.2	1	20	11	22	33	5	0,10	8	117711	1289	328565	103169	19713	21341	58789	479291	701902
1-Preheat-Cooldown 3.3	1	20	10	20	30	5	0,10	8	119165	1276	325329	102153	19519	21305	58827	422625	644041
1-Preheat-Cooldown 3.4	1	20	9	18	27	5	0,10	8	117701	1291	329159	103356	19749	21376	58904	369083	592105
1-Preheat-Cooldown 3.5	1	20	8	16	24	5	0,10	8	118045	1281	326483	102515	19589	21419	58883	324083	546118
1-Preheat-Cooldown 3.6	1	20	7	14	21	5	0,10	8	117741	1297	330499	103776	19829	21391	58915	276875	500427
1-Preheat-Cooldown 3.7	1	20	6	12	18	5	0,10	8	118049	1308	333463	104707	20007	21468	58938	242750	467518
1-Preheat-Cooldown 3.8	1	20	5	10	15	5	0,10	8	118187	1289	328528	103157	19711	21428	58897	197458	420286
1-Preheat-Cooldown 3.9	1	20	4	8	12	5	0,10	8	117681	1285	327590	102863	19655	21474	58931	155791	378359
1-Preheat-Cooldown 3.10	1	20	3	6	9	5	0,10	8	118467	1299	330987	103930	19859	21533	58969	123958	347907
1-Preheat-Cooldown 3.11	1	20	2	4	6	5	0,10	8	117761	1302	331898	104216	19913	21482	58942	70041	294244
1-Preheat-Cooldown 3.12	1	20	1	2	3	5	0,10	8	118856	1318	335801	105441	20148	21560	58957	56541	282301

Name	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utilization	Waiting time in queue	Number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
1-Preheat-Cooldown 1.1	6,938	7,005	9,999	7,199	7,478	10,415	7,069	7,241	10,207	24,517	---	0	376635	59357	0	72,1
1-Preheat-Cooldown 1.2	6,531	7,033	9,177	6,769	7,509	9,553	6,65	7,271	9,365	23,286	---	0	377851	59342	0	72,15
1-Preheat-Cooldown 1.3	6,108	7,017	8,334	6,346	7,54	8,701	6,227	7,278	8,517	22,023	---	0	378027	59332	0	72,17
1-Preheat-Cooldown 1.4	5,695	7,019	7,506	5,913	7,542	7,833	5,804	7,281	7,669	20,754	---	0	377949	59316	0	72,18
1-Preheat-Cooldown 1.5	5,28	7,021	6,674	5,481	7,544	6,967	5,381	7,283	6,821	19,484	---	0	377842	59303	0	72,2
1-Preheat-Cooldown 1.6	4,865	7,024	5,842	5,046	7,543	6,097	4,955	7,284	5,969	18,208	---	0	377804	59300	0	72,22
1-Preheat-Cooldown 1.7	4,449	7,026	5,009	4,613	7,546	5,228	4,531	7,286	5,118	16,935	---	0	377804	59279	0	72,22
1-Preheat-Cooldown 1.8	4,034	7,033	4,177	4,178	7,549	4,358	4,106	7,291	4,268	15,664	---	0	377815	59276	0	72,25
1-Preheat-Cooldown 1.9	3,62	7,034	3,345	3,744	7,55	3,488	3,682	7,292	3,416	14,39	---	0	377651	59279	0	72,3
1-Preheat-Cooldown 1.10	3,204	7,033	2,511	3,309	7,552	2,617	3,256	7,292	2,564	13,113	---	0	377424	59287	0	72,35
1-Preheat-Cooldown 1.11	2,787	7,035	1,674	2,874	7,555	1,745	2,83	7,295	1,71	11,835	---	0	377424	59266	0	72,35
1-Preheat-Cooldown 1.12	2,369	7,037	0,84	2,438	7,559	0,87	2,403	7,298	0,86	10,557	---	0	377458	59271	0	72,38
1-Preheat-Cooldown 2.1	12,41	12,585	17,159	12,574	12,574	17,378	12,492	12,58	17,268	42,34	19,4	0,005	385179	59866	1,533	123
1-Preheat-Cooldown 2.2	11,758	12,394	15,85	11,761	12,302	15,88	11,76	12,348	15,865	39,972	13,741	0,003	379406	59883	1,183	123,4
1-Preheat-Cooldown 2.3	11,008	12,785	14,367	11,099	12,656	14,454	11,054	12,721	14,41	38,185	16,131	0,004	393092	59836	1,45	123,2
1-Preheat-Cooldown 2.4	10,299	12,711	12,927	10,389	12,597	13,033	10,344	12,654	12,98	35,978	14,03	0,003	388576	59849	1,317	123,3
1-Preheat-Cooldown 2.5	9,539	12,55	11,436	9,684	12,776	11,644	9,612	12,663	11,54	33,815	---	0,002	387293	59839	1,1	123,3
1-Preheat-Cooldown 2.6	8,793	11,977	10,011	8,884	12,583	10,166	8,838	12,28	10,089	31,207	---	0,002	376280	59779	1,15	123,1
1-Preheat-Cooldown 2.7	8,147	12,556	8,63	8,098	13,64	8,682	8,122	13,098	8,656	29,876	---	0,003	400353	59776	1,45	123,2
1-Preheat-Cooldown 2.8	7,245	12,425	7,152	7,345	12,541	7,261	7,295	12,483	7,207	26,985	---	0,001	382625	59852	1	123,2
1-Preheat-Cooldown 2.9	6,436	12,143	5,732	6,511	12,047	5,813	6,473	12,095	5,773	24,341	---	0,001	370109	59798	1	123,3
1-Preheat-Cooldown 2.10	5,669	12,314	4,291	5,738	12,528	4,367	5,703	12,421	4,329	22,453	4,094	0,001	379930	59755	1	123,2
1-Preheat-Cooldown 2.11	4,788	11,88	2,806	5,026	12,865	2,975	4,907	12,372	2,891	20,17	---	0	378882	59827	0	123,5
1-Preheat-Cooldown 2.12	4,107	12,283	1,425	4,185	12,513	1,463	4,146	12,398	1,444	17,988	---	0	379299	59796	1	123,4
1-Preheat-Cooldown 3.1	23,906	43,62	30,447	23,783	43,904	30,349	23,844	43,762	30,398	98,004	30,108	2,032	390000	60152	580,97	426,2
1-Preheat-Cooldown 3.2	24,142	43,709	29,835	24,332	43,297	30,105	24,237	43,503	29,97	97,71	28,091	1,864	386218	60095	570,62	426,8
1-Preheat-Cooldown 3.3	24,888	42,651	29,653	24,57	43,44	29,289	24,729	43,045	29,471	97,246	26,177	1,691	383226	60135	555,35	426,1
1-Preheat-Cooldown 3.4	24,948	43,328	28,357	24,782	43,655	28,173	24,865	43,491	28,265	96,621	24,507	1,541	386317	60213	540,08	427,5
1-Preheat-Cooldown 3.5	24,922	43,585	26,85	25,237	42,734	27,234	25,08	43,159	27,042	95,281	22,665	1,353	382249	60191	513,1	428,4
1-Preheat-Cooldown 3.6	24,712	43,688	25,014	24,699	43,637	25,028	24,706	43,662	25,021	93,389	21,289	1,183	387386	60225	477,02	427,8
1-Preheat-Cooldown 3.7	24,521	43,714	22,849	24,028	44,363	22,536	24,274	44,039	22,692	91,005	20,225	1,033	389732	60247	439,03	429,4
1-Preheat-Cooldown 3.8	23,813	43,531	20,081	23,766	43,315	20,117	23,79	43,423	20,099	87,312	18,973	0,854	384726	60206	385,62	428,6
1-Preheat-Cooldown 3.9	22,818	43,2	16,839	22,572	43,331	16,697	22,695	43,265	16,768	82,728	18,353	0,718	382680	60240	335,13	429,5
1-Preheat-Cooldown 3.10	21,188	43,834	13,007	21,277	43,539	13,03	21,233	43,687	13,018	77,937	17,654	0,617	385172	60279	296,75	430,7
1-Preheat-Cooldown 3.11	19,415	44,18	8,892	19,476	43,48	8,966	19,446	43,83	8,929	72,205	16,298	0,489	387584	60252	255,45	429,7
1-Preheat-Cooldown 3.12	17,377	44,397	4,593	17,218	44,264	4,553	17,297	44,33	4,573	66,2	15,308	0,393	391094	60267	220,08	431,2

Table 9-11: Results of two machines with flexible material - Start volume - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Material change time	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue	Number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs		%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Start volume 1.1	1	70	4	8	12	5	1	8	78746	359	91603	28763	5496	6165	58544	3625	122109	6,46	12,231	5,749	6,49	12,127	5,791	6,475	12,179	5,77	24,424	---	0,001	372761	59845	1	123,3
Start volume 1.2	1	70	4	8	12	5	0,90	8	78746	359	91603	28763	5496	6165	58544	3625	122109	6,46	12,231	5,749	6,49	12,127	5,791	6,475	12,179	5,77	24,424	---	0,001	372761	59845	1	123,3
Start volume 1.3	1	70	4	8	12	5	0,80	8	78746	359	91603	28763	5496	6165	58544	3625	122109	6,46	12,231	5,749	6,49	12,127	5,791	6,475	12,179	5,77	24,424	---	0,001	372761	59845	1	123,3
Start volume 1.4	1	70	4	8	12	5	0,70	8	78746	359	91603	28763	5496	6165	58544	3625	122109	6,46	12,231	5,749	6,49	12,127	5,791	6,475	12,179	5,77	24,424	---	0,001	372761	59845	1	123,3
Start volume 1.5	1	70	4	8	12	5	0,60	8	78746	359	91603	28763	5496	6165	58544	3625	122109	6,46	12,231	5,749	6,49	12,127	5,791	6,475	12,179	5,77	24,424	---	0,001	372761	59845	1	123,3
Start volume 1.6	1	70	4	8	12	5	0,50	8	78746	359	91603	28763	5496	6165	58544	3625	122109	6,46	12,231	5,749	6,49	12,127	5,791	6,475	12,179	5,77	24,424	---	0,001	372761	59845	1	123,3
Start volume 1.7	1	70	4	8	12	5	0,40	8	78746	359	91603	28763	5496	6165	58544	3625	122109	6,46	12,231	5,749	6,49	12,127	5,791	6,475	12,179	5,77	24,424	---	0,001	372761	59845	1	123,3
Start volume 1.8	1	70	4	8	12	5	0,30	8	78746	359	91603	28763	5496	6165	58544	3625	122109	6,46	12,231	5,749	6,49	12,127	5,791	6,475	12,179	5,77	24,424	---	0,001	372761	59845	1	123,3
Start volume 1.9	1	70	4	8	12	5	0,20	8	78746	359	91603	28763	5496	6165	58544	3625	122109	6,46	12,231	5,749	6,49	12,127	5,791	6,475	12,179	5,77	24,424	---	0,001	372761	59845	1	123,3
Start volume 1.10	1	70	4	8	12	5	0,10	8	78751	356	90874	28534	5452	6163	58498	2625	120773	6,436	12,143	5,732	6,511	12,047	5,813	6,473	12,095	5,773	24,341	---	0,001	370109	59798	1	123,3
Start volume 1.11	1	70	4	8	12	5	0,00	8	78957	361	92148	28934	5528	6164	58451	1666	120229	6,683	11,965	5,962	6,167	12,58	5,594	6,425	12,273	5,778	24,476	4,06	0,001	378191	59750	1	123,3

Table 9-12: Results of two machines with flexible material - Elapse time - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Material change time	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue	Number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs		%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Elapse time 1.1	1	70	4	8	12	5	0,10	12	78595	385	98306	30868	5898	6154	58505	23708	144636	6,656	12,953	5,782	6,601	13,199	5,746	6,629	13,076	5,764	25,469	---	0,002	400099	59805	1,217	123,1
Elapse time 1.2	1	70	4	8	12	5	0,10	11	78596	371	94719	29742	5683	6161	58524	18833	138452	6,522	12,635	5,714	6,647	12,548	5,825	6,585	12,592	5,77	24,946	---	0,002	385888	59824	1	123,2
Elapse time 1.3	1	70	4	8	12	5	0,10	10	78867	368	93821	29459	5629	6166	58609	19416	138818	6,479	12,328	5,678	6,623	12,591	5,853	6,551	12,46	5,765	24,776	8,151	0,001	381935	59911	1	123,3
Elapse time 1.4	1	70	4	8	12	5	0,10	9	78963	364	92862	29158	5571	6160	58536	8291	127230	6,504	12,381	5,731	6,51	12,316	5,802	6,507	12,348	5,766	24,622	6,688	0,001	378446	59836	1	123,2
Elapse time 1.5	1	70	4	8	12	5	0,10	8	78751	356	90874	28534	5452	6163	58498	2625	120773	6,436	12,143	5,732	6,511	12,047	5,813	6,473	12,095	5,773	24,341	---	0,001	370109	59798	1	123,3
Elapse time 1.6	1	70	4	8	12	5	0,10	7	79277	363	92563	29065	5553	6170	58560	2250	121119	6,49	12,358	5,778	6,456	12,256	5,767	6,473	12,307	5,772	24,552	---	0,001	377883	59861	1	123,4
Elapse time 1.7	1	70	4	8	12	5	0,10	6	79156	362	92275	28974	5536	6162	58510	1541	120229	6,398	12,534	5,75	6,468	12,024	5,792	6,433	12,279	5,771	24,482	---	0,001	376270	59810	1	123,3
Elapse time 1.8	1	70	4	8	12	5	0,10	5	79120	366	93293	29294	5597	6159	58459	2041	121039	6,397	12,391	5,734	6,459	12,455	5,811	6,428	12,423	5,772	24,623	4,238	0,001	380066	59759	1	123,2
Elapse time 1.9	1	70	4	8	12	5	0,10	4	79161	365	93127	29242	5587	6169	58467	291	119247	6,43	12,439	5,791	6,398	12,363	5,771	6,414	12,401	5,781	24,596	2,939	0	379858	59766	0	123,4
Elapse time 1.10	1	70	4	8	12	5	0,10	3	79095	359	91685	28789	5501	6170	58382	0	118304	6,365	12,054	5,753	6,415	12,404	5,828	6,39	12,229	5,791	24,41	---	0	373626	59680	0	123,4
Elapse time 1.11	1	70	4	8	12	5	0,10	2	79183	360	91724	28801	5503	6167	58485	0	118452	6,27	11,752	5,687	6,441	12,662	5,87	6,355	12,207	5,779	24,341	---	0	373839	59784	0	123,4
Elapse time 1.12	1	70	4	8	12	5	0,10	1	79111	362	92315	28987	5538	6176	58501	0	118704	6,268	11,827	5,71	6,415	12,737	5,86	6,342	12,282	5,785	24,408	---	0	375655	59801	0	123,5
Elapse time 1.13	1	70	4	8	12	5	0,10	0	79503	361	92032	28898	5521	6178	58419	0	118490	6,286	11,976	5,73	6,418	12,543	5,859	6,352	12,259	5,794	24,406	---	0	373541	59717	0	123,6

Table 9-13: Results of two machines with flexible material - Change over time - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Material change time	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue	Number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
1-Change over time 1.1	1	120	4	8	12	1	0,10	8	72062	213	54326	17058	3259	3615	57989	458	101711	3,488	7,035	3,345	3,629	7,55	3,488	3,558	7,292	3,416	14,266	---	0	377651	59278	0	72,3
1-Change over time 1.2	1	120	4	8	12	2	0,10	8	72062	213	54326	17058	3259	3615	57990	791	102044	3,521	7,034	3,345	3,657	7,55	3,488	3,589	7,292	3,416	14,297	---	0	377651	59278	0	72,3
1-Change over time 1.3	1	120	4	8	12	3	0,10	8	72062	213	54326	17058	3259	3615	57990	791	102045	3,554	7,034	3,345	3,686	7,55	3,488	3,62	7,292	3,416	14,328	---	0	377651	59278	0	72,3
1-Change over time 1.4	1	120	4	8	12	4	0,10	8	72062	213	54326	17058	3259	3615	57990	875	102128	3,587	7,034	3,345	3,715	7,55	3,488	3,651	7,292	3,416	14,359	---	0	377651	59279	0	72,3
1-Change over time 1.5	1	120	4	8	12	5	0,10	8	72062	213	54326	17058	3259	3615	57990	1041	102295	3,62	7,034	3,345	3,744	7,55	3,488	3,682	7,292	3,416	14,39	---	0	377651	59279	0	72,3
1-Change over time 1.6	1	120	4	8	12	6	0,10	8	72062	213	54326	17058	3259	3615	57990	1041	102295	3,653	7,034	3,345	3,773	7,55	3,488	3,713	7,292	3,416	14,421	---	0	377651	59279	0	72,3
1-Change over time 1.7	1	120	4	8	12	7	0,10	8	72062	213	54326	17058	3259	3615	57990	1041	102296	3,686	7,034	3,345	3,801	7,55	3,488	3,743	7,292	3,416	14,452	---	0	377651	59279	0	72,3
1-Change over time 1.8	1	120	4	8	12	8	0,10	8	72062	213	54326	17058	3259	3615	57991	1041	102296	3,719	7,034	3,345	3,83	7,55	3,488	3,774	7,292	3,416	14,483	---	0	377651	59279	0	72,3
1-Change over time 1.9	1	120	4	8	12	9	0,10	8	72062	213	54326	17058	3259	3615	57991	1041	102296	3,751	7,034	3,345	3,859	7,55	3,488	3,805	7,292	3,416	14,513	---	0	377651	59279	0	72,3
1-Change over time 1.10	1	120	4	8	12	10	0,10	8	72062	213	54326	17058	3259	3615	57991	1041	102296	3,784	7,034	3,345	3,888	7,549	3,488	3,836	7,292	3,416	14,544	---	0	377651	59280	0	72,3
1-Change over time 2.1	1	70	4	8	12	1	0,10	8	78986	358	91349	28683	5480	6162	58515	625	118973	6,035	12,072	5,744	6,089	12,234	5,798	6,062	12,153	5,771	23,986	---	0,001	371950	59816	0,617	123,3
1-Change over time 2.2	1	70	4	8	12	2	0,10	8	78981	356	90942	28556	5456	6168	58517	1916	120120	6,126	12,024	5,733	6,211	12,175	5,819	6,168	12,099	5,776	24,044	---	0,001	370090	59817	0,633	123,4
1-Change over time 2.3	1	70	4	8	12	3	0,10	8	78914	356	90897	28541	5453	6165	58523	1791	119984	6,215	12,189	5,721	6,32	11,997	5,824	6,267	12,093	5,772	24,133	---	0,001	369863	59824	0,667	123,3
1-Change over time 2.4	1	70	4	8	12	4	0,10	8	78861	356	90899	28542	5453	6163	58509	2208	120380	6,321	12,203	5,729	6,415	11,986	5,814	6,368	12,095	5,772	24,234	---	0,001	370250	59809	0,65	123,3
1-Change over time 2.5	1	70	4	8	12	5	0,10	8	78751	356	90874	28534	5452	6163	58498	2625	120773	6,436	12,143	5,732	6,511	12,047	5,813	6,473	12,095	5,773	24,341	---	0,001	370109	59798	0,65	123,3
1-Change over time 2.6	1	70	4	8	12	6	0,10	8	78827	358	91273	28659	5476	6166	58494	2750	121045	6,559	12,193	5,744	6,612	12,105	5,808	6,585	12,149	5,776	24,51	---	0,001	371428	59794	0,667	123,3
1-Change over time 2.7	1	70	4	8	12	7	0,10	8	79014	359	91717	28799	5503	6168	58543	2625	121153	6,665	12,175	5,757	6,708	12,218	5,789	6,686	12,196	5,773	24,655	---	0,001	373195	59844	0,7	123,4
1-Change over time 2.8	1	70	4	8	12	8	0,10	8	79101	360	91968	28878	5518	6168	58562	2666	121315	6,768	12,232	5,761	6,813	12,217	5,781	6,791	12,225	5,771	24,786	---	0,001	374328	59864	0,7	123,4
1-Change over time 2.9	1	70	4	8	12	9	0,10	8	79206	363	92555	29062	5553	6167	58588	2750	121651	6,871	12,255	5,753	6,926	12,34	5,783	6,898	12,297	5,768	24,964	---	0,001	376679	59890	0,75	123,4
1-Change over time 2.10	1	70	4	8	12	10	0,10	8	79125	360	91722	28800	5503	6169	58590	2625	121218	6,928	12,106	5,728	7,055	12,267	5,811	6,992	12,187	5,77	24,948	---	0,001	372873	59892	0,75	123,4
1-Change over time 3.1	1	20	4	8	12	1	0,10	8	118504	1299	331023	103941	19861	21475	58946	119500	343373	18,694	44,325	17,038	18,975	43,088	17,31	18,835	43,706	17,174	79,715	18,051	0,651	387134	60256	308,82	429,5
1-Change over time 3.2	1	20	4	8	12	2	0,10	8	118586	1278	325665	102259	19539	21438	58937	124083	345904	19,922	43,222	17,166	20,008	42,791	17,236	19,965	43,007	17,201	80,173	17,73	0,639	380959	60247	307,97	428,8
1-Change over time 3.3	1	20	4	8	12	3	0,10	8	118777	1303	331990	104245	19919	21451	58892	144875	369015	20,699	44,142	16,853	20,82	43,605	16,957	20,759	43,874	16,905	81,538	18,515	0,706	388299	60201	325,58	429
1-Change over time 3.4	1	20	4	8	12	4	0,10	8	117582	1293	329541	103476	19772	21561	58944	150708	374111	21,853	43,634	16,927	21,738	43,395	16,873	21,796	43,514	16,9	82,21	18,295	0,707	383477	60254	331,28	431,2
1-Change over time 3.5	1	20	4	8	12	5	0,10	8	117681	1285	327590	102863	19655	21474	58931	155791	378359	22,818	43,2	16,839	22,572	43,331	16,697	22,695	43,265	16,768	82,728	18,353	0,718	382680	60240	335,13	429,5
1-Change over time 3.6	1	20	4	8	12	6	0,10	8	117968	1308	333384	104682	20003	21494	58950	161583	386363	23,625	43,766	16,671	23,309	44,271	16,453	23,467	44,019	16,562	84,048	18,517	0,764	388854	60260	352,28	429,9
1-Change over time 3.7	1	20	4	8	12	7	0,10	8	118012	1286	327867	102950	19672	21436	58931	157500	380135	24,76	42,997	16,688	24,357	43,606	16,453	24,559	43,301	16,571	84,431	18,361	0,759	384205	60241	353,27	428,7
1-Change over time 3.8	1	20	4	8	12	8	0,10	8	118649	1292	329203	103369	19752	21417	58926	168041	391150	25,427	43,41	16,293	25,17	43,553	16,231	25,299	43,481	16,262	85,042	18,897	0,801	385278	60235	363,7	428,4
1-Change over time 3.9	1	20	4	8	12	9	0,10	8	119207	1318	335873	105464	20152	21507	58905	186333	411999	25,845	44,585	16,057	25,979	44,176	16,106	25,912	44,38	16,082	86,374	19,215	0,86	391943	60214	384,27	430,2
1-Change over time 3.10	1	20	4	8	12	10	0,10	8	117471	1293	329526	103471	19771	21450	58923	177791	401048	26,741	43,765	16,022	27,019	43,307	16,08	26,88	43,536	16,051	86,467	19,133	0,857	385169	60232	383,48	429

Table 9-14: Results of two machines with flexible material - Change over time - No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Material change time	Produc-tion start volume	Elapse time	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total mainte-nance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utilization	Waiting time in queue	Number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs		%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
0-Change over time 1.1	0	120	4	8	12	1	0,10	8	72062	213	54339	17062	3260	3618	57971	0	101236	3,492	7,037	3,349	3,634	7,556	3,492	3,563	7,296	3,421	14,28	---	0	377345	59259	0	72,37
0-Change over time 1.2	0	120	4	8	12	2	0,10	8	72062	213	54339	17062	3260	3618	57971	0	101236	3,524	7,037	3,349	3,663	7,556	3,492	3,594	7,296	3,421	14,31	---	0	377345	59259	0	72,37
0-Change over time 1.3	0	120	4	8	12	3	0,10	8	72062	213	54339	17062	3260	3618	57971	0	101236	3,557	7,036	3,349	3,692	7,556	3,492	3,625	7,296	3,421	14,341	---	0	377345	59259	0	72,37
0-Change over time 1.4	0	120	4	8	12	4	0,10	8	72062	213	54339	17062	3260	3618	57971	0	101236	3,59	7,036	3,349	3,721	7,556	3,492	3,656	7,296	3,421	14,372	---	0	377345	59259	0	72,37
0-Change over time 1.5	0	120	4	8	12	5	0,10	8	72062	213	54339	17062	3260	3618	57971	0	101237	3,623	7,036	3,349	3,75	7,555	3,492	3,687	7,296	3,421	14,403	---	0	377345	59260	0	72,37
0-Change over time 1.6	0	120	4	8	12	6	0,10	8	72062	213	54339	17062	3260	3618	57971	0	101237	3,656	7,036	3,349	3,778	7,555	3,492	3,717	7,296	3,421	14,434	---	0	377345	59260	0	72,37
0-Change over time 1.7	0	120	4	8	12	7	0,10	8	72062	213	54339	17062	3260	3618	57972	0	101237	3,689	7,036	3,349	3,807	7,555	3,492	3,748	7,296	3,421	14,465	---	0	377345	59260	0	72,37
0-Change over time 1.8	0	120	4	8	12	8	0,10	8	72062	213	54339	17062	3260	3618	57972	0	101237	3,722	7,036	3,349	3,836	7,555	3,492	3,779	7,296	3,421	14,496	---	0	377345	59260	0	72,37
0-Change over time 1.9	0	120	4	8	12	9	0,10	8	72062	213	54339	17062	3260	3618	57972	416	101654	3,755	7,036	3,349	3,865	7,555	3,492	3,81	7,296	3,421	14,527	---	0	377345	59260	0	72,37
0-Change over time 1.10	0	120	4	8	12	10	0,10	8	72062	213	54339	17062	3260	3618	57972	791	102029	3,788	7,036	3,349	3,894	7,555	3,492	3,841	7,296	3,42	14,557	---	0	377345	59260	0	72,37
0-Change over time 2.1	0	70	4	8	12	1	0,10	8	79317	365	93143	29247	5588	6173	58479	83	119064	5,935	12,087	5,676	6,154	12,704	5,892	6,045	12,395	5,784	24,224	---	0	379020	59778	0,233	123,5
0-Change over time 2.2	0	70	4	8	12	2	0,10	8	79319	366	93330	29305	5599	6179	58421	0	118980	6,05	12,151	5,712	6,219	12,714	5,879	6,134	12,433	5,795	24,362	---	0	379371	59719	0,283	123,6
0-Change over time 2.3	0	70	4	8	12	3	0,10	8	79315	362	92343	28995	5540	6181	58424	0	118617	6,161	12,104	5,752	6,255	12,494	5,842	6,208	12,299	5,797	24,304	---	0	375176	59722	0,283	123,6
0-Change over time 2.4	0	70	4	8	12	4	0,10	8	79415	361	92222	28957	5533	6180	58424	0	118570	6,217	12,102	5,739	6,344	12,465	5,852	6,281	12,284	5,795	24,36	---	0	374540	59722	0,3	123,6
0-Change over time 2.5	0	70	4	8	12	5	0,10	8	79230	359	91508	28733	5490	6176	58399	0	118266	6,277	11,893	5,721	6,427	12,497	5,868	6,352	12,195	5,794	24,341	---	0	372004	59697	0,333	123,5
0-Change over time 2.6	0	70	4	8	12	6	0,10	8	79408	361	92084	28914	5525	6183	58422	0	118519	6,327	11,87	5,712	6,517	12,665	5,885	6,422	12,268	5,799	24,488	---	0	373442	59720	0,317	123,7
0-Change over time 2.7	0	70	4	8	12	7	0,10	8	79463	363	92571	29067	5554	6184	58434	0	118718	6,433	11,947	5,73	6,572	12,711	5,867	6,502	12,329	5,798	24,63	---	0	375410	59732	0,4	123,7
0-Change over time 2.8	0	70	4	8	12	8	0,10	8	79453	364	92792	29136	5567	6179	58426	0	118785	6,495	12,021	5,712	6,656	12,705	5,878	6,576	12,363	5,795	24,734	---	0	377026	59724	0,433	123,6
0-Change over time 2.9	0	70	4	8	12	9	0,10	8	79630	363	92585	29071	5555	6180	58425	416	119124	6,548	12,111	5,69	6,769	12,561	5,901	6,659	12,336	5,796	24,79	---	0	376455	59724	0,483	123,6
0-Change over time 2.10	0	70	4	8	12	10	0,10	8	79568	361	92003	28889	5520	6175	58443	1416	119926	6,627	12,055	5,696	6,812	12,453	5,883	6,719	12,254	5,79	24,763	---	0	374388	59742	0,467	123,5
0-Change over time 3.1	0	20	4	8	12	1	0,10	8	117919	1309	333666	104771	20019	21462	58900	95875	320663	19,269	44,031	17,659	19,25	44,153	17,628	19,259	44,092	17,644	80,995	17,454	0,533	390361	60209	258,15	429,3
0-Change over time 3.2	0	20	4	8	12	2	0,10	8	117508	1295	330083	103646	19804	21515	58946	97125	320686	20,43	43,228	17,739	20,113	43,942	17,491	20,272	43,585	17,615	81,471	17,312	0,532	384900	60256	262,05	430,3
0-Change over time 3.3	0	20	4	8	12	3	0,10	8	118065	1298	330851	103887	19851	21465	58943	99541	323337	21,109	43,657	17,427	21,194	43,72	17,515	21,152	43,688	17,471	82,311	17,643	0,56	386640	60253	270,4	429,3
0-Change over time 3.4	0	20	4	8	12	4	0,10	8	117382	1299	331100	103965	19866	21501	58950	109833	333767	22,348	43,131	17,543	21,855	44,304	17,193	22,102	43,717	17,368	83,187	17,799	0,588	386307	60260	279,4	430
0-Change over time 3.5	0	20	4	8	12	5	0,10	8	117911	1295	330027	103628	19801	21503	58913	115750	339234	23,085	43,996	17,247	23,25	43,203	17,375	23,168	43,599	17,311	84,078	17,687	0,598	384850	60222	288,8	430,1
0-Change over time 3.6	0	20	4	8	12	6	0,10	8	117868	1293	329669	103516	19780	21507	58977	121666	345107	24,082	43,321	17,206	23,931	43,694	17,095	24,006	43,508	17,15	84,664	18,207	0,624	384430	60288	294	430,2
0-Change over time 3.7	0	20	4	8	12	7	0,10	8	117928	1275	324887	102014	19493	21469	58906	118458	339978	25,226	42,605	17,269	24,89	43,254	17,003	25,058	42,93	17,136	85,123	18,328	0,637	379989	60215	295,68	429,4
0-Change over time 3.8	0	20	4	8	12	8	0,10	8	118373	1311	334169	104929	20050	21485	58928	132833	357870	25,409	44,55	16,662	25,94	43,722	16,986	25,675	44,136	16,824	86,635	18,453	0,692	389832	60238	319,97	429,7
0-Change over time 3.9	0	20	4	8	12	9	0,10	8	118636	1293	329666	103515	19780	21515	58925	147333	370710	26,645	43,433	16,833	26,598	43,657	16,764	26,622	43,545	16,798	86,965	18,843	0,708	384295	60234	321,48	430,3
0-Change over time 3.10	0	20	4	8	12	10	0,10	8	118474	1291	328952	103290	19737	21475	58909	153750	376798	27,094	43,936	16,484	27,725	43,019	16,834	27,409	43,477	16,659	87,546	19,038	0,735	384365	60218	330,32	429,5

2.3 RESULTS OF THREE MACHINES WITH FIXED MATERIAL

Table 9-15: Results of three machines with fixed material - Upper limit - No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Waiting time in queue machine 3	Number in queue machine 3	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs	%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.			mm³	€	pcs.	pcs.
Upper limit 1.1	0	150	4	8	12	0.1	8	69652	170	43315	13601	2598	2891	84904	83	132381	1,95	3,97	1,89	1,90	3,97	1,84	1,92	3,96	1,86	1,92	3,97	1,86	7,76	---	0,000	1,688	0,000	---	0,000	372421	86791	0	58
Upper limit 1.2	0	140	4	8	12	0.1	8	70277	179	45693	14347	2741	3094	85108	125	133786	2,09	4,18	2,02	2,00	4,08	1,94	2,07	4,27	2,01	2,06	4,18	1,99	8,22	---	0,000	2,358	0,000	---	0,001	366214	86999	1	62
Upper limit 1.3	0	130	4	8	12	0.1	8	70873	193	49284	15475	2957	3333	85584	166	136044	2,24	4,45	2,17	2,14	4,36	2,07	2,23	4,63	2,16	2,20	4,48	2,13	8,82	---	0,001	3,855	0,001	---	0,001	366354	87485	1	67
Upper limit 1.4	0	120	4	8	12	0.1	8	71627	212	54173	17010	3250	3614	86052	250	138861	2,43	4,98	2,35	2,31	4,73	2,24	2,40	4,97	2,32	2,38	4,90	2,30	9,57	---	0,001	6,133	0,001	---	0,001	371087	87964	1	72
Upper limit 1.5	0	110	4	8	12	0.1	8	72672	231	59000	18526	3540	3933	85639	291	140477	2,65	5,37	2,56	2,55	5,26	2,47	2,60	5,45	2,52	2,60	5,36	2,52	10,47	---	0,002	8,732	0,001	---	0,002	371409	87542	1	79
Upper limit 1.6	0	100	4	8	12	0.1	8	73840	258	65867	20682	3952	4329	85995	625	144249	2,91	6,03	2,81	2,80	5,95	2,71	2,84	5,89	2,75	2,85	5,96	2,76	11,57	---	0,002	12,936	0,002	---	0,002	377977	87906	1	87
Upper limit 1.7	0	90	4	8	12	0.1	8	75279	287	73362	23035	4401	4809	86357	1000	148389	3,23	6,65	3,13	3,12	6,74	3,02	3,10	6,45	3,01	3,15	6,61	3,05	12,82	---	0,003	16,346	0,003	---	0,003	378169	88276	2	96
Upper limit 1.8	0	80	4	8	12	0.1	8	76238	323	82461	25892	4947	5394	86734	1041	152922	3,50	7,21	3,39	3,51	7,39	3,39	3,53	7,61	3,42	3,51	7,40	3,40	14,31	---	0,005	20,457	0,003	---	0,005	381780	88661	2	108
Upper limit 1.9	0	70	4	8	12	0.1	8	79037	381	97275	30544	5836	6170	86978	2291	160813	4,01	8,84	3,88	3,89	8,29	3,76	4,10	8,97	3,97	4,00	8,70	3,87	16,57	---	0,008	22,278	0,006	---	0,007	395455	88910	5	123
Upper limit 1.10	0	60	4	8	12	0.1	8	81454	446	113655	35687	6819	7211	87285	3875	169974	4,63	9,99	4,49	4,70	10,26	4,56	4,63	10,15	4,48	4,65	10,13	4,51	19,30	28,047	0,011	28,398	0,013	27,923	0,013	393399	89225	10	144
Upper limit 1.11	0	50	4	8	12	0.1	8	84699	522	133202	41825	7992	8633	87448	8291	183340	5,44	11,76	5,27	5,63	11,97	5,44	5,54	11,83	5,36	5,53	11,86	5,36	22,75	31,121	0,020	30,599	0,022	28,360	0,020	384995	89391	17	173
Upper limit 1.12	0	40	4	8	12	0.1	8	90584	657	167516	52600	10050	10782	87651	16750	207051	6,81	14,95	6,59	6,81	14,64	6,59	6,88	15,04	6,66	6,83	14,88	6,61	28,32	35,735	0,040	38,414	0,042	37,190	0,045	387772	89598	29	216
Upper limit 1.13	0	30	4	8	12	0.1	8	99682	861	219421	68898	13165	14366	87964	31000	244715	8,85	19,01	8,57	8,81	19,93	8,53	8,85	19,31	8,57	8,84	19,42	8,56	36,81	33,400	0,074	35,529	0,089	33,844	0,075	381820	89918	58	287
Upper limit 1.14	0	20	4	8	12	0.1	8	117537	1290	328677	103204	19720	21558	88122	118041	380022	12,14	27,85	11,75	12,30	29,23	11,91	12,07	30,01	11,68	12,17	29,03	11,78	52,98	30,941	0,221	31,073	0,231	33,372	0,258	381669	90080	190	431
Upper limit 1.15	0	10	4	8	12	0.1	8	173652	2556	651390	204536	39083	42624	88267	1001541	1405475	14,01	56,88	13,50	13,56	58,60	13,07	13,88	56,85	13,38	13,82	57,44	13,32	84,58	51,393	1,443	55,118	1,585	51,181	1,436	381999	90228	722	852

Table 9-16: Results of three machines with fixed material - Upper limit - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Waiting time in queue machine 3	Number in queue machine 3	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs	%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.			mm³	€	pcs.	pcs.
Upper limit 2.1	1	150	4	8	12	0.1	8	69610	168	42977	13494	2578	2888	84931	125	132329	1,95	3,97	1,89	1,89	3,89	1,83	1,93	3,96	1,86	1,92	3,94	1,86	7,72	---	0,000	1,648	0,000	---	0,000	370411	86819	0	58
Upper limit 2.2	1	140	4	8	12	0.1	8	70320	179	45634	14329	2738	3092	85182	166	133903	2,08	4,15	2,02	2,00	4,04	1,94	2,07	4,31	2,01	2,05	4,17	1,99	8,21	---	0,000	3,102	0,000	---	0,001	365605	87075	1	62
Upper limit 2.3	1	130	4	8	12	0.1	8	70873	193	49241	15461	2954	3330	85632	250	136172	2,24	4,45	2,17	2,13	4,35	2,07	2,23	4,62	2,16	2,20	4,47	2,13	8,80	---	0,001	4,832	0,001	---	0,001	366389	87534	1	67
Upper limit 2.4	1	120	4	8	12	0.1	8	71625	212	54203	17019	3252	3614	86130	291	139018	2,43	4,99	2,35	2,30	4,73	2,23	2,40	4,97	2,32	2,37	4,89	2,30	9,57	---	0,001	7,594	0,001	---	0,001	371185	88044	1	72
Upper limit 2.5	1	110	4	8	12	0.1	8	72672	231	58987	18521	3539	3930	85657	416	140618	2,64	5,36	2,56	2,54	5,27	2,46	2,60	5,44	2,52	2,59	5,36	2,51	10,46	---	0,002	10,335	0,001	---	0,002	371609	87561	1	79
Upper limit 2.6	1	100	4	8	12	0.1	8	73829	261	66556	20898	3993	4325	86044	666	144610	2,91	6,13	2,82	2,78	5,97	2,69	2,84	5,96	2,75	2,84	6,02	2,75	11,62	---	0,003	14,202	0,002	---	0,003	382482	87956	1	87
Upper limit 2.7	1	90	4	8	12	0.1	8	75175	286	73023	22929	4381	4800	86496	1083	148522	3,22	6,64	3,12	3,06	6,56	2,97	3,13	6,52	3,03	3,14	6,57	3,04	12,75	---	0,003	18,527	0,004	---	0,004	377518	88418	2	96
Upper limit 2.8	1	80	4	8	12	0.1	8	76755	322	82158	25797	4929	5400	86745	1250	153038	3,50	7,27	3,39	3,50	7,24	3,39	3,54	7,61	3,43	3,51	7,37	3,40	14,29	---	0,005	22,989	0,004	---	0,005	380940	88672	3	108
Upper limit 2.9	1	70	4	8	12	0.1	8	78614	372	94971	29820	5698	6165	86878	2333	159855	3,98	8,44	3,86	4,03	8,73	3,90	4,00	8,37	3,87	4,01	8,51	3,88	16,40	20,728	0,007	---	0,008	32,151	0,009	386172	88809	7	123
Upper limit 2.10	1	60	4	8	12	0.1	8	80950	438	111829	35114	6709	7186	87228	4375	169690	4,51	9,74	4,37	4,78	10,26	4,62	4,63	9,94	4,48	4,64	9,98	4,49	19,11	25,097	0,012	29,575	0,018	---	0,014	389143	89166	13	144
Upper limit 2.11	1	50	4	8	12	0.1	8	84927	523	133282	41850	7996	8625	87335	10125	185044	5,50	11,59	5,33	5,57	12,23	5,39	5,50	11,81	5,32	5,52	11,88	5,35	22,75	34,886	0,024	37,390	0,030	33,919	0,025	385175	89276	19	173
Upper limit 2.12	1	40	4	8	12	0.1	8	90881	653	166419	52255	9985	10771	87706	20083	210038	6,84	14,65	6,63	6,65	14,53	6,44	6,86	15,11	6,64	6,79	14,77	6,57	28,12	37,718	0,048	38,654	0,050	41,796	0,055	386413	89655	33	215
Upper limit 2.13	1	30	4	8	12	0.1	8	99471	857	218570	68631	13114	14369	87942	41291	254663	8,66	18,99	8,38	8,84	19,50	8,57	8,71	19,54	8,43	8,74	19,34	8,46	36,54	28,421	0,093	29,728	0,108	29,204	0,102	379543	89896	87	287
Upper limit 2.14	1	20	4	8	12	0.1	8	120076	1291	329071	103328	19744	21483	88208	147291	409459	11,82	29,21	11,45	12,02	29,16	11,64	11,76	28,73	11,39	11,87	29,03	11,49	52,39	31,776	0,280	30,796	0,276	32,297	0,282	383055	90168	226	430
Upper limit 2.15	1	10	4	8	12	0.1	8	174410	2548	649347	203895	38960	42590	88131	1014875	1417829	13,05	57,16	12,57	13,45	55,92	12,97	12,73	58,97	12,25	13,07	57,35	12,60	83,02	51,841	1,480	50,456	1,439	55,213	1,606	381329	90090	730	852

Table 9-17: Results of three machines with fixed material – Preheat and cool down - No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs	hrs	%	hrs	€	kg	kg	€	€	€	€	€	€
0-Preheat-Cooldown 1.1	0	130	12	24	36	0.1	8	70985	192	49011	15389	2940	3320	85587	17208	152976
0-Preheat-Cooldown 1.2	0	130	11	22	33	0.1	8	70985	192	49146	15432	2948	3322	85574	17291	153094
0-Preheat-Cooldown 1.3	0	130	10	20	30	0.1	8	70968	193	49246	15463	2954	3325	85578	17416	153265
0-Preheat-Cooldown 1.4	0	130	9	18	27	0.1	8	70904	193	49278	15473	2956	3327	85635	17291	153229
0-Preheat-Cooldown 1.5	0	130	8	16	24	0.1	8	70873	193	49238	15460	2954	3329	85660	12708	148666
0-Preheat-Cooldown 1.6	0	130	7	14	21	0.1	8	70873	193	49241	15461	2954	3330	85643	2958	138896
0-Preheat-Cooldown 1.7	0	130	6	12	18	0.1	8	70873	193	49278	15473	2956	3331	85631	250	136186
0-Preheat-Cooldown 1.8	0	130	5	10	15	0.1	8	70873	193	49278	15473	2956	3331	85599	250	136145
0-Preheat-Cooldown 1.9	0	130	4	8	12	0.1	8	70873	193	49284	15475	2957	3333	85584	166	136044
0-Preheat-Cooldown 1.10	0	130	3	6	9	0.1	8	70840	194	49461	15530	2967	3335	85621	125	136121
0-Preheat-Cooldown 1.11	0	130	2	4	6	0.1	8	70845	195	49905	15670	2994	3337	85634	125	136306
0-Preheat-Cooldown 1.12	0	130	1	2	3	0.1	8	70877	194	49486	15538	2969	3336	85638	83	136112
0-Preheat-Cooldown 2.1	0	60	12	24	36	0.1	8	81207	431	110057	34558	6603	7187	87210	49083	213712
0-Preheat-Cooldown 2.2	0	60	11	22	33	0.1	8	81158	425	108298	34005	6497	7165	87165	44458	208349
0-Preheat-Cooldown 2.3	0	60	10	20	30	0.1	8	81417	424	108273	33997	6496	7180	87222	43583	207554
0-Preheat-Cooldown 2.4	0	60	9	18	27	0.1	8	80714	429	109394	34349	6563	7176	87269	44458	208907
0-Preheat-Cooldown 2.5	0	60	8	16	24	0.1	8	81057	432	110223	34610	6613	7185	87192	31333	195999
0-Preheat-Cooldown 2.6	0	60	7	14	21	0.1	8	81267	434	110659	34746	6639	7180	87425	12833	177968
0-Preheat-Cooldown 2.7	0	60	6	12	18	0.1	8	80862	436	111321	34954	6679	7183	87106	6375	171334
0-Preheat-Cooldown 2.8	0	60	5	10	15	0.1	8	80609	428	109202	34289	6552	7191	87214	4958	169277
0-Preheat-Cooldown 2.9	0	60	4	8	12	0.1	8	81454	446	113655	35687	6819	7211	87285	3875	169974
0-Preheat-Cooldown 2.10	0	60	3	6	9	0.1	8	81339	439	111901	35137	6714	7206	87275	2666	168092
0-Preheat-Cooldown 2.11	0	60	2	4	6	0.1	8	81583	432	110162	34591	6609	7192	87097	2166	166690
0-Preheat-Cooldown 2.12	0	60	1	2	3	0.1	8	81391	435	110858	34809	6651	7190	86992	2291	166933
0-Preheat-Cooldown 3.1	0	20	12	24	36	0.1	8	118461	1285	327464	102823	19647	21349	88092	412625	673903
0-Preheat-Cooldown 3.2	0	20	11	22	33	0.1	8	119003	1284	327171	102731	19630	21403	88202	375125	636493
0-Preheat-Cooldown 3.3	0	20	10	20	30	0.1	8	117554	1293	329525	103471	19771	21395	88157	335083	597265
0-Preheat-Cooldown 3.4	0	20	9	18	27	0.1	8	117879	1286	327655	102883	19659	21390	88135	309916	571364
0-Preheat-Cooldown 3.5	0	20	8	16	24	0.1	8	118050	1292	329269	103390	19756	21438	88238	262750	524986
0-Preheat-Cooldown 3.6	0	20	7	14	21	0.1	8	118588	1292	329367	103421	19762	21495	88202	222041	484322
0-Preheat-Cooldown 3.7	0	20	6	12	18	0.1	8	117570	1293	329448	103446	19766	21464	88194	179041	441312
0-Preheat-Cooldown 3.8	0	20	5	10	15	0.1	8	118334	1309	333521	104725	20011	21498	88168	148250	412043
0-Preheat-Cooldown 3.9	0	20	4	8	12	0.1	8	117537	1290	328677	103204	19720	21558	88122	118041	380022
0-Preheat-Cooldown 3.10	0	20	3	6	9	0.1	8	118739	1309	333687	104777	20021	21523	88184	101208	365109
0-Preheat-Cooldown 3.11	0	20	2	4	6	0.1	8	118810	1297	330681	103834	19840	21501	88164	85750	348479
0-Preheat-Cooldown 3.12	0	20	1	2	3	0.1	8	118496	1309	333523	104726	20011	21545	88132	75750	339542

Name	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Waiting time in queue machine 3	Number in queue machine 3	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.			mm³	€	pcs.	pcs.
0-Preheat-Cooldown 1.1	4,39	4,45	6,49	4,21	4,33	6,22	4,36	4,59	6,43	4,32	4,46	6,38	15,15	---	0,001	8,073	0,001	---	0,002	365225	87489	1	66
0-Preheat-Cooldown 1.2	4,13	4,46	5,95	3,96	4,35	5,70	4,09	4,60	5,90	4,06	4,47	5,85	14,38	---	0,001	7,556	0,001	---	0,002	365953	87476	1	66
0-Preheat-Cooldown 1.3	3,85	4,44	5,40	3,71	4,37	5,19	3,83	4,63	5,37	3,79	4,48	5,32	13,59	---	0,001	7,039	0,001	---	0,001	366900	87480	1	67
0-Preheat-Cooldown 1.4	3,58	4,45	4,86	3,44	4,35	4,66	3,57	4,63	4,85	3,53	4,48	4,79	12,80	---	0,001	5,890	0,001	---	0,001	366972	87538	1	67
0-Preheat-Cooldown 1.5	3,33	4,45	4,34	3,16	4,35	4,13	3,30	4,62	4,31	3,26	4,47	4,26	11,99	---	0,001	5,440	0,001	---	0,001	366434	87563	1	67
0-Preheat-Cooldown 1.6	3,06	4,45	3,80	2,91	4,35	3,61	3,03	4,62	3,77	3,00	4,47	3,73	11,20	---	0,001	4,990	0,001	---	0,001	366389	87546	1	67
0-Preheat-Cooldown 1.7	2,79	4,45	3,26	2,65	4,36	3,10	2,76	4,62	3,23	2,73	4,48	3,20	10,41	---	0,001	4,540	0,001	---	0,001	366473	87534	1	67
0-Preheat-Cooldown 1.8	2,52	4,45	2,72	2,39	4,36	2,58	2,50	4,63	2,70	2,47	4,48	2,67	9,61	---	0,001	4,090	0,001	---	0,001	366473	87502	1	67
0-Preheat-Cooldown 1.9	2,24	4,45	2,17	2,14	4,36	2,07	2,23	4,63	2,16	2,20	4,48	2,13	8,82	---	0,001	3,855	0,001	---	0,001	366354	87485	1	67
0-Preheat-Cooldown 1.10	1,97	4,44	1,63	1,88	4,39	1,55	1,96	4,66	1,62	1,94	4,49	1,60	8,03	---	0,001	3,355	0,000	---	0,001	367211	87523	1	67
0-Preheat-Cooldown 1.11	1,69	4,43	1,08	1,63	4,49	1,04	1,69	4,68	1,08	1,67	4,53	1,07	7,27	---	0,000	2,980	0,000	---	0,001	370385	87537	1	67
0-Preheat-Cooldown 1.12	1,43	4,46	0,54	1,36	4,41	0,52	1,42	4,62	0,54	1,40	4,50	0,53	6,44	---	0,000	2,588	0,000	---	0,001	368469	87541	1	67
0-Preheat-Cooldown 2.1	9,06	9,69	13,37	9,03	9,66	13,33	9,22	10,11	13,61	9,10	9,82	13,43	32,36	38,354	0,027	---	0,026	35,735	0,026	381024	89148	19	144
0-Preheat-Cooldown 2.2	8,68	10,22	12,51	8,55	9,51	12,33	8,33	9,29	12,01	8,52	9,67	12,28	30,48	39,126	0,027	33,928	0,022	---	0,021	377978	89102	16	143
0-Preheat-Cooldown 2.3	8,02	9,41	11,24	7,95	9,74	11,14	7,98	9,85	11,20	7,98	9,67	11,19	28,84	32,513	0,021	34,730	0,021	---	0,023	377067	89160	15	144
0-Preheat-Cooldown 2.4	7,31	9,75	9,92	7,43	9,87	10,08	7,52	9,64	10,21	7,42	9,75	10,07	27,24	31,597	0,020	32,089	0,019	---	0,019	380607	89208	14	144
0-Preheat-Cooldown 2.5	6,86	9,77	8,96	6,86	9,67	8,94	6,94	10,09	9,05	6,89	9,84	8,98	25,71	30,543	0,018	27,678	0,016	---	0,018	383294	89130	14	144
0-Preheat-Cooldown 2.6	6,11	9,42	7,60	6,42	10,26	7,98	6,37	9,88	7,92	6,30	9,86	7,83	23,99	29,846	0,015	30,123	0,017	---	0,015	384435	89368	13	144
0-Preheat-Cooldown 2.7	5,64	9,75	6,60	5,84	10,20	6,83	5,80	9,90	6,78	5,76	9,95	6,74	22,44	25,113	0,013	---	0,015	28,071	0,014	387112	89042	13	144
0-Preheat-Cooldown 2.8	5,15	9,80	5,56	5,23	9,68	5,64	5,23	9,75	5,65	5,20	9,74	5,62	20,56	32,252	0,013	---	0,013	26,340	0,013	378971	89152	11	144
0-Preheat-Cooldown 2.9	4,63	9,99	4,49	4,70	10,26	4,56	4,63	10,15	4,48	4,65	10,13	4,51	19,30	28,047	0,011	28,398	0,013	27,923	0,013	393399	89225	10	144
0-Preheat-Cooldown 2.10	4,15	10,39	3,43	4,05	10,00	3,34	4,07	9,56	3,36	4,09	9,98	3,38	17,45	26,275	0,011	---	0,010	31,036	0,010	388692	89215	8	144
0-Preheat-Cooldown 2.11	3,44	9,89	2,20	3,58	9,70	2,29	3,57	9,95	2,28	3,53	9,85	2,25	15,63	33,792	0,012	25,500	0,007	27,086	0,009	384077	89033	7	144
0-Preheat-Cooldown 2.12	2,92	10,12	1,11	2,96	9,56	1,13	3,02	10,07	1,15	2,97	9,92	1,13	14,01	---	0,011	25,986	0,007	---	0,008	386445	88925	6	144
0-Preheat-Cooldown 3.1	19,23	28,98	28,34	19,24	28,49	28,36	19,12	29,33	28,18	19,20	28,93	28,30	76,42	44,016	0,564	43,123	0,542	43,709	0,552	383276	90050	325	427
0-Preheat-Cooldown 3.2	18,52	28,94	26,66	18,51	28,54	26,65	18,53	29,13	26,68	18,52	28,87	26,66	74,05	40,784	0,500	41,409	0,501	41,421	0,510	382025	90162	314	428
0-Preheat-Cooldown 3.3	17,82	28,78	24,97	18,11	29,36	25,38	17,95	29,13	25,16	17,96	29,09	25,17	72,22	39,527	0,460	39,208	0,465	39,278	0,457	384839	90116	300	428
0-Preheat-Cooldown 3.4	17,34	28,82	23,52	17,18	29,11	23,30	17,08	28,88	23,16	17,20	28,93	23,33	69,47	37,567	0,422	38,563	0,426	37,845	0,414	383126	90093	284	428
0-Preheat-Cooldown 3.5	16,53	29,56	21,55	16,37	28,13	21,35	16,42	29,45	21,42	16,44	29,05	21,44	66,93	36,137	0,388	35,054	0,356	36,590	0,393	384331	90199	270	429
0-Preheat-Cooldown 3.6	15,52	29,39	19,28	15,57	28,68	19,34	15,39	29,13	19,12	15,49	29,07	19,25	63,80	35,284	0,351	33,900	0,335	35,611	0,357	383182	90162	254	430
0-Preheat-Cooldown 3.7	14,29	28,90	16,70	14,52	29,01	16,97	14,65	29,31	17,11	14,49	29,07	16,93	60,49	32,966	0,300	33,342	0,310	33,396	0,314	383844	90154	236	429
0-Preheat-Cooldown 3.8	13,28	29,00	14,33	13,36	29,59	14,42	13,47	29,75	14,53	13,37	29,44	14,43	57,23	32,488	0,272	32,349	0,277	31,984	0,273	388122	90127	217	430
0-Preheat-Cooldown 3.9	12,14	27,85	11,75	12,30	29,23	11,91	12,07	30,01	11,68	12,17	29,03	11,78	52,98	30,941	0,221	31,073	0,231	33,372	0,258	381669	90080	190	431
0-Preheat-Cooldown 3.10	10,60	30,19	8,75	11,07	28,61	9,14	10,67	29,57	8,81	10,78	29,46	8,90	49,13	37,148	0,236	31,500	0,199	35,552	0,225	387532	90143	160	430
0-Preheat-Cooldown 3.11	9,55	29,52	6,10	9,43	29,16	6,02	9,31	28,89	5,94	9,43	29,19	6,02	44,64	35,551	0,187	37,997	0,198	36,044	0,190	384852	90124	133	430
0-Preheat-Cooldown 3.12	7,98	29,41	3,03	8,03	29,78	3,05	7,99	29,18	3,04	8,00	29,46	3,04	40,49	37,556	0,171	40,084	0,190	36,414	0,168	386624	90091	117	431

Table 9-18: Results of three machines with fixed material – Preheat and cool down - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs	hrs	%	hrs	€	kg	kg	€	€	€	€	€	€
1-Preheat-Cooldown 1.1	1	130	12	24	36	0.1	8	70993	193	49232	15458	2953	3319	85567	20791	156614
1-Preheat-Cooldown 1.2	1	130	11	22	33	0.1	8	70985	192	48978	15379	2938	3320	85614	20708	156498
1-Preheat-Cooldown 1.3	1	130	10	20	30	0.1	8	70966	192	49041	15399	2942	3320	85600	18541	154337
1-Preheat-Cooldown 1.4	1	130	9	18	27	0.1	8	70940	193	49176	15441	2950	3322	85591	17333	153170
1-Preheat-Cooldown 1.5	1	130	8	16	24	0.1	8	70894	192	49167	15438	2950	3324	85575	15375	151188
1-Preheat-Cooldown 1.6	1	130	7	14	21	0.1	8	70873	193	49198	15448	2951	3326	85611	14625	150600
1-Preheat-Cooldown 1.7	1	130	6	12	18	0.1	8	70873	193	49235	15459	2954	3328	85626	14625	150536
1-Preheat-Cooldown 1.8	1	130	5	10	15	0.1	8	70873	193	49238	15460	2954	3329	85648	9833	145775
1-Preheat-Cooldown 1.9	1	130	4	8	12	0.1	8	70873	193	49241	15461	2954	3330	85632	250	136172
1-Preheat-Cooldown 1.10	1	130	3	6	9	0.1	8	70833	193	49346	15494	2960	3331	85634	208	136175
1-Preheat-Cooldown 1.11	1	130	2	4	6	0.1	8	70836	193	49319	15486	2959	3332	85614	125	136056
1-Preheat-Cooldown 1.12	1	130	1	2	3	0.1	8	70841	193	49259	15467	2955	3332	85603	125	136018
1-Preheat-Cooldown 2.1	1	60	12	24	36	0.1	8	81286	428	109270	34310	6556	7160	87318	60708	225161
1-Preheat-Cooldown 2.2	1	60	11	22	33	0.1	8	81364	433	110422	34672	6625	7176	87208	55541	220294
1-Preheat-Cooldown 2.3	1	60	10	20	30	0.1	8	81350	444	113313	35580	6798	7165	87174	51083	216860
1-Preheat-Cooldown 2.4	1	60	9	18	27	0.1	8	81378	434	110704	34761	6642	7176	87252	45666	210583
1-Preheat-Cooldown 2.5	1	60	8	16	24	0.1	8	81091	421	107262	33680	6435	7179	87332	38166	201904
1-Preheat-Cooldown 2.6	1	60	7	14	21	0.1	8	81229	437	111411	34983	6684	7176	87292	37916	203151
1-Preheat-Cooldown 2.7	1	60	6	12	18	0.1	8	81112	429	109482	34377	6568	7187	87237	37916	202367
1-Preheat-Cooldown 2.8	1	60	5	10	15	0.1	8	81264	423	107985	33907	6479	7184	87231	25458	189337
1-Preheat-Cooldown 2.9	1	60	4	8	12	0.1	8	80950	438	111829	35114	6709	7186	87228	4375	169690
1-Preheat-Cooldown 2.10	1	60	3	6	9	0.1	8	80571	430	109661	34433	6579	7186	87052	3583	167852
1-Preheat-Cooldown 2.11	1	60	2	4	6	0.1	8	81089	432	110257	34620	6615	7209	87342	3416	168318
1-Preheat-Cooldown 2.12	1	60	1	2	3	0.1	8	81110	433	110449	34681	6626	7208	87289	2416	167318
1-Preheat-Cooldown 3.1	1	20	12	24	36	0.1	8	118174	1301	331546	104105	19892	21391	88162	441500	704440
1-Preheat-Cooldown 3.2	1	20	11	22	33	0.1	8	117878	1276	325213	102116	19512	21348	88158	393041	653563
1-Preheat-Cooldown 3.3	1	20	10	20	30	0.1	8	118246	1285	327448	102818	19646	21339	88128	359666	620976
1-Preheat-Cooldown 3.4	1	20	9	18	27	0.1	8	117615	1298	330816	103876	19848	21437	88203	326250	589016
1-Preheat-Cooldown 3.5	1	20	8	16	24	0.1	8	118953	1291	328949	103290	19736	21423	88125	296000	557950
1-Preheat-Cooldown 3.6	1	20	7	14	21	0.1	8	118361	1304	332430	104383	19945	21447	88091	259000	522232
1-Preheat-Cooldown 3.7	1	20	6	12	18	0.1	8	117141	1289	328620	103186	19717	21448	88187	243166	505101
1-Preheat-Cooldown 3.8	1	20	5	10	15	0.1	8	118533	1306	332856	104516	19971	21400	88174	208708	472162
1-Preheat-Cooldown 3.9	1	20	4	8	12	0.1	8	120076	1291	329071	103328	19744	21483	88208	147291	409459
1-Preheat-Cooldown 3.10	1	20	3	6	9	0.1	8	118172	1284	327197	102740	19631	21528	88190	117708	379195
1-Preheat-Cooldown 3.11	1	20	2	4	6	0.1	8	118323	1293	329445	103445	19766	21540	88126	100583	362838
1-Preheat-Cooldown 3.12	1	20	1	2	3	0.1	8	118772	1326	338043	106145	20282	21511	88137	88500	353956

Name	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Waiting time in queue machine 3	Number in queue machine 3	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.			mm³	€	pcs.	pcs.
1-Preheat-Cooldown 1.1	4,39	4,50	6,48	4,21	4,32	6,21	4,36	4,61	6,44	4,32	4,48	6,38	15,18	---	0,001	9,406	0,001	---	0,002	367240	87469	1	66
1-Preheat-Cooldown 1.2	4,12	4,45	5,94	3,95	4,32	5,70	4,09	4,59	5,89	4,05	4,45	5,84	14,35	---	0,001	8,890	0,001	---	0,002	365066	87516	1	66
1-Preheat-Cooldown 1.3	3,85	4,44	5,40	3,69	4,32	5,18	3,83	4,62	5,37	3,79	4,46	5,31	13,56	---	0,001	8,373	0,001	---	0,002	365833	87502	1	66
1-Preheat-Cooldown 1.4	3,58	4,44	4,86	3,43	4,35	4,66	3,56	4,62	4,83	3,52	4,47	4,79	12,78	---	0,001	7,856	0,001	---	0,002	366561	87494	1	66
1-Preheat-Cooldown 1.5	3,32	4,44	4,34	3,16	4,35	4,13	3,30	4,62	4,30	3,26	4,47	4,26	11,99	---	0,001	7,670	0,001	---	0,002	366254	87477	1	66
1-Preheat-Cooldown 1.6	3,05	4,45	3,80	2,90	4,35	3,61	3,03	4,62	3,77	3,00	4,47	3,73	11,19	---	0,001	6,182	0,001	---	0,001	366430	87513	1	67
1-Preheat-Cooldown 1.7	2,78	4,45	3,25	2,65	4,35	3,10	2,77	4,63	3,24	2,73	4,47	3,20	10,40	---	0,001	5,732	0,001	---	0,001	366470	87529	1	67
1-Preheat-Cooldown 1.8	2,51	4,45	2,71	2,39	4,35	2,58	2,49	4,62	2,69	2,46	4,47	2,66	9,60	---	0,001	5,282	0,001	---	0,001	366434	87551	1	67
1-Preheat-Cooldown 1.9	2,24	4,45	2,17	2,13	4,35	2,07	2,23	4,62	2,16	2,20	4,47	2,13	8,80	---	0,001	4,832	0,001	---	0,001	366389	87534	1	67
1-Preheat-Cooldown 1.10	1,97	4,44	1,63	1,87	4,36	1,55	1,96	4,66	1,62	1,93	4,48	1,60	8,02	---	0,001	4,382	0,001	---	0,001	366922	87537	1	67
1-Preheat-Cooldown 1.11	1,70	4,44	1,09	1,62	4,35	1,03	1,69	4,66	1,08	1,67	4,48	1,07	7,22	---	0,001	3,932	0,001	---	0,001	366650	87517	1	67
1-Preheat-Cooldown 1.12	1,43	4,43	0,54	1,36	4,35	0,52	1,42	4,65	0,54	1,40	4,48	0,53	6,41	---	0,000	3,689	0,001	---	0,001	366250	87506	1	67
1-Preheat-Cooldown 2.1	9,10	10,17	13,43	9,09	9,44	13,42	8,90	9,62	13,13	9,03	9,74	13,33	32,10	33,386	0,034	33,538	0,030	34,635	0,033	380274	89259	24	143
1-Preheat-Cooldown 2.2	8,42	9,72	12,13	8,45	9,67	12,18	8,75	10,20	12,62	8,54	9,87	12,31	30,71	32,495	0,025	34,946	0,028	34,959	0,029	384760	89146	20	144
1-Preheat-Cooldown 2.3	7,92	9,85	11,11	8,01	9,96	11,23	7,94	10,55	11,13	7,95	10,12	11,16	29,23	34,992	0,026	36,776	0,026	38,712	0,030	396130	89111	19	143
1-Preheat-Cooldown 2.4	7,38	9,93	10,02	7,31	9,69	9,92	7,53	10,00	10,22	7,41	9,88	10,06	27,34	35,461	0,023	36,340	0,023	36,053	0,026	385085	89191	17	144
1-Preheat-Cooldown 2.5	6,68	9,63	8,72	7,01	9,85	9,16	6,86	9,19	8,95	6,85	9,56	8,95	25,36	32,931	0,020	33,297	0,020	---	0,020	374165	89272	14	144
1-Preheat-Cooldown 2.6	6,43	10,14	7,99	6,23	10,08	7,74	6,24	9,58	7,76	6,30	9,93	7,83	24,06	32,685	0,023	33,343	0,018	---	0,018	387451	89232	15	144
1-Preheat-Cooldown 2.7	5,65	9,71	6,61	5,86	9,92	6,85	5,76	9,69	6,74	5,76	9,77	6,73	22,26	31,139	0,018	30,520	0,018	---	0,017	379601	89176	14	144
1-Preheat-Cooldown 2.8	5,10	9,49	5,51	5,24	9,75	5,66	5,25	9,68	5,67	5,20	9,64	5,61	20,45	27,507	0,014	28,354	0,016	---	0,016	374364	89169	13	144
1-Preheat-Cooldown 2.9	4,51	9,74	4,37	4,78	10,26	4,62	4,63	9,94	4,48	4,64	9,98	4,49	19,11	25,097	0,012	29,575	0,018	---	0,014	389143	89166	13	144
1-Preheat-Cooldown 2.10	4,07	9,74	3,36	4,20	10,04	3,47	3,98	9,63	3,29	4,08	9,80	3,37	17,26	26,599	0,013	25,583	0,014	28,499	0,013	381829	88986	12	144
1-Preheat-Cooldown 2.11	3,57	10,22	2,28	3,50	9,62	2,24	3,48	9,65	2,22	3,52	9,83	2,25	15,60	28,370	0,013	24,143	0,011	32,217	0,013	382036	89283	10	144
1-Preheat-Cooldown 2.12	2,98	10,06	1,13	2,96	9,98	1,12	2,97	9,52	1,13	2,97	9,86	1,13	13,95	23,849	0,009	---	0,011	32,131	0,011	383785	89229	9	144
1-Preheat-Cooldown 3.1	18,41	29,13	27,13	18,69	28,52	27,56	18,67	30,17	27,52	18,59	29,27	27,40	75,26	44,418	0,566	44,680	0,582	45,094	0,609	387007	90121	335	428
1-Preheat-Cooldown 3.2	18,21	28,25	26,23	18,16	28,78	26,16	18,11	29,11	26,09	18,16	28,71	26,16	73,03	40,698	0,507	42,129	0,543	42,330	0,544	380802	90117	326	427
1-Preheat-Cooldown 3.3	17,40	28,86	24,38	17,37	29,34	24,33	17,42	28,55	24,41	17,39	28,92	24,37	70,68	40,682	0,499	41,362	0,514	39,594	0,478	383815	90086	314	427
1-Preheat-Cooldown 3.4	16,82	28,87	22,81	16,73	29,62	22,69	16,63	29,09	22,54	16,72	29,19	22,68	68,59	38,771	0,455	39,216	0,469	39,886	0,461	385581	90163	302	429
1-Preheat-Cooldown 3.5	15,88	29,72	20,71	16,03	28,57	20,92	15,76	28,88	20,54	15,89	29,06	20,72	65,67	37,218	0,427	37,829	0,423	37,868	0,411	383736	90083	286	428
1-Preheat-Cooldown 3.6	15,05	29,78	18,71	15,13	29,22	18,80	15,01	29,12	18,66	15,07	29,37	18,72	63,16	37,213	0,395	35,856	0,384	35,475	0,371	387453	90049	272	429
1-Preheat-Cooldown 3.7	14,08	29,15	16,46	14,15	28,79	16,54	14,18	29,08	16,58	14,14	29,01	16,53	59,67	34,130	0,334	34,652	0,347	34,850	0,347	382483	90147	253	429
1-Preheat-Cooldown 3.8	13,05	30,02	14,09	12,88	29,55	13,90	12,94	28,59	13,97	12,96	29,39	13,98	56,33	34,358	0,332	34,700	0,328	33,195	0,302	389158	90134	240	428
1-Preheat-Cooldown 3.9	11,82	29,21	11,45	12,02	29,16	11,64	11,76	28,73	11,39	11,87	29,03	11,49	52,39	31,776	0,280	30,796	0,276	32,297	0,282	383055	90168	226	430
1-Preheat-Cooldown 3.10	10,76	28,65	8,88	10,60	29,03	8,76	10,54	28,95	8,71	10,63	28,88	8,78	48,29	29,034	0,239	30,555	0,260	30,902	0,253	379584	90149	212	431
1-Preheat-Cooldown 3.11	9,27	29,15	5,92	9,30	28,73	5,94	9,21	29,43	5,88	9,26	29,10	5,91	44,27	30,315	0,227	30,243	0,222	31,275	0,236	382145	90084	190	431
1-Preheat-Cooldown 3.12	7,77	30,21	2,95	7,94	29,79	3,02	7,84	29,57	2,98	7,85	29,86	2,98	40,69	32,536	0,214	32,989	0,220	32,699	0,206	392820	90096	165	430

Table 9-19: Results of three machines with fixed material – Start volume - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Waiting time in queue machine 3	Number in queue machine 3	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs	%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.			mm³	€	pcs.	pcs.
Start volume 1.1	1	60	4	8	12	1	8	81046	437	111540	35023	6692	7182	87170	5416	170542	4,50	9,65	4,36	4,77	10,41	4,62	4,65	9,81	4,50	4,64	9,96	4,49	19,09	26,275	0,013	28,452	0,017	---	0,014	388152	89107	13	144
Start volume 1.2	1	60	4	8	12	0.9	8	81046	437	111540	35023	6692	7182	87170	5416	170542	4,50	9,65	4,36	4,77	10,41	4,62	4,65	9,81	4,50	4,64	9,96	4,49	19,09	26,275	0,013	28,452	0,017	---	0,014	388152	89107	13	144
Start volume 1.3	1	60	4	8	12	0.8	8	81046	437	111540	35023	6692	7182	87170	5416	170542	4,50	9,65	4,36	4,77	10,41	4,62	4,65	9,81	4,50	4,64	9,96	4,49	19,09	26,275	0,013	28,452	0,017	---	0,014	388152	89107	13	144
Start volume 1.4	1	60	4	8	12	0.7	8	81046	437	111540	35023	6692	7182	87170	5416	170542	4,50	9,65	4,36	4,77	10,41	4,62	4,65	9,81	4,50	4,64	9,96	4,49	19,09	26,275	0,013	28,452	0,017	---	0,014	388152	89107	13	144
Start volume 1.5	1	60	4	8	12	0.6	8	81046	437	111540	35023	6692	7182	87170	5416	170542	4,50	9,65	4,36	4,77	10,41	4,62	4,65	9,81	4,50	4,64	9,96	4,49	19,09	26,275	0,013	28,452	0,017	---	0,014	388152	89107	13	144
Start volume 1.6	1	60	4	8	12	0.5	8	81046	437	111540	35023	6692	7182	87170	5416	170542	4,50	9,65	4,36	4,77	10,41	4,62	4,65	9,81	4,50	4,64	9,96	4,49	19,09	26,275	0,013	28,452	0,017	---	0,014	388152	89107	13	144
Start volume 1.7	1	60	4	8	12	0.4	8	81046	437	111540	35023	6692	7182	87170	5416	170542	4,50	9,65	4,36	4,77	10,41	4,62	4,65	9,81	4,50	4,64	9,96	4,49	19,09	26,275	0,013	28,452	0,017	---	0,014	388152	89107	13	144
Start volume 1.8	1	60	4	8	12	0.3	8	81046	437	111540	35023	6692	7182	87170	5416	170542	4,50	9,65	4,36	4,77	10,41	4,62	4,65	9,81	4,50	4,64	9,96	4,49	19,09	26,275	0,013	28,452	0,017	---	0,014	388152	89107	13	144
Start volume 1.9	1	60	4	8	12	0.2	8	81046	437	111540	35023	6692	7182	87170	5416	170542	4,50	9,65	4,36	4,77	10,41	4,62	4,65	9,81	4,50	4,64	9,96	4,49	19,09	26,275	0,013	28,452	0,017	---	0,014	388152	89107	13	144
Start volume 1.10	1	60	4	8	12	0.1	8	80950	438	111829	35114	6709	7186	87228	4375	169690	4,51	9,74	4,37	4,78	10,26	4,62	4,63	9,94	4,48	4,64	9,98	4,49	19,11	25,097	0,012	29,575	0,018	---	0,014	389143	89166	13	144
Start volume 1.11	1	60	4	8	12	0.0	8	81298	430	109643	34427	6578	7189	87144	4125	168513	4,58	9,61	4,44	4,74	10,12	4,59	4,61	9,63	4,46	4,64	9,79	4,50	18,92	---	0,011	29,683	0,017	26,402	0,014	380906	89081	12	144

Table 9-20: Results of three machines with fixed material – Elapse time - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Waiting time in queue machine 1	Number in queue machine 1	Waiting time in queue machine 2	Number in queue machine 2	Waiting time in queue machine 3	Number in queue machine 3	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs	%	hrs	€	kg	kg	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	hrs	pcs.			mm³	€	pcs.	pcs.
Elapse time 1.1	1	60	4	8	12	0.1	12	81062	432	110112	34575	6606	7185	87246	30166	194863	4,64	10,04	4,50	4,65	9,67	4,50	4,62	9,77	4,47	4,64	9,83	4,49	18,95	26,855	0,015	30,558	0,017	---	0,016	381967	89185	13	144
Elapse time 1.2	1	60	4	8	12	0.1	11	80885	427	108970	34216	6538	7182	87121	24583	188682	4,56	9,89	4,42	4,70	9,63	4,56	4,66	9,69	4,51	4,64	9,74	4,50	18,88	27,695	0,015	30,390	0,017	---	0,015	378550	89057	13	144
Elapse time 1.3	1	60	4	8	12	0.1	10	81014	436	111289	34945	6677	7189	87122	24083	189057	4,52	9,74	4,38	4,70	10,14	4,55	4,72	9,96	4,57	4,65	9,95	4,50	19,09	27,768	0,014	31,847	0,018	---	0,015	385853	89058	13	144
Elapse time 1.4	1	60	4	8	12	0.1	9	80936	439	112016	35173	6721	7180	87209	11250	176604	4,50	9,78	4,36	4,74	10,20	4,59	4,66	10,02	4,51	4,63	10,00	4,49	19,12	25,484	0,013	29,795	0,018	---	0,014	389697	89147	13	144
Elapse time 1.5	1	60	4	8	12	0.1	8	80950	438	111829	35114	6709	7186	87228	4375	169690	4,51	9,74	4,37	4,78	10,26	4,62	4,63	9,94	4,48	4,64	9,98	4,49	19,11	25,097	0,012	29,575	0,018	---	0,014	389143	89166	13	144
Elapse time 1.6	1	60	4	8	12	0.1	7	80813	429	109412	34355	6564	7186	87103	3583	167828	4,55	9,70	4,40	4,78	10,04	4,64	4,60	9,57	4,46	4,65	9,77	4,50	18,92	25,571	0,011	29,158	0,016	---	0,014	380553	89039	12	144
Elapse time 1.7	1	60	4	8	12	0.1	6	80638	437	111345	34962	6680	7191	86966	3583	168373	4,55	9,84	4,41	4,75	10,15	4,60	4,65	9,91	4,51	4,65	9,97	4,51	19,12	25,640	0,012	---	0,015	25,756	0,013	386755	88898	13	144
Elapse time 1.8	1	60	4	8	12	0.1	5	80351	434	110762	34779	6645	7187	87081	3916	168638	4,60	9,73	4,46	4,75	10,19	4,60	4,58	9,80	4,43	4,64	9,91	4,50	19,05	27,835	0,013	27,842	0,016	28,695	0,013	385806	89016	12	144
Elapse time 1.9	1	60	4	8	12	0.1	4	80429	435	110925	34830	6655	7193	87079	4416	169202	4,68	9,95	4,54	4,68	9,84	4,53	4,58	9,94	4,43	4,65	9,91	4,50	19,06	29,788	0,013	26,886	0,014	26,584	0,013	385925	89014	12	144
Elapse time 1.10	1	60	4	8	12	0.1	3	80906	432	110133	34581	6608	7203	87232	4208	168910	4,71	9,96	4,56	4,61	9,65	4,47	4,61	9,88	4,47	4,65	9,83	4,50	18,97	28,390	0,012	26,162	0,013	28,540	0,013	381999	89170	11	144
Elapse time 1.11	1	60	4	8	12	0.1	2	81019	433	110420	34672	6625	7206	87239	3916	168740	4,74	10,27	4,59	4,67	9,71	4,52	4,55	9,58	4,41	4,65	9,85	4,50	19,01	28,134	0,013	26,372	0,012	27,409	0,012	381807	89178	11	144
Elapse time 1.12	1	60	4	8	12	0.1	1	81416	439	111959	35155	6717	7205	87135	3708	168966	4,64	10,02	4,49	4,77	10,36	4,62	4,57	9,63	4,42	4,66	10,00	4,51	19,17	25,896	0,012	27,470	0,013	26,116	0,011	388835	89071	11	144
Elapse time 1.13	1	60	4	8	12	0.1	0	81760	445	113568	35660	6814	7212	87231	3875	169870	4,68	10,11	4,53	4,70	10,32	4,56	4,59	9,96	4,44	4,66	10,13	4,51	19,30	28,692	0,012	30,229	0,014	26,860	0,012	393094	89169	10	144

2.4 RESULTS OF THREE MACHINES WITH FLEXIBLE MATERIAL

Table 9-21: Results of three machines with flexible material - Upper limit - No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Material change time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs	hrs	%	hrs	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Upper limit 1.1	0	150	4	5	8	12	0.1	8	70143	177	45150	14177	2709	2894	84929	0	133019	2,049	4,450	1,849	2,029	4,023	1,844	2,124	3,927	1,909	2,067	4,133	1,868	8,068	---	0,000	391594	86816	0,000	58
Upper limit 1.2	0	140	4	5	8	12	0.1	8	70526	189	48189	15131	2891	3095	85318	0	134876	2,139	4,794	1,932	2,214	4,363	2,014	2,246	4,036	2,017	2,200	4,398	1,988	8,585	---	0,000	392299	87214	0,000	62
Upper limit 1.3	0	130	4	5	8	12	0.1	8	71190	201	51233	16087	3073	3328	85308	0	136234	2,292	5,054	2,080	2,401	4,600	2,193	2,375	4,369	2,145	2,356	4,674	2,139	9,169	---	0,000	386891	87204	0,000	67
Upper limit 1.4	0	120	4	5	8	12	0.1	8	72098	218	55700	17490	3342	3605	85976	0	139073	2,450	5,368	2,232	2,576	4,983	2,362	2,540	4,782	2,303	2,522	5,044	2,299	9,865	---	0,000	388451	87887	0,000	72
Upper limit 1.5	0	110	4	5	8	12	0.1	8	73004	237	60423	18973	3625	3928	85627	0	140697	2,654	5,742	2,425	2,838	5,490	2,612	2,752	5,277	2,504	2,748	5,503	2,513	10,765	---	0,000	386872	87530	0,000	79
Upper limit 1.6	0	100	4	5	8	12	0.1	8	74128	260	66425	20857	3985	4321	86358	0	144310	2,905	6,215	2,666	3,110	6,154	2,871	2,949	5,590	2,689	2,988	5,986	2,742	11,716	---	0,000	386260	88277	0,000	86
Upper limit 1.7	0	90	4	5	8	12	0.1	8	75358	287	73256	23002	4395	4795	86229	0	147166	3,216	6,907	2,967	3,455	6,845	3,201	3,249	6,089	2,973	3,307	6,614	3,047	12,968	---	0,000	383365	88145	0,000	96
Upper limit 1.8	0	80	4	5	8	12	0.1	8	76998	324	82694	25966	4961	5393	86708	0	151932	3,586	7,518	3,287	3,816	7,689	3,522	3,755	7,058	3,418	3,719	7,422	3,409	14,550	---	0,000	385448	88635	0,000	108
Upper limit 1.9	0	70	4	5	8	12	0.1	8	79145	380	96845	30409	5810	6172	87030	0	158433	4,039	8,429	3,684	4,307	8,538	3,894	4,558	9,019	4,081	4,301	8,662	3,886	16,850	---	0,000	395338	88964	0,000	123
Upper limit 1.10	0	60	4	5	8	12	0.1	8	81466	423	107811	33852	6468	7188	87275	0	163877	4,797	9,320	4,306	5,053	9,086	4,465	5,408	10,445	4,769	5,086	9,617	4,513	19,216	---	0,000	376009	89214	0,000	144
Upper limit 1.11	0	50	4	5	8	12	0.1	8	84767	512	130540	40989	7832	8623	87579	41	174260	5,853	10,811	5,151	6,302	11,565	5,443	6,504	12,427	5,590	6,220	11,601	5,394	23,215	---	0,000	380149	89525	0,067	172
Upper limit 1.12	0	40	4	5	8	12	0.1	8	90275	657	167623	52633	10057	10775	87814	166	190719	7,428	13,988	6,454	7,858	14,772	6,725	8,217	15,796	6,992	7,835	14,852	6,724	29,410	---	0,001	391011	89766	0,233	216
Upper limit 1.13	0	30	4	5	8	12	0.1	8	99982	861	219501	68923	13170	14424	88138	458	214494	10,154	18,301	8,495	10,817	19,202	8,921	11,657	20,644	9,486	10,876	19,383	8,968	39,226	6,191	0,003	382545	90097	3,217	288
Upper limit 1.14	0	20	4	5	8	12	0.1	8	117594	1298	330758	103858	19845	21550	88351	11833	274890	16,720	28,284	12,588	18,147	29,059	13,536	18,837	30,075	13,970	17,901	29,139	13,365	60,406	10,620	0,094	386009	90315	73,467	431
Upper limit 1.15	0	10	4	5	8	12	0.1	8	174999	2056	523870	164495	31432	33762	88448	2124333	2471954	30,144	46,129	20,882	30,172	46,070	20,946	30,190	46,104	20,919	30,169	46,101	20,916	97,186	12,450	8,806	390217	90413	58.618,067	675

Table 9-22: Results of three machines with flexible material - Upper limit - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Material change time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs	hrs	%	hrs	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Upper limit 2.3	1	130	4	5	8	12	0.1	8	71190	201	51229	16086	3073	3327	85381	916	137246	2,291	5,050	2,078	2,400	4,596	2,190	2,371	4,364	2,142	2,354	4,670	2,137	9,160	---	0,000	386950	87279	0,000	67
Upper limit 2.4	1	120	4	5	8	12	0.1	8	72098	218	55694	17488	3341	3604	86011	916	140032	2,448	5,366	2,231	2,576	4,979	2,360	2,536	4,780	2,301	2,520	5,041	2,297	9,858	---	0,000	388609	87922	0,000	72
Upper limit 2.5	1	110	4	5	8	12	0.1	8	73004	237	60414	18970	3624	3925	85690	958	141732	2,651	5,737	2,422	2,835	5,485	2,607	2,747	5,273	2,501	2,744	5,498	2,510	10,752	---	0,000	387059	87594	0,000	79
Upper limit 2.6	1	100	4	5	8	12	0.1	8	74119	260	66404	20851	3984	4318	86368	1041	145352	2,909	6,240	2,669	3,097	6,115	2,858	2,949	5,598	2,692	2,985	5,985	2,739	11,709	---	0,000	386701	88287	0,000	86
Upper limit 2.7	1	90	4	5	8	12	0.1	8	75574	288	73389	23044	4403	4795	86230	1208	148425	3,173	6,784	2,918	3,468	6,952	3,212	3,298	6,139	3,009	3,313	6,625	3,046	12,985	---	0,000	384700	88146	0,000	96
Upper limit 2.8	1	80	4	5	8	12	0.1	8	76639	325	83001	26062	4980	5392	86881	1708	153984	3,683	7,432	3,363	3,753	7,388	3,417	3,769	7,495	3,422	3,735	7,438	3,401	14,574	---	0,000	386319	88811	0,000	108
Upper limit 2.9	1	70	4	5	8	12	0.1	8	78525	375	95613	30022	5736	6161	87197	2833	161017	4,124	8,274	3,698	4,371	8,225	3,877	4,584	9,098	4,040	4,360	8,532	3,871	16,764	---	0,000	389911	89135	0,000	123
Upper limit 2.10	1	60	4	5	8	12	0.1	8	81248	425	108452	34054	6507	7186	87356	4791	169015	4,991	9,380	4,408	5,008	9,324	4,335	5,522	10,279	4,781	5,174	9,661	4,508	19,342	---	0,000	378199	89298	0,000	144
Upper limit 2.11	1	50	4	5	8	12	0.1	8	85045	512	130647	41023	7838	8617	87407	6333	180355	5,985	11,098	5,253	6,269	11,655	5,414	6,489	12,147	5,539	6,248	11,634	5,402	23,283	---	0,000	381334	89349	0,100	172
Upper limit 2.12	1	40	4	5	8	12	0.1	8	90402	654	166860	52394	10011	10763	87822	8000	198266	7,444	13,698	6,401	7,891	14,979	6,718	8,412	15,682	7,029	7,915	14,786	6,716	29,418	---	0,001	390320	89774	0,417	215
Upper limit 2.13	1	30	4	5	8	12	0.1	8	100245	879	224051	70352	13443	14368	88149	22791	238487	10,730	18,995	8,464	11,539	19,871	8,961	12,235	20,487	9,368	11,501	19,784	8,931	40,217	8,173	0,008	392578	90108	7,117	287
Upper limit 2.14	1	20	4	5	8	12	0.1	8	118375	1277	325464	102195	19527	21538	88349	52375	313436	17,601	27,618	12,867	18,507	28,953	13,397	19,074	29,447	13,750	18,394	28,673	13,338	60,405	10,744	0,139	379486	90313	108,983	431
Upper limit 2.15	1	10	4	5	8	12	0.1	8	173105	2044	520792	163528	31247	33880	88426	2163500	2510058	30,333	45,692	21,018	30,154	46,038	20,899	30,279	45,788	21,012	30,255	45,839	20,976	97,071	12,368	8,144	386791	90391	59.223,117	678

Table 9-23: Results of three machines with flexible material – Preheat and cool down - No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Material change time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs	hrs	hrs	%	hrs	€	kg	kWh	€	€	€	€	€	€
0-Preheat-Cooldown 1.1	0	40	12	5	24	36	0.1	8	90529	659	167922	52727	10075	10747	88031	65291	256217
0-Preheat-Cooldown 1.2	0	40	11	5	22	33	0.1	8	89940	659	168064	52772	10083	10760	87920	60000	250844
0-Preheat-Cooldown 1.3	0	40	10	5	20	30	0.1	8	89967	648	165157	51859	9909	10754	87847	57250	246903
0-Preheat-Cooldown 1.4	0	40	9	5	18	27	0.1	8	90919	650	165849	52076	9950	10762	87967	60791	250871
0-Preheat-Cooldown 1.5	0	40	8	5	16	24	0.1	8	90497	644	164271	51581	9856	10753	87843	46291	235607
0-Preheat-Cooldown 1.6	0	40	7	5	14	21	0.1	8	90449	652	166314	52222	9978	10774	87867	21625	211757
0-Preheat-Cooldown 1.7	0	40	6	5	12	18	0.1	8	90476	652	166145	52169	9968	10765	87794	7041	197004
0-Preheat-Cooldown 1.8	0	40	5	5	10	15	0.1	8	89689	652	166148	52170	9968	10758	87773	0	189929
0-Preheat-Cooldown 1.9	0	40	4	5	8	12	0.1	8	90275	657	167623	52633	10057	10775	87814	166	190719
0-Preheat-Cooldown 1.10	0	40	3	5	6	9	0.1	8	90531	654	166820	52381	10009	10781	87738	0	190157
0-Preheat-Cooldown 1.11	0	40	2	5	4	6	0.1	8	90602	653	166558	52299	9993	10780	87808	0	190151
0-Preheat-Cooldown 1.12	0	40	1	5	2	3	0.1	8	90252	660	168284	52841	10097	10774	87785	41	190802
0-Preheat-Cooldown 2.1	0	20	12	5	24	36	0.1	8	118750	1239	315784	99156	18947	20623	88388	973375	1229952
0-Preheat-Cooldown 2.2	0	20	11	5	22	33	0.1	8	117947	1287	328054	103009	19683	21147	88384	605583	867268
0-Preheat-Cooldown 2.3	0	20	10	5	20	30	0.1	8	117939	1289	328626	103188	19717	21352	88374	286166	548258
0-Preheat-Cooldown 2.4	0	20	9	5	18	27	0.1	8	117338	1299	331012	103937	19860	21464	88417	185625	448778
0-Preheat-Cooldown 2.5	0	20	8	5	16	24	0.1	8	118215	1298	330824	103879	19849	21473	88393	132833	395893
0-Preheat-Cooldown 2.6	0	20	7	5	14	21	0.1	8	118070	1283	326985	102673	19619	21475	88417	92458	354116
0-Preheat-Cooldown 2.7	0	20	6	5	12	18	0.1	8	117596	1314	334948	105173	20096	21484	88336	51958	316495
0-Preheat-Cooldown 2.8	0	20	5	5	10	15	0.1	8	117793	1289	328451	103133	19707	21522	88357	18500	280673
0-Preheat-Cooldown 2.9	0	20	4	5	8	12	0.1	8	117594	1298	330758	103858	19845	21550	88351	11833	274890
0-Preheat-Cooldown 2.10	0	20	3	5	6	9	0.1	8	119208	1325	337740	106050	20264	21566	88281	6166	271756
0-Preheat-Cooldown 2.11	0	20	2	5	4	6	0.1	8	117901	1296	330259	103701	19815	21535	88259	2375	265106
0-Preheat-Cooldown 2.12	0	20	1	5	2	3	0.1	8	118799	1316	335468	105336	20128	21580	88301	2500	267280
0-Preheat-Cooldown 3.1	0	15	12	5	24	36	0.1	8	137186	1259	320870	100753	19252	20714	88363	1363625	1622162
0-Preheat-Cooldown 3.2	0	15	11	5	22	33	0.1	8	137247	1325	337646	106021	20258	21750	88412	1411000	1676914
0-Preheat-Cooldown 3.3	0	15	10	5	20	30	0.1	8	135779	1386	353285	110931	21197	22995	88429	1470625	1743656
0-Preheat-Cooldown 3.4	0	15	9	5	18	27	0.1	8	136613	1470	374578	117617	22474	24231	88417	1500375	1782589
0-Preheat-Cooldown 3.5	0	15	8	5	16	24	0.1	8	137037	1570	400198	125662	24011	25559	88419	1543375	1836501
0-Preheat-Cooldown 3.6	0	15	7	5	14	21	0.1	8	136253	1644	418998	131565	25139	27099	88401	1320250	1621923
0-Preheat-Cooldown 3.7	0	15	6	5	12	18	0.1	8	136658	1671	425875	133724	25552	28369	88448	533833	839411
0-Preheat-Cooldown 3.8	0	15	5	5	10	15	0.1	8	136037	1723	439132	137887	26347	28577	88422	190041	500751
0-Preheat-Cooldown 3.9	0	15	4	5	8	12	0.1	8	137570	1728	440299	138254	26417	28609	88437	87833	399031
0-Preheat-Cooldown 3.10	0	15	3	5	6	9	0.1	8	137182	1710	435812	136845	26148	28611	88438	38958	348482
0-Preheat-Cooldown 3.11	0	15	2	5	4	6	0,10	8	137128	1729	440759	138398	26445	28720	88403	22166	333602
0-Preheat-Cooldown 3.12	0	15	1	5	2	3	0,10	8	136366	1770	451177	141669	27070	28660	88369	15250	330476

Name	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
0-Preheat-Cooldown 1.1	14,309	14,168	18,654	15,543	14,865	20,023	16,849	15,506	21,530	15,567	14,846	20,069	50,482	9,563	0,005	392469	89988	4,050	215
0-Preheat-Cooldown 1.2	13,403	14,383	17,180	14,625	15,068	18,371	15,815	15,176	19,774	14,615	14,876	18,441	47,932	8,268	0,004	392500	89874	3,367	215
0-Preheat-Cooldown 1.3	12,594	13,565	15,718	13,587	14,928	16,806	14,530	15,411	17,782	13,570	14,634	16,769	44,973	---	0,002	386621	89799	2,400	215
0-Preheat-Cooldown 1.4	11,732	13,853	14,354	12,315	14,777	14,845	13,395	15,392	16,048	12,481	14,674	15,082	42,237	4,519	0,001	387882	89922	1,667	215
0-Preheat-Cooldown 1.5	10,758	13,843	12,748	11,198	14,596	13,131	12,376	15,220	14,367	11,444	14,553	13,415	39,413	3,374	0,001	384585	89795	1,133	215
0-Preheat-Cooldown 1.6	9,866	13,906	11,161	10,280	14,795	11,530	11,301	15,485	12,582	10,482	14,729	11,757	36,969	---	0,001	388456	89819	0,883	215
0-Preheat-Cooldown 1.7	9,022	13,825	9,642	9,702	15,020	10,233	9,959	15,346	10,359	9,561	14,730	10,078	34,370	2,146	0,001	387370	89745	0,600	215
0-Preheat-Cooldown 1.8	8,079	13,762	7,904	8,767	14,958	8,488	9,155	15,484	8,794	8,667	14,735	8,395	31,796	---	0,000	387289	89723	0,283	215
0-Preheat-Cooldown 1.9	7,428	13,988	6,454	7,858	14,772	6,725	8,217	15,796	6,992	7,835	14,852	6,724	29,410	---	0,001	391011	89766	0,233	216
0-Preheat-Cooldown 1.10	6,499	13,991	4,794	6,993	14,826	5,090	7,403	15,587	5,267	6,965	14,801	5,051	26,817	---	0,000	388901	89688	0,117	216
0-Preheat-Cooldown 1.11	5,748	14,081	3,238	6,069	14,731	3,351	6,460	15,482	3,501	6,092	14,765	3,363	24,220	---	0,000	388222	89760	0,050	216
0-Preheat-Cooldown 1.12	4,958	14,054	1,615	5,251	15,175	1,678	5,612	15,537	1,751	5,274	14,922	1,681	21,877	---	0,000	392428	89736	0,113	215
0-Preheat-Cooldown 2.1	31,115	28,045	38,180	31,172	27,937	38,289	31,446	27,441	38,596	31,244	27,807	38,355	97,407	19,198	9,222	385317	90352	4.033,000	412
0-Preheat-Cooldown 2.2	30,384	28,810	36,012	30,375	28,789	36,087	30,407	29,070	36,061	30,389	28,890	36,054	95,332	17,450	4,118	389744	90348	1.948,067	423
0-Preheat-Cooldown 2.3	28,506	29,234	32,613	29,152	28,549	33,347	29,186	29,042	33,333	28,948	28,942	33,098	90,987	15,405	1,493	386344	90338	802,833	427
0-Preheat-Cooldown 2.4	26,794	29,000	29,413	27,220	29,457	29,978	27,774	28,956	30,397	27,263	29,138	29,929	86,330	14,073	0,793	387031	90382	468,617	429
0-Preheat-Cooldown 2.5	24,815	28,328	26,095	25,311	29,617	26,518	26,071	29,445	27,253	25,399	29,130	26,622	81,151	12,897	0,453	386869	90358	291,433	429
0-Preheat-Cooldown 2.6	22,768	27,885	22,595	23,510	28,986	23,312	24,290	29,482	23,963	23,523	28,784	23,290	75,597	12,058	0,262	382374	90382	182,383	430
0-Preheat-Cooldown 2.7	20,839	28,842	19,415	21,940	29,139	20,154	22,400	30,555	20,400	21,726	29,512	19,990	71,228	11,867	0,200	391975	90299	140,267	430
0-Preheat-Cooldown 2.8	18,943	27,803	16,050	20,095	28,602	16,773	20,747	30,395	17,227	19,928	28,933	16,683	65,545	11,179	0,133	382903	90321	98,250	430
0-Preheat-Cooldown 2.9	16,720	28,284	12,588	18,147	29,059	13,536	18,837	30,075	13,970	17,901	29,139	13,365	60,406	10,620	0,094	386009	90315	73,467	431
0-Preheat-Cooldown 2.10	15,031	29,006	9,595	15,753	29,673	9,991	16,794	30,651	10,532	15,859	29,777	10,039	55,676	9,825	0,069	393313	90243	57,467	431
0-Preheat-Cooldown 2.11	12,861	28,070	6,405	13,678	28,994	6,636	14,461	30,303	7,014	13,667	29,123	6,685	49,474	8,988	0,038	385188	90220	32,783	431
0-Preheat-Cooldown 2.12	10,937	28,392	3,187	11,578	29,529	3,348	12,367	30,787	3,508	11,628	29,569	3,348	44,545	9,721	0,034	390279	90264	26,900	432
0-Preheat-Cooldown 3.1	31,702	27,567	38,885	31,397	28,271	38,520	31,114	28,947	38,202	31,404	28,262	38,536	98,201	20,263	7,214	389001	90327	32.381,250	414
0-Preheat-Cooldown 3.2	31,176	30,010	36,897	31,413	29,435	37,251	31,374	29,727	37,064	31,321	29,724	37,071	98,116	19,307	6,230	390443	90377	29.524,550	435
0-Preheat-Cooldown 3.3	31,650	30,284	36,009	31,147	31,376	35,477	31,059	31,627	35,382	31,285	31,095	35,623	98,003	18,222	5,754	386194	90394	25.402,900	460
0-Preheat-Cooldown 3.4	30,970	33,202	33,665	31,204	32,775	33,868	31,101	32,944	33,832	31,092	32,973	33,788	97,853	17,306	4,058	388678	90382	20.938,650	485
0-Preheat-Cooldown 3.5	30,741	35,246	31,652	30,618	35,559	31,484	30,945	34,887	31,897	30,768	35,230	31,677	97,676	16,233	3,314	393763	90384	16.003,317	511
0-Preheat-Cooldown 3.6	30,627	36,706	29,499	30,438	37,184	29,203	30,713	36,776	29,485	30,593	36,888	29,396	96,877	14,998	1,439	388503	90366	8.751,650	542
0-Preheat-Cooldown 3.7	29,487	37,300	26,283	29,661	37,608	26,310	29,861	37,524	26,493	29,669	37,477	26,362	93,509	13,154	3,977	377046	90414	2.532,750	567
0-Preheat-Cooldown 3.8	27,064	38,339	21,961	27,519	38,534	22,120	27,814	39,086	22,329	27,466	38,653	22,136	88,255	12,070	1,681	386271	90387	1.170,467	572
0-Preheat-Cooldown 3.9	24,562	37,783	17,545	24,829	39,127	17,604	25,489	39,344	18,028	24,960	38,751	17,726	81,437	11,295	0,883	386486	90403	661,950	572
0-Preheat-Cooldown 3.10	21,769	37,076	13,001	22,246	38,854	13,163	23,199	39,133	13,721	22,405	38,354	13,295	74,054	10,532	0,485	382925	90404	387,567	572
0-Preheat-Cooldown 3.11	19,265	37,742	8,668	19,777	38,981	8,868	20,587	39,700	9,167	19,877	38,808	8,901	67,585	9,878	0,318	385614	90367	269,083	574
0-Preheat-Cooldown 3.12	16,327	38,307	4,320	16,978	39,704	4,471	17,451	41,208	4,538	16,918	39,740	4,443	61,101	9,613	0,239	395822	90333	204,083	573

Table 9-24: Results of three machines with flexible material – Preheat and cool down - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Material change time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs	hrs	hrs	%	hrs	€	kg	kWh	€	€	€	€	€	€
1-Preheat-Cooldown 1.1	1	100	12	5	24	36	0,10	8	73965	268	68468	21499	4108	4313	86389	27791	172897
1-Preheat-Cooldown 1.2	1	100	11	5	22	33	0,10	8	74269	265	67550	21210	4053	4314	86208	28541	173064
1-Preheat-Cooldown 1.3	1	100	10	5	20	30	0,10	8	74416	259	66088	20751	3965	4318	86362	24875	169060
1-Preheat-Cooldown 1.4	1	100	9	5	18	27	0,10	8	74161	257	65525	20575	3931	4311	86337	24083	168019
1-Preheat-Cooldown 1.5	1	100	8	5	16	24	0,10	8	74350	260	66258	20805	3975	4316	86300	18750	162913
1-Preheat-Cooldown 1.6	1	100	7	5	14	21	0,10	8	74300	261	66622	20919	3997	4317	86469	16041	160568
1-Preheat-Cooldown 1.7	1	100	6	5	12	18	0,10	8	74226	260	66255	20804	3975	4316	86401	15333	159631
1-Preheat-Cooldown 1.8	1	100	5	5	10	15	0,10	8	74118	260	66393	20847	3983	4317	86362	12541	156839
1-Preheat-Cooldown 1.9	1	100	4	5	8	12	0,10	8	74119	260	66404	20851	3984	4318	86368	1041	145352
1-Preheat-Cooldown 1.10	1	100	3	5	6	9	0,10	8	74150	260	66465	20870	3987	4320	86402	583	144965
1-Preheat-Cooldown 1.11	1	100	2	5	4	6	0,10	8	74150	260	66472	20872	3988	4321	86391	0	144370
1-Preheat-Cooldown 1.12	1	100	1	5	2	3	0,10	8	74150	261	66508	20883	3990	4323	86383	0	144376
1-Preheat-Cooldown 2.1	1	60	12	5	24	36	0,10	8	81761	428	109067	34247	6544	7166	87329	45875	210272
1-Preheat-Cooldown 2.2	1	60	11	5	22	33	0,10	8	80822	427	109006	34228	6540	7176	87439	43791	208323
1-Preheat-Cooldown 2.3	1	60	10	5	20	30	0,10	8	80919	436	111217	34922	6673	7182	87449	41791	207169
1-Preheat-Cooldown 2.4	1	60	9	5	18	27	0,10	8	80858	435	110955	34839	6657	7194	87413	39541	204785
1-Preheat-Cooldown 2.5	1	60	8	5	16	24	0,10	8	81500	425	108402	34038	6504	7187	87154	31458	195395
1-Preheat-Cooldown 2.6	1	60	7	5	14	21	0,10	8	80963	428	109294	34318	6557	7180	87344	27083	191599
1-Preheat-Cooldown 2.7	1	60	6	5	12	18	0,10	8	81139	421	107417	33729	6445	7168	87340	25041	188838
1-Preheat-Cooldown 2.8	1	60	5	5	10	15	0,10	8	81458	419	106985	33593	6419	7194	87349	19541	183215
1-Preheat-Cooldown 2.9	1	60	4	5	8	12	0,10	8	81248	425	108452	34054	6507	7186	87356	4791	169015
1-Preheat-Cooldown 2.10	1	60	3	5	6	9	0,10	8	80965	428	109287	34316	6557	7186	87223	2583	166940
1-Preheat-Cooldown 2.11	1	60	2	5	4	6	0,10	8	81993	427	108996	34224	6539	7205	87168	0	164194
1-Preheat-Cooldown 2.12	1	60	1	5	2	3	0,10	8	81562	447	113910	35767	6834	7200	87298	0	166201
1-Preheat-Cooldown 3.1	1	20	12	5	24	36	0,10	8	118243	1241	316178	99279	18970	20555	88341	1020250	1276845
1-Preheat-Cooldown 3.2	1	20	11	5	22	33	0,10	8	117851	1293	329493	103461	19769	21100	88389	656083	918266
1-Preheat-Cooldown 3.3	1	20	10	5	20	30	0,10	8	117557	1302	331904	104218	19914	21354	88347	358750	622032
1-Preheat-Cooldown 3.4	1	20	9	5	18	27	0,10	8	118882	1290	328781	103237	19726	21407	88394	197166	459398
1-Preheat-Cooldown 3.5	1	20	8	5	16	24	0,10	8	118306	1291	329054	103323	19743	21451	88385	146583	408948
1-Preheat-Cooldown 3.6	1	20	7	5	14	21	0,10	8	117938	1296	330397	103744	19823	21448	88331	122125	384917
1-Preheat-Cooldown 3.7	1	20	6	5	12	18	0,10	8	118402	1304	332380	104367	19942	21500	88375	97333	360977
1-Preheat-Cooldown 3.8	1	20	5	5	10	15	0,10	8	118413	1296	330336	103725	19820	21465	88378	83375	346225
1-Preheat-Cooldown 3.9	1	20	4	5	8	12	0,10	8	118375	1277	325464	102195	19527	21538	88349	52375	313436
1-Preheat-Cooldown 3.10	1	20	3	5	6	9	0,10	8	117979	1343	342221	107457	20533	21529	88342	39166	306476
1-Preheat-Cooldown 3.11	1	20	2	5	4	6	0,10	8	118305	1284	327314	102776	19638	21501	88334	4875	266571
1-Preheat-Cooldown 3.12	1	20	1	5	2	3	0,10	8	118396	1314	334998	105189	20099	21516	88347	3000	267603

Name	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
1-Preheat-Cooldown 1.1	5,695	6,236	8,116	5,669	6,032	8,053	5,997	6,245	8,460	5,787	6,171	8,210	20,168	---	0,000	396670	88308	0,000	86
1-Preheat-Cooldown 1.2	5,126	6,143	7,141	5,584	6,056	7,766	5,572	6,082	7,702	5,428	6,093	7,537	19,058	---	0,000	391458	88124	0,000	86
1-Preheat-Cooldown 1.3	4,940	6,038	6,689	5,192	6,155	7,045	5,060	5,687	6,808	5,064	5,960	6,847	17,871	---	0,000	383799	88281	0,000	86
1-Preheat-Cooldown 1.4	4,489	5,957	5,885	4,830	6,268	6,343	4,797	5,493	6,236	4,705	5,906	6,155	16,766	---	0,000	379878	88256	0,000	86
1-Preheat-Cooldown 1.5	4,159	6,027	5,221	4,578	6,414	5,770	4,368	5,494	5,454	4,368	5,978	5,482	15,829	---	0,000	385272	88217	0,000	86
1-Preheat-Cooldown 1.6	3,854	6,165	4,594	4,178	6,322	5,013	4,002	5,496	4,754	4,011	5,994	4,787	14,793	---	0,000	388162	88390	0,000	86
1-Preheat-Cooldown 1.7	3,577	6,312	4,000	3,801	6,118	4,274	3,627	5,462	4,040	3,668	5,964	4,105	13,737	---	0,000	385540	88321	0,000	86
1-Preheat-Cooldown 1.8	3,246	6,236	3,337	3,455	6,149	3,575	3,278	5,552	3,357	3,326	5,979	3,423	12,729	---	0,000	386544	88281	0,000	86
1-Preheat-Cooldown 1.9	2,909	6,240	2,669	3,097	6,115	2,858	2,949	5,598	2,692	2,985	5,985	2,739	11,709	---	0,000	386701	88287	0,000	86
1-Preheat-Cooldown 1.10	2,559	6,212	1,991	2,750	6,132	2,152	2,611	5,617	2,021	2,640	5,987	2,055	10,682	---	0,000	386532	88322	0,000	86
1-Preheat-Cooldown 1.11	2,229	6,215	1,329	2,392	6,131	1,435	2,275	5,619	1,348	2,299	5,988	1,370	9,657	---	0,000	386416	88311	0,000	86
1-Preheat-Cooldown 1.12	1,898	6,224	0,665	2,034	6,133	0,718	1,939	5,617	0,674	1,957	5,991	0,686	8,634	---	0,000	386449	88303	0,000	86
1-Preheat-Cooldown 2.1	9,239	9,270	12,772	9,962	9,860	13,600	10,406	10,027	14,099	9,869	9,719	13,490	33,078	---	0,000	383245	89270	0,050	143
1-Preheat-Cooldown 2.2	8,818	10,055	11,930	9,113	9,187	12,241	9,783	9,875	12,937	9,238	9,705	12,369	31,313	---	0,000	382411	89383	0,000	144
1-Preheat-Cooldown 2.3	8,027	9,850	10,546	8,839	9,397	11,466	9,079	10,456	11,742	8,648	9,901	11,251	29,800	---	0,000	390859	89392	0,083	144
1-Preheat-Cooldown 2.4	7,640	9,594	9,684	8,046	9,897	10,138	8,510	10,138	10,613	8,065	9,876	10,145	28,087	---	0,000	387900	89356	0,017	144
1-Preheat-Cooldown 2.5	7,187	9,472	8,779	7,399	9,646	8,919	7,832	9,928	9,415	7,473	9,682	9,038	26,192	---	0,000	380049	89091	0,000	144
1-Preheat-Cooldown 2.6	6,795	9,626	7,841	6,689	9,649	7,595	7,229	9,940	8,219	6,905	9,738	7,885	24,528	---	0,000	385049	89285	0,000	144
1-Preheat-Cooldown 2.7	6,171	9,214	6,630	6,079	9,364	6,436	6,767	10,144	7,172	6,339	9,574	6,746	22,659	---	0,000	377066	89281	0,000	143
1-Preheat-Cooldown 2.8	5,548	9,282	5,496	5,639	9,421	5,486	6,089	9,889	5,940	5,759	9,531	5,641	20,930	---	0,000	372981	89291	0,000	144
1-Preheat-Cooldown 2.9	4,991	9,380	4,408	5,008	9,324	4,335	5,522	10,279	4,781	5,174	9,661	4,508	19,342	---	0,000	378199	89298	0,000	144
1-Preheat-Cooldown 2.10	4,341	9,574	3,247	4,602	9,311	3,373	4,820	10,370	3,538	4,588	9,752	3,386	17,726	---	0,000	382727	89161	0,000	144
1-Preheat-Cooldown 2.11	3,726	9,287	2,134	4,092	9,707	2,306	4,184	10,206	2,353	4,000	9,733	2,264	15,998	---	0,000	380745	89105	0,000	144
1-Preheat-Cooldown 2.12	3,188	9,441	1,070	3,378	9,861	1,110	3,703	11,168	1,210	3,423	10,157	1,130	14,710	---	0,000	397315	89238	0,000	144
1-Preheat-Cooldown 3.1	31,096	28,018	38,112	31,372	27,505	38,424	31,144	28,047	38,186	31,204	27,857	38,240	97,301	19,348	9,334	386601	90304	4.078,700	411
1-Preheat-Cooldown 3.2	30,274	29,172	35,829	30,317	29,151	35,921	30,498	28,722	36,123	30,363	29,015	35,958	95,336	17,505	4,682	392391	90353	2.205,250	422
1-Preheat-Cooldown 3.3	29,062	29,153	33,078	29,169	29,015	33,207	28,969	29,559	32,976	29,066	29,242	33,087	91,396	15,728	1,992	389965	90310	1.047,633	427
1-Preheat-Cooldown 3.4	27,394	28,747	29,787	27,366	29,026	29,787	27,500	29,078	29,908	27,420	28,950	29,827	86,197	14,110	0,953	385330	90359	567,917	428
1-Preheat-Cooldown 3.5	25,269	29,442	26,164	25,819	28,857	26,619	26,027	28,637	26,898	25,705	28,979	26,560	81,244	13,001	0,610	385145	90349	396,350	429
1-Preheat-Cooldown 3.6	23,312	29,541	22,756	24,266	28,396	23,577	24,089	29,402	23,465	23,889	29,113	23,266	76,268	12,055	0,408	387098	90294	285,250	429
1-Preheat-Cooldown 3.7	21,697	28,612	19,720	21,999	29,627	19,916	22,533	29,576	20,295	22,076	29,272	19,977	71,326	11,617	0,285	388159	90338	209,200	430
1-Preheat-Cooldown 3.8	19,587	28,321	16,226	20,258	29,241	16,645	20,810	29,709	16,982	20,218	29,090	16,618	65,926	11,015	0,195	386461	90342	148,067	429
1-Preheat-Cooldown 3.9	17,601	27,618	12,867	18,507	28,953	13,397	19,074	29,447	13,750	18,394	28,673	13,338	60,405	10,744	0,139	379486	90313	108,983	431
1-Preheat-Cooldown 3.10	15,752	29,012	9,559	17,072	29,848	10,242	17,126	31,592	10,215	16,650	30,150	10,005	56,806	10,520	0,118	398975	90305	93,300	431
1-Preheat-Cooldown 3.11	13,821	28,019	6,370	14,836	28,877	6,711	15,464	29,626	6,902	14,707	28,841	6,661	50,209	9,292	0,065	382253	90297	58,350	430
1-Preheat-Cooldown 3.12	12,028	28,151	3,199	12,794	29,643	3,357	13,376	30,742	3,443	12,732	29,512	3,333	45,578	9,107	0,054	390541	90311	49,133	430

Table 9-25: Results of three machines with flexible material – Start volume - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Material change time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs	hrs	%	hrs	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Start volume 1.1	1	60	4	5	8	12	1	8	81441	430	109725	34453	6583	7184	87340	7458	172133	4,991	9,294	4,395	5,043	9,598	4,352	5,527	10,435	4,774	5,187	9,776	4,507	19,470	---	0,000	382590	89281	0,000	144
Start volume 1.2	1	60	4	5	8	12	0,90	8	81441	430	109725	34453	6583	7184	87340	7458	172133	4,991	9,294	4,395	5,043	9,598	4,352	5,527	10,435	4,774	5,187	9,776	4,507	19,470	---	0,000	382590	89281	0,000	144
Start volume 1.3	1	60	4	5	8	12	0,80	8	81441	430	109725	34453	6583	7184	87340	7458	172133	4,991	9,294	4,395	5,043	9,598	4,352	5,527	10,435	4,774	5,187	9,776	4,507	19,470	---	0,000	382590	89281	0,000	144
Start volume 1.4	1	60	4	5	8	12	0,70	8	81441	430	109725	34453	6583	7184	87340	7458	172133	4,991	9,294	4,395	5,043	9,598	4,352	5,527	10,435	4,774	5,187	9,776	4,507	19,470	---	0,000	382590	89281	0,000	144
Start volume 1.5	1	60	4	5	8	12	0,60	8	81441	430	109725	34453	6583	7184	87340	7458	172133	4,991	9,294	4,395	5,043	9,598	4,352	5,527	10,435	4,774	5,187	9,776	4,507	19,470	---	0,000	382590	89281	0,000	144
Start volume 1.6	1	60	4	5	8	12	0,50	8	81441	430	109725	34453	6583	7184	87340	7458	172133	4,991	9,294	4,395	5,043	9,598	4,352	5,527	10,435	4,774	5,187	9,776	4,507	19,470	---	0,000	382590	89281	0,000	144
Start volume 1.7	1	60	4	5	8	12	0,40	8	81441	430	109725	34453	6583	7184	87340	7458	172133	4,991	9,294	4,395	5,043	9,598	4,352	5,527	10,435	4,774	5,187	9,776	4,507	19,470	---	0,000	382590	89281	0,000	144
Start volume 1.8	1	60	4	5	8	12	0,30	8	81441	430	109725	34453	6583	7184	87340	7416	172092	4,991	9,294	4,395	5,043	9,598	4,352	5,527	10,435	4,774	5,187	9,776	4,507	19,470	---	0,000	382590	89281	0,000	144
Start volume 1.9	1	60	4	5	8	12	0,20	8	81288	426	108703	34132	6522	7175	87287	6916	171130	4,987	9,279	4,385	5,038	9,535	4,346	5,545	10,255	4,782	5,190	9,690	4,504	19,384	---	0,000	379676	89227	0,000	144
Start volume 1.10	1	60	4	5	8	12	0,10	8	81248	425	108452	34054	6507	7186	87356	4791	169015	4,991	9,380	4,408	5,008	9,324	4,335	5,522	10,279	4,781	5,174	9,661	4,508	19,342	---	0,000	378199	89298	0,000	144
Start volume 1.11	1	60	4	5	8	12	0,00	8	81498	424	108085	33938	6485	7190	87136	2416	166213	4,945	9,620	4,413	5,173	9,189	4,534	5,247	10,153	4,615	5,122	9,654	4,520	19,297	---	0,000	379018	89073	0,000	144

Table 9-26: Results of three machines with flexible material – Elapse time - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Material change time	Cool down	Sum of setup and cool down	Production start volume	Elapse time	Total warehousing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total maintenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utilization 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utilization 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utilization 3	Machine cool down tracking 3	System setup	System utilization	System cool down	Total system utilization	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depreciation	Parts in queue total	AM parts out
	Switch	hrs	hrs	hrs	hrs	hrs	%	hrs	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Elapse time 1.1	1	60	4	5	8	12	0,10	12	81377	417	106422	33416	6385	7181	87324	22375	185791	4,954	9,121	4,356	5,062	9,283	4,378	5,549	10,044	4,786	5,188	9,482	4,506	19,177	---	0,000	371722	89265	0,000	144
Elapse time 1.2	1	60	4	5	8	12	0,10	11	81373	421	107478	33748	6448	7186	87356	20166	184026	4,992	9,271	4,393	5,069	9,504	4,386	5,491	9,946	4,745	5,184	9,574	4,508	19,266	---	0,000	375021	89298	0,000	144
Elapse time 1.3	1	60	4	5	8	12	0,10	10	81199	420	107123	33636	6427	7180	87348	18916	182625	4,901	9,214	4,321	5,106	9,401	4,424	5,527	10,010	4,767	5,178	9,542	4,504	19,224	---	0,000	374408	89289	0,000	144
Elapse time 1.4	1	60	4	5	8	12	0,10	9	81495	423	107953	33897	6477	7187	87379	9750	173818	4,938	9,368	4,364	5,047	9,391	4,369	5,544	10,082	4,789	5,176	9,613	4,507	19,297	---	0,000	376741	89321	0,000	144
Elapse time 1.5	1	60	4	5	8	12	0,10	8	81248	425	108452	34054	6507	7186	87356	4791	169015	4,991	9,380	4,408	5,008	9,324	4,335	5,522	10,279	4,781	5,174	9,661	4,508	19,342	---	0,000	378199	89298	0,000	144
Elapse time 1.6	1	60	4	5	8	12	0,10	7	81117	432	110094	34569	6605	7180	87287	3458	168196	4,958	9,604	4,383	5,056	9,338	4,376	5,496	10,514	4,764	5,170	9,819	4,508	19,496	---	0,000	384692	89227	0,000	144
Elapse time 1.7	1	60	4	5	8	12	0,10	6	81158	422	107677	33810	6460	7185	87281	2666	166497	4,917	9,565	4,375	5,064	8,845	4,399	5,471	10,401	4,762	5,150	9,604	4,512	19,266	---	0,000	375928	89220	0,000	144
Elapse time 1.8	1	60	4	5	8	12	0,10	5	80989	428	109157	34275	6549	7188	87201	2708	166989	4,892	9,623	4,336	5,168	9,282	4,501	5,403	10,323	4,714	5,154	9,743	4,517	19,414	---	0,000	382136	89139	0,000	144
Elapse time 1.9	1	60	4	5	8	12	0,10	4	81146	424	108170	33965	6490	7179	87145	1083	164912	4,832	9,249	4,295	5,158	9,272	4,502	5,421	10,460	4,745	5,137	9,660	4,514	19,311	---	0,000	380364	89082	0,000	144
Elapse time 1.10	1	60	4	5	8	12	0,10	3	81227	427	108805	34164	6528	7188	87168	0	164105	4,827	9,546	4,292	5,142	9,320	4,493	5,442	10,283	4,770	5,137	9,717	4,518	19,372	---	0,000	381723	89105	0,000	144
Elapse time 1.11	1	60	4	5	8	12	0,10	2	81633	421	107277	33685	6436	7192	87207	0	163591	4,797	9,291	4,285	5,187	9,445	4,568	5,363	9,984	4,704	5,116	9,573	4,519	19,208	---	0,000	376237	89145	0,000	144
Elapse time 1.12	1	60	4	5	8	12	0,10	1	81745	423	107979	33905	6478	7195	87331	0	164022	4,804	9,211	4,310	5,066	9,386	4,483	5,410	10,281	4,754	5,094	9,626	4,515	19,235	---	0,000	376349	89272	0,000	144
Elapse time 1.13	1	60	4	5	8	12	0,10	0	81550	423	107806	33851	6468	7195	87284	0	163895	4,800	9,414	4,298	5,057	9,091	4,464	5,447	10,344	4,791	5,101	9,616	4,518	19,235	---	0,000	376351	89224	0,000	144

Table 9-27: Results of three machines with flexible material – Material changeover time - Waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Material change time	Cool down	Sum of setup and cool down	Produc-tion start volume	Elapse time	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total mainte-nance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs	hrs	hrs	%	hrs	€	kg	kWh	€	€	€	€	€	€
1-Change over time 1.1	1	100	4	1	8	12	0,10	8	74139	260	66254	20803	3975	4318	86374	291	144554
1-Change over time 1.2	1	100	4	2	8	12	0,10	8	74139	260	66254	20803	3975	4318	86374	583	144846
1-Change over time 1.3	1	100	4	3	8	12	0,10	8	74139	260	66254	20803	3975	4318	86374	750	145013
1-Change over time 1.4	1	100	4	4	8	12	0,10	8	74139	260	66254	20803	3975	4318	86374	833	145097
1-Change over time 1.5	1	100	4	5	8	12	0,10	8	74119	260	66404	20851	3984	4318	86368	1041	145352
1-Change over time 1.6	1	100	4	6	8	12	0,10	8	74119	260	66404	20851	3984	4318	86368	1041	145353
1-Change over time 1.7	1	100	4	7	8	12	0,10	8	74176	260	66333	20828	3979	4317	86301	1041	145236
1-Change over time 1.8	1	100	4	8	8	12	0,10	8	74176	260	66333	20828	3979	4317	86301	1041	145236
1-Change over time 1.9	1	100	4	9	8	12	0,10	8	74176	260	66333	20828	3979	4317	86301	1041	145236
1-Change over time 1.10	1	100	4	10	8	12	0,10	8	74176	260	66333	20828	3979	4317	86302	1041	145237
1-Change over time 2.1	1	60	4	1	8	12	0,10	8	81121	432	110140	34583	6608	7200	87269	958	165710
1-Change over time 2.2	1	60	4	2	8	12	0,10	8	81195	430	109699	34445	6581	7195	87323	2916	167570
1-Change over time 2.3	1	60	4	3	8	12	0,10	8	81209	426	108700	34131	6522	7192	87316	3083	167352
1-Change over time 2.4	1	60	4	4	8	12	0,10	8	81100	427	108926	34203	6535	7192	87362	3625	168039
1-Change over time 2.5	1	60	4	5	8	12	0,10	8	81248	425	108452	34054	6507	7186	87356	4791	169015
1-Change over time 2.6	1	60	4	6	8	12	0,10	8	81181	426	108633	34110	6518	7186	87343	4791	169065
1-Change over time 2.7	1	60	4	7	8	12	0,10	8	80971	424	108209	33977	6492	7176	87335	4833	168927
1-Change over time 2.8	1	60	4	8	8	12	0,10	8	81056	422	107710	33821	6462	7179	87337	4583	168496
1-Change over time 2.9	1	60	4	9	8	12	0,10	8	81151	420	107100	33629	6426	7181	87346	4541	168240
1-Change over time 2.10	1	60	4	10	8	12	0,10	8	81184	423	107863	33869	6471	7183	87360	4833	168837
1-Change over time 3.1	1	20	4	1	8	12	0,10	8	117779	1305	332698	104467	19961	21533	88392	18666	282486
1-Change over time 3.2	1	20	4	2	8	12	0,10	8	118416	1312	334508	105035	20070	21479	88368	40333	304742
1-Change over time 3.3	1	20	4	3	8	12	0,10	8	118521	1327	338268	106216	20296	21490	88337	43583	309369
1-Change over time 3.4	1	20	4	4	8	12	0,10	8	117783	1293	329668	103515	19780	21491	88350	48416	311005
1-Change over time 3.5	1	20	4	5	8	12	0,10	8	118375	1277	325464	102195	19527	21538	88349	52375	313436
1-Change over time 3.6	1	20	4	6	8	12	0,10	8	118861	1293	329550	103478	19773	21490	88399	57208	319816
1-Change over time 3.7	1	20	4	7	8	12	0,10	8	117932	1327	338175	106187	20290	21521	88368	57708	323532
1-Change over time 3.8	1	20	4	8	8	12	0,10	8	117883	1305	332622	104443	19957	21496	88346	58750	322443
1-Change over time 3.9	1	20	4	9	8	12	0,10	8	118096	1283	326979	102671	19618	21477	88360	58916	320498
1-Change over time 3.10	1	20	4	10	8	12	0,10	8	118978	1304	332365	104362	19941	21501	88351	66208	329816

Name	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utili-zation 3	Machine cool down tracking 3	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm^3	€	pcs.	pcs.
1-Change over time 1.1	2,784	6,188	2,665	2,984	6,142	2,862	2,812	5,580	2,690	2,860	5,970	2,739	11,569	---	0,000	385739	88293	0,000	86
1-Change over time 1.2	2,814	6,188	2,665	3,013	6,142	2,862	2,846	5,580	2,690	2,891	5,970	2,739	11,601	---	0,000	385739	88293	0,000	86
1-Change over time 1.3	2,845	6,188	2,665	3,043	6,142	2,862	2,880	5,580	2,690	2,923	5,970	2,739	11,632	---	0,000	385739	88294	0,000	86
1-Change over time 1.4	2,875	6,188	2,665	3,073	6,142	2,862	2,914	5,580	2,690	2,954	5,970	2,739	11,664	---	0,000	385739	88294	0,000	86
1-Change over time 1.5	2,909	6,240	2,669	3,097	6,115	2,858	2,949	5,598	2,692	2,985	5,985	2,739	11,709	---	0,000	386701	88287	0,000	86
1-Change over time 1.6	2,940	6,240	2,669	3,127	6,115	2,858	2,983	5,598	2,692	3,017	5,985	2,739	11,741	---	0,000	386701	88287	0,000	86
1-Change over time 1.7	2,968	6,257	2,666	3,169	6,130	2,870	3,013	5,559	2,687	3,050	5,982	2,741	11,773	---	0,000	386443	88219	0,000	86
1-Change over time 1.8	2,999	6,257	2,666	3,199	6,130	2,870	3,047	5,559	2,687	3,082	5,982	2,741	11,805	---	0,000	386443	88219	0,000	86
1-Change over time 1.9	3,030	6,257	2,666	3,228	6,130	2,870	3,081	5,559	2,687	3,113	5,982	2,741	11,836	---	0,000	386443	88219	0,000	86
1-Change over time 1.10	3,061	6,257	2,666	3,258	6,130	2,870	3,116	5,559	2,687	3,145	5,982	2,741	11,868	---	0,000	386443	88219	0,000	86
1-Change over time 2.1	4,672	9,553	4,436	4,613	9,579	4,360	5,038	10,324	4,764	4,774	9,819	4,520	19,113	---	0,000	384236	89208	0,000	144
1-Change over time 2.2	4,731	9,482	4,411	4,681	9,553	4,325	5,203	10,287	4,808	4,872	9,774	4,515	19,160	---	0,000	382471	89264	0,000	144
1-Change over time 2.3	4,815	9,388	4,411	4,788	9,433	4,329	5,308	10,241	4,801	4,970	9,687	4,514	19,171	---	0,000	379077	89257	0,000	144
1-Change over time 2.4	4,924	9,429	4,424	4,883	9,354	4,319	5,417	10,324	4,791	5,074	9,702	4,511	19,288	---	0,000	379906	89303	0,000	144
1-Change over time 2.5	4,991	9,380	4,408	5,008	9,324	4,335	5,522	10,279	4,781	5,174	9,661	4,508	19,342	---	0,000	378199	89298	0,000	144
1-Change over time 2.6	5,075	9,388	4,406	5,125	9,373	4,337	5,644	10,275	4,783	5,281	9,679	4,509	19,469	---	0,000	379063	89284	0,000	144
1-Change over time 2.7	5,114	9,283	4,367	5,256	9,392	4,356	5,766	10,253	4,786	5,379	9,643	4,503	19,524	---	0,000	378343	89276	0,000	144
1-Change over time 2.8	5,224	9,324	4,372	5,375	9,333	4,364	5,859	10,138	4,777	5,486	9,598	4,504	19,589	---	0,000	376458	89278	0,000	144
1-Change over time 2.9	5,283	9,224	4,352	5,481	9,227	4,365	5,980	10,182	4,801	5,581	9,544	4,506	19,632	---	0,000	374279	89287	0,000	144
1-Change over time 2.10	5,410	9,340	4,375	5,591	9,310	4,357	6,080	10,183	4,786	5,694	9,611	4,506	19,810	---	0,000	376970	89301	0,000	144
1-Change over time 3.1	14,133	27,947	12,852	14,723	29,808	13,375	15,191	30,134	13,772	14,682	29,296	13,333	57,312	10,659	0,113	388204	90357	89,917	431
1-Change over time 3.2	14,873	28,685	12,791	15,677	29,442	13,373	16,160	30,266	13,755	15,570	29,464	13,306	58,340	10,647	0,118	391301	90331	93,783	430
1-Change over time 3.3	15,813	28,990	12,834	16,583	30,041	13,359	17,152	30,381	13,759	16,516	29,804	13,317	59,638	11,009	0,136	395744	90300	103,667	430
1-Change over time 3.4	16,625	28,060	12,846	17,597	29,108	13,394	18,068	29,964	13,704	17,430	29,044	13,315	59,789	10,963	0,143	385844	90314	108,617	430
1-Change over time 3.5	17,601	27,618	12,867	18,507	28,953	13,397	19,074	29,447	13,750	18,394	28,673	13,338	60,405	10,744	0,139	379486	90313	108,983	431
1-Change over time 3.6	18,746	27,739	13,000	19,335	29,418	13,313	20,045	29,893	13,615	19,376	29,016	13,309	61,701	10,680	0,150	384729	90363	118,167	430
1-Change over time 3.7	19,406	29,286	12,850	20,770	29,525	13,462	21,163	30,541	13,686	20,446	29,784	13,332	63,563	10,947	0,171	394615	90332	132,850	430
1-Change over time 3.8	20,553	28,505	12,944	21,580	29,484	13,360	22,142	29,928	13,652	21,425	29,306	13,319	64,049	10,822	0,184	388487	90310	140,917	430
1-Change over time 3.9	21,786	28,091	12,953	22,745	28,558	13,519	22,812	29,761	13,430	22,447	28,803	13,301	64,551	10,927	0,183	382405	90323	141,817	430
1-Change over time 3.10	22,744	28,562	13,023	23,660	29,064	13,398	23,954	30,214	13,539	23,453	29,280	13,320	66,053	11,167	0,220	388095	90314	164,567	430

Table 9-28: Results of three machines with flexible material – Material changeover time – No waiting

Name	Elapse time or volume filled	Mean arrival	Machine setup base time	Material change time	Cool down	Sum of setup and cool down	Produc-tion start volume	Elapse time	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total mainte-nance cost	Total penalty	Total AM cost
	Switch	hrs	hrs	hrs	hrs	hrs	%	hrs	€	kg	kWh	€	€	€	€	€	€
0-Change over time 1.1	0	120	4	1	8	12	0,10	8	72098	218	55700	17490	3342	3605	85975	0	139072
0-Change over time 1.2	0	120	4	2	8	12	0,10	8	72098	218	55700	17490	3342	3605	85976	0	139072
0-Change over time 1.3	0	120	4	3	8	12	0,10	8	72098	218	55700	17490	3342	3605	85976	0	139073
0-Change over time 1.4	0	120	4	4	8	12	0,10	8	72098	218	55700	17490	3342	3605	85976	0	139073
0-Change over time 1.5	0	120	4	5	8	12	0,10	8	72098	218	55700	17490	3342	3605	85976	0	139073
0-Change over time 1.6	0	120	4	6	8	12	0,10	8	72098	218	55700	17490	3342	3605	85977	0	139074
0-Change over time 1.7	0	120	4	7	8	12	0,10	8	72098	218	55700	17490	3342	3605	85977	0	139074
0-Change over time 1.8	0	120	4	8	8	12	0,10	8	72098	218	55700	17490	3342	3605	85977	0	139074
0-Change over time 1.9	0	120	4	9	8	12	0,10	8	72098	218	55700	17490	3342	3605	85977	208	139283
0-Change over time 1.10	0	120	4	10	8	12	0,10	8	72098	218	55700	17490	3342	3605	85978	541	139617
0-Change over time 2.1	0	70	4	1	8	12	0,10	8	78837	376	95886	30108	5753	6169	87091	0	158152
0-Change over time 2.2	0	70	4	2	8	12	0,10	8	78773	374	95537	29998	5732	6166	87099	0	158029
0-Change over time 2.3	0	70	4	3	8	12	0,10	8	78973	375	95618	30024	5737	6172	87085	0	158047
0-Change over time 2.4	0	70	4	4	8	12	0,10	8	79163	377	96061	30163	5763	6173	87046	0	158162
0-Change over time 2.5	0	70	4	5	8	12	0,10	8	79145	380	96845	30409	5810	6172	87030	0	158433
0-Change over time 2.6	0	70	4	6	8	12	0,10	8	78996	382	97495	30613	5849	6167	87058	0	158709
0-Change over time 2.7	0	70	4	7	8	12	0,10	8	79034	381	97105	30491	5826	6172	87082	0	158599
0-Change over time 2.8	0	70	4	8	8	12	0,10	8	79205	378	96551	30317	5793	6170	87080	0	158387
0-Change over time 2.9	0	70	4	9	8	12	0,10	8	79250	378	96512	30305	5790	6165	87089	375	158755
0-Change over time 2.10	0	70	4	10	8	12	0,10	8	79146	378	96546	30315	5792	6170	87051	1625	159971
0-Change over time 3.1	0	20	4	1	8	12	0,10	8	118411	1310	333923	104851	20035	21527	88287	6500	270631
0-Change over time 3.2	0	20	4	2	8	12	0,10	8	118180	1310	333774	104805	20026	21534	88279	8791	272864
0-Change over time 3.3	0	20	4	3	8	12	0,10	8	117690	1315	335247	105267	20114	21525	88315	10833	275495
0-Change over time 3.4	0	20	4	4	8	12	0,10	8	117915	1306	332970	104552	19978	21537	88326	11375	275211
0-Change over time 3.5	0	20	4	5	8	12	0,10	8	117594	1298	330758	103858	19845	21550	88351	11833	274890
0-Change over time 3.6	0	20	4	6	8	12	0,10	8	117794	1312	334389	104998	20063	21525	88370	12416	276832
0-Change over time 3.7	0	20	4	7	8	12	0,10	8	118949	1302	331797	104184	19907	21475	88328	12375	275713
0-Change over time 3.8	0	20	4	8	8	12	0,10	8	118892	1294	329704	103527	19782	21510	88342	14791	277400
0-Change over time 3.9	0	20	4	9	8	12	0,10	8	117939	1302	331767	104175	19906	21540	88364	23916	287357
0-Change over time 3.10	0	20	4	10	8	12	0,10	8	118716	1271	323934	101715	19436	21540	88380	39458	299989

Name	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	Machine setup tracking 3	Machine utili-zation 3	Machine cool down tracking 3	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	%	%	%	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
0-Change over time 1.1	2,334	5,368	2,232	2,464	4,983	2,362	2,411	4,782	2,303	2,403	5,044	2,299	9,746	---	0,000	388451	87886	0,000	72
0-Change over time 1.2	2,363	5,368	2,232	2,492	4,983	2,362	2,443	4,782	2,303	2,433	5,044	2,299	9,776	---	0,000	388451	87886	0,000	72
0-Change over time 1.3	2,392	5,368	2,232	2,520	4,983	2,362	2,475	4,782	2,303	2,462	5,044	2,299	9,806	---	0,000	388451	87887	0,000	72
0-Change over time 1.4	2,421	5,368	2,232	2,548	4,983	2,362	2,508	4,782	2,303	2,492	5,044	2,299	9,836	---	0,000	388451	87887	0,000	72
0-Change over time 1.5	2,450	5,368	2,232	2,576	4,983	2,362	2,540	4,782	2,303	2,522	5,044	2,299	9,865	---	0,000	388451	87887	0,000	72
0-Change over time 1.6	2,478	5,368	2,232	2,605	4,983	2,362	2,572	4,782	2,303	2,552	5,044	2,299	9,895	---	0,000	388451	87887	0,000	72
0-Change over time 1.7	2,507	5,368	2,232	2,633	4,983	2,362	2,605	4,782	2,303	2,582	5,044	2,299	9,925	---	0,000	388451	87887	0,000	72
0-Change over time 1.8	2,536	5,368	2,232	2,661	4,983	2,362	2,637	4,782	2,303	2,611	5,044	2,299	9,955	---	0,000	388451	87888	0,000	72
0-Change over time 1.9	2,565	5,368	2,232	2,689	4,983	2,362	2,669	4,782	2,303	2,641	5,044	2,299	9,984	---	0,000	388451	87888	0,000	72
0-Change over time 1.10	2,594	5,368	2,232	2,717	4,983	2,362	2,702	4,782	2,303	2,671	5,044	2,299	10,014	---	0,000	388451	87888	0,000	72
0-Change over time 2.1	3,848	8,520	3,682	4,087	8,524	3,904	4,257	8,672	4,058	4,064	8,572	3,881	16,517	---	0,000	391100	89026	0,000	123
0-Change over time 2.2	3,902	8,410	3,690	4,145	8,552	3,905	4,311	8,657	4,043	4,119	8,540	3,880	16,539	---	0,000	389702	89034	0,000	123
0-Change over time 2.3	3,983	8,474	3,722	4,171	8,405	3,876	4,386	8,766	4,053	4,180	8,548	3,884	16,611	---	0,000	389850	89020	0,000	123
0-Change over time 2.4	4,041	8,457	3,727	4,231	8,452	3,882	4,451	8,863	4,049	4,241	8,591	3,886	16,718	---	0,000	391417	88981	0,000	123
0-Change over time 2.5	4,039	8,429	3,684	4,307	8,538	3,894	4,558	9,019	4,081	4,301	8,662	3,886	16,850	---	0,000	395338	88964	0,000	123
0-Change over time 2.6	4,100	8,459	3,695	4,345	8,586	3,876	4,623	9,102	4,077	4,356	8,716	3,883	16,954	---	0,000	397381	88993	0,000	123
0-Change over time 2.7	4,147	8,502	3,704	4,427	8,429	3,898	4,667	9,120	4,052	4,413	8,684	3,885	16,982	---	0,000	395266	89017	0,000	123
0-Change over time 2.8	4,211	8,531	3,719	4,459	8,342	3,871	4,750	9,029	4,060	4,473	8,634	3,883	16,990	---	0,000	393076	89015	0,000	123
0-Change over time 2.9	4,256	8,549	3,703	4,519	8,347	3,857	4,852	8,997	4,080	4,542	8,631	3,880	17,053	---	0,000	394574	89024	0,000	123
0-Change over time 2.10	4,304	8,532	3,708	4,567	8,411	3,856	4,936	8,974	4,090	4,603	8,639	3,885	17,126	---	0,000	394162	88985	0,000	123
0-Change over time 3.1	13,820	28,547	12,694	14,652	28,859	13,425	15,278	30,908	13,963	14,583	29,438	13,361	57,382	9,878	0,069	389830	90249	57,717	431
0-Change over time 3.2	14,539	28,398	12,693	15,401	29,143	13,378	16,245	30,746	14,027	15,395	29,429	13,366	58,190	10,350	0,084	389729	90241	66,900	431
0-Change over time 3.3	15,482	28,190	12,813	16,171	29,489	13,250	17,111	30,963	14,002	16,255	29,547	13,355	59,157	10,078	0,087	390838	90277	69,233	431
0-Change over time 3.4	16,248	28,253	12,819	17,269	29,440	13,476	17,776	30,333	13,789	17,098	29,342	13,361	59,800	10,228	0,093	388128	90289	73,083	431
0-Change over time 3.5	16,720	28,284	12,588	18,147	29,059	13,536	18,837	30,075	13,970	17,901	29,139	13,365	60,406	10,620	0,094	386009	90315	73,467	431
0-Change over time 3.6	18,037	27,836	12,916	18,652	29,958	13,252	19,764	30,557	13,873	18,818	29,451	13,347	61,616	10,627	0,106	390161	90334	81,983	431
0-Change over time 3.7	18,652	28,220	12,862	19,533	29,594	13,260	20,603	29,901	13,843	19,596	29,239	13,322	62,156	10,839	0,105	388106	90291	80,600	430
0-Change over time 3.8	19,398	27,916	12,822	20,673	28,964	13,392	21,476	30,269	13,813	20,516	29,049	13,342	62,907	10,755	0,110	384929	90305	84,817	430
0-Change over time 3.9	20,413	28,247	12,901	21,389	29,667	13,259	22,576	29,750	13,911	21,459	29,221	13,357	64,038	11,078	0,131	386778	90327	97,567	431
0-Change over time 3.10	21,163	27,357	12,859	22,534	28,589	13,414	23,359	29,634	13,792	22,352	28,527	13,355	64,233	11,030	0,128	377370	90344	95,667	431

2.5 RESULTS OF PART SIZE DISTRIBUTION

Table 9-29: Results of part size simulations - Upper limit - No waiting

Name	Elapse time or volume filled	Mean arrival	Reas-sign big parts	Reas-sign mid parts	Reas-sign small parts	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total main-tenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	%	%	%	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Case 1 - No waiting 1	0	150	5	20	75	69763	198	50557	15875	3033	2895	53892	0	93659	2,816	6,885	2,675	2,961	6,750	2,815	2,888	6,817	2,745	12,451	,---	0,000	414912	55089	0	58
Case 1 - No waiting 2	0	140	5	20	75	70370	210	53517	16804	3211	3105	55332	0	96897	3,108	7,188	2,955	3,083	7,223	2,932	3,095	7,206	2,944	13,245	,---	0,000	424916	56562	0	62
Case 1 - No waiting 3	0	130	5	20	75	70966	227	58011	18215	3480	3336	56414	0	100252	3,358	7,754	3,195	3,283	7,869	3,125	3,321	7,811	3,160	14,292	,---	0,000	435118	57668	0	67
Case 1 - No waiting 4	0	120	5	20	75	71798	243	61939	19449	3716	3611	56486	0	102092	3,632	8,275	3,460	3,534	8,359	3,368	3,583	8,317	3,414	15,315	,---	0,000	428051	57741	0	72
Case 1 - No waiting 5	0	110	5	20	75	72728	264	67348	21147	4040	3939	56509	0	104473	3,944	8,942	3,763	3,855	9,151	3,678	3,900	9,047	3,721	16,667	,---	0,000	424253	57765	0	79
Case 1 - No waiting 6	0	100	5	20	75	73722	290	73964	23224	4437	4335	57714	0	108951	4,317	9,744	4,125	4,233	10,050	4,042	4,275	9,897	4,083	18,255	,---	0,000	422889	58997	0	87
Case 1 - No waiting 7	0	90	5	20	75	75242	320	81679	25647	4900	4806	57748	0	112352	4,789	10,840	4,581	4,669	10,995	4,466	4,729	10,918	4,523	20,170	,---	0,000	424607	59031	0	96
Case 1 - No waiting 8	0	80	5	20	75	76589	356	90888	28538	5453	5415	57896	0	116603	5,435	12,893	5,207	5,183	11,357	4,966	5,309	12,125	5,087	22,521	,---	0,000	418808	59182	0	108
Case 1 - No waiting 9	0	70	5	20	75	78841	407	103920	32631	6235	6191	58600	83	123275	5,965	13,607	5,722	6,109	13,997	5,857	6,037	13,802	5,789	25,628	,---	0,001	421819	59902	0	124
Case 1 - No waiting 10	0	60	5	20	75	81448	463	118206	37116	7092	7216	58585	125	129664	6,877	15,784	6,603	7,181	15,625	6,896	7,029	15,705	6,749	29,483	7,990	0,002	412226	59887	1,35	144
Case 1 - No waiting 11	0	50	5	20	75	85056	577	147024	46165	8821	8633	58703	1541	143433	8,486	18,992	8,159	8,248	19,996	7,925	8,367	19,494	8,042	35,903	15,429	0,008	428807	60007	4,25	173
Case 1 - No waiting 12	0	40	5	20	75	90275	726	185036	58101	11102	10780	58816	2875	161281	10,376	24,682	9,992	10,347	24,289	9,958	10,361	24,486	9,975	44,822	21,271	0,027	431063	60123	10,333	216
Case 1 - No waiting 13	0	30	5	20	75	100420	954	243155	76350	14589	14384	58863	14125	197934	13,365	32,211	12,887	13,543	32,091	13,058	13,454	32,151	12,973	58,577	17,926	0,088	424932	60171	41,583	288
Case 1 - No waiting 14	0	20	5	20	75	118922	1415	360640	113241	21638	21569	58928	118791	353811	17,535	47,470	16,924	17,302	47,798	16,700	17,419	47,634	16,812	81,865	18,342	0,479	419658	60238	223,183	431
Case 1 - No Waiting 15	0	10	5	20	75	173508	2624	668551	209925	40113	39544	57220	2241875	2607751	4,359	91,021	4,164	4,437	90,869	4,237	4,398	90,945	4,200	99,543	112,190	11,585	424347	58492	859,783	791
Case 2 - No waiting 1	0	150	33	33	33	69721	614	156454	49126	9387	2882	57690	0	138316	2,855	20,858	2,705	2,923	21,377	2,773	2,889	21,118	2,739	26,746	,---	0,000	1361442	58972	0	58
Case 2 - No waiting 2	0	140	33	33	33	70787	671	171052	53710	10263	3088	57967	0	144352	3,056	23,327	2,901	3,092	22,615	2,937	3,074	22,971	2,919	28,964	,---	0,000	1389412	59256	0	62
Case 2 - No waiting 3	0	130	33	33	33	71121	730	186092	58432	11165	3321	58115	0	150407	3,285	25,357	3,122	3,305	24,490	3,142	3,295	24,923	3,132	31,351	,---	0,000	1404459	59407	0	66
Case 2 - No waiting 4	0	120	33	33	33	72036	795	202694	63645	12161	3593	58057	0	156811	3,559	27,468	3,388	3,566	26,870	3,394	3,562	27,169	3,391	34,123	,---	0,000	1413452	59348	0	72
Case 2 - No waiting 5	0	110	33	33	33	72940	872	222357	69820	13341	3919	58181	0	164656	3,867	29,989	3,686	3,878	29,499	3,697	3,873	29,744	3,691	37,308	,---	0,000	1421694	59474	0	78
Case 2 - No waiting 6	0	100	33	33	33	73900	960	244675	76828	14680	4317	58393	0	173684	4,241	32,849	4,047	4,249	32,369	4,056	4,245	32,609	4,052	40,906	,---	0,000	1419298	59691	0,017	86
Case 2 - No waiting 7	0	90	33	33	33	75000	1043	265805	83463	15948	4786	58283	0	181909	4,662	35,362	4,455	4,752	35,640	4,546	4,707	35,501	4,501	44,709	,---	0,000	1391308	59579	0,25	96
Case 2 - No waiting 8	0	80	33	33	33	76559	1154	294123	92354	17647	5389	58433	2375	195676	5,303	38,643	5,075	5,255	39,697	5,032	5,279	39,170	5,054	49,503	8,648	0,005	1368484	59731	5,033	108
Case 2 - No waiting 9	0	70	33	33	33	78917	1299	331181	103990	19870	6136	58509	13541	221553	5,947	44,228	5,703	6,028	43,879	5,783	5,988	44,054	5,743	55,785	17,284	0,033	1356907	59809	16,067	123
Case 2 - No waiting 10	0	60	33	33	33	81861	1545	393733	123632	23624	7147	58631	37541	270121	6,870	52,356	6,597	6,872	52,178	6,596	6,871	52,267	6,596	65,734	27,124	0,107	1381031	59934	33,383	143
Case 2 - No waiting 11	0	50	33	33	33	84511	1843	469711	147489	28182	8562	58686	111833	374317	7,502	62,489	7,208	7,552	62,112	7,251	7,527	62,300	7,229	77,056	30,712	0,267	1375055	59991	73,85	171
Case 2 - No waiting 12	0	40	33	33	33	91122	2296	585102	183722	35106	10621	58615	346750	654353	6,994	77,671	6,714	6,905	77,733	6,628	6,949	77,702	6,671	91,322	48,656	0,898	1381652	59917	157	212
Case 2 - No waiting 13	0	30	33	33	33	99919	2673	681148	213880	40868	12460	56392	758166	1100566	2,588	93,997	2,448	2,571	94,050	2,430	2,579	94,024	2,439	99,042	188,914	7,339	1376228	57646	307,283	249
Case 2 - No waiting 14	0	20	33	33	33	118429	2750	700744	220033	42044	13331	56159	880958	1231248	1,349	97,118	1,246	1,349	97,116	1,247	1,349	97,117	1,247	99,712	378,530	61,939	1332053	57407	1305,58	267
Case 2 - No waiting 15	0	10	33	33	33	174122	2747	700082	219825	42004	13873	55781	947583	1297662	1,136	97,694	1,038	1,141	97,671	1,044	1,139	97,682	1,041	99,862	423,534	268,584	1287276	57020	5076,67	277
Case 3 - No waiting 1	0	150	50	50	0	69888	916	233478	73312	14008	2875	57854	0	167335	2,801	30,941	2,654	2,945	31,892	2,792	2,873	31,417	2,723	37,013	,---	0,000	2035562	59140	0	58
Case 3 - No waiting 2	0	140	50	50	0	70751	968	246665	77452	14799	3078	58027	0	172701	3,031	32,674	2,876	3,094	33,497	2,937	3,062	33,085	2,907	39,054	,---	0,000	2008771	59317	0	62
Case 3 - No waiting 3	0	130	50	50	0	71353	1043	265935	83503	15956	3310	58103	0	180241	3,225	35,046	3,065	3,345	36,203	3,179	3,285	35,624	3,122	42,032	,---	0,000	2012450	59394	0	66
Case 3 - No waiting 4	0	120	50	50	0	72021	1135	289223	90816	17353	3589	58325	0	189525	3,514	38,173	3,343	3,575	39,025	3,401	3,544	38,599	3,372	45,515	,---	0,000	2018571	59621	0	72
Case 3 - No waiting 5	0	110	50	50	0	72842	1236	314996	98909	18899	3910	58295	0	199447	3,837	41,695	3,656	3,879	42,426	3,696	3,858	42,061	3,676	49,595	,---	0,000	2018395	59591	0	78
Case 3 - No waiting 6	0	100	50	50	0	73853	1357	345893	108610	20753	4300	58320	0	211425	4,215	45,796	4,022	4,253	46,532	4,059	4,234	46,164	4,040	54,439	,---	0,000	2014314	59616	0,033	86
Case 3 - No waiting 7	0	90	50	50	0	75075	1507	384042	120589	23042	4781	58536	375	226837	4,634	50,602	4,430	4,730	51,522	4,521	4,682	51,062	4,476	60,220	1,988	0,001	2011654	59837	0,867	96
Case 3 - No waiting 8	0	80	50	50	0	76577	1703	433942	136258	26036	5361	58543	8166	253880	5,238	57,607	5,012	5,246	57,765	5,024	5,242	57,686	5,018	67,946	9,107	0,013	2028771	59844	11,3	107
Case 3 - No waiting 9	0	70	50	50	0	78488	1934	492821	154746	29569	6118	58590	63708	332262	5,915	65,410	5,671	5,960	65,531	5,715	5,937	65,471	5,693	77,101	20,299	0,103	2019197	59892	43,167	122
Case 3 - No waiting 10	0	60	50	50	0	81379	2269	578277	181579	34696	7107	58641	173833	475405	6,191	76,579	5,934	6,163	76,927	5,914	6,177	76,753	5,924	88,854	36,168	0,365	2037167	59944	85,65	142
Case 3 - No waiting 11	0	50	50	50	0	84942	2606	664121	208533	39847	8260	58033	430000	764019	4,296	89,073	4,105	4,335	89,098	4,141	4,316	89,086	4,123	97,524	74,010	1,365	2013353	59323	155,817	165
Case 3 - No waiting 12	0	40	50	50	0	90958	2709	690398	216785	41423	8589	55855	560166	901438	1,655	96,299	1,543	1,708	96,107	1,594	1,682	96,203	1,569	99,453	274,731	10,943	2015068	57096	311,317	172
Case 3 - No waiting 13	0	30	50	50	0	101142	2756	702200	220490	42132	8742	56185	580541	926820	1,272	97,290	1,172	1,271	97,257	1,170	1,271	97,273	1,171	99,716	385,281	43,934	2014433	57433	920,983	175
Case 3 - No waiting 14	0	20	50	50	0	118692	2758	702752	220664	42165	8841	56027	592541	938916	1,126	97,653	1,030	1,142	97,596	1,046	1,134	97,624	1,038	99,796	413,552	113,145	1992654	57273	2194,68	177
Case 3 - No waiting 15	0	10	50	50	0	174714	2789	710618	223134	42637	9320	56541	646875	997354	1,069	97,824	0.,976	1,070	97,813	0.,977	1,070	97,819	0.,977	99,865	427,764	325,685	1911787	57797	6238,63	186

Name	Elapse time or volume filled	Mean arrival	Reas-sign big parts	Reas-sign mid parts	Reas-sign small parts	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total main-tenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	%	%	%	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Case 4 - No waiting 1	0	150	50	0	50	69837	711	181305	56929	10878	2880	57822	0	147785	2,790	24,075	2,643	2,970	24,765	2,815	2,880	24,420	2,729	30,029	,---	0,000	1581199	59107	0	58
Case 4 - No waiting 2	0	140	50	0	50	70846	747	190456	59803	11427	3082	57914	0	151532	3,031	25,248	2,875	3,115	25,937	2,958	3,073	25,592	2,916	31,582	,---	0,000	1553091	59201	0	62
Case 4 - No waiting 3	0	130	50	0	50	71306	805	205137	64413	12308	3315	58044	0	157430	3,217	27,131	3,057	3,369	27,887	3,203	3,293	27,509	3,130	33,932	,---	0,000	1553658	59334	0	66
Case 4 - No waiting 4	0	120	50	0	50	71997	867	220970	69384	13258	3592	58198	0	163833	3,510	29,255	3,340	3,600	29,856	3,425	3,555	29,555	3,383	36,493	,---	0,000	1544375	59491	0	72
Case 4 - No waiting 5	0	110	50	0	50	72742	947	241518	75836	14491	3917	58266	0	171934	3,823	31,863	3,643	3,908	32,660	3,725	3,865	32,262	3,684	39,811	,---	0,000	1548508	59561	0	78
Case 4 - No waiting 6	0	100	50	0	50	73744	1043	265761	83449	15945	4307	58296	0	181430	4,199	35,019	4,008	4,283	35,931	4,088	4,241	35,475	4,048	43,764	,---	0,000	1548307	59591	0,017	86
Case 4 - No waiting 7	0	90	50	0	50	75201	1154	294224	92386	17653	4795	58438	375	193128	4,673	38,848	4,467	4,736	39,532	4,527	4,705	39,190	4,497	48,391	1,823	0,000	1538840	59736	0,75	96
Case 4 - No waiting 8	0	80	50	0	50	76908	1334	340066	106780	20403	5376	58399	6416	216843	5,257	45,630	5,032	5,282	45,008	5,058	5,270	45,319	5,045	55,634	9,946	0,012	1588798	59697	10,333	108
Case 4 - No waiting 9	0	70	50	0	50	78979	1513	385698	121109	23141	6130	58568	40791	269264	5,967	51,749	5,722	5,956	50,774	5,715	5,962	51,262	5,719	62,942	21,640	0,077	1579102	59869	30,2	123
Case 4 - No waiting 10	0	60	50	0	50	81672	1760	448596	140859	26915	7150	58619	87250	340335	6,591	59,938	6,327	6,651	59,192	6,384	6,621	59,565	6,356	72,541	34,668	0,211	1576280	59922	52,05	143
Case 4 - No waiting 11	0	50	50	0	50	84307	2095	533920	167651	32035	8523	58569	209958	496261	6,467	71,071	6,205	6,583	70,839	6,319	6,525	70,955	6,262	83,742	44,006	0,516	1572035	59871	99,117	170
Case 4 - No waiting 12	0	40	50	0	50	91235	2533	645365	202644	38721	10313	57984	502375	831367	4,661	86,479	4,457	4,594	86,827	4,397	4,628	86,653	4,427	95,707	84,546	1,855	1573617	59272	184,85	206
Case 4 - No waiting 13	0	30	50	0	50	100414	2720	693123	217640	41587	11664	56245	745083	1090969	1,746	95,942	1,632	1,794	95,879	1,677	1,770	95,911	1,654	99,335	281,440	14,750	1515322	57495	413,85	233
Case 4 - No waiting 14	0	20	50	0	50	117552	2735	696857	218813	41811	14518	55807	972375	1321927	1,305	97,178	1,206	1,290	97,204	1,191	1,298	97,191	1,198	99,687	366,194	53,739	1236622	57047	1151,07	290
Case 4 - No waiting 15	0	10	50	0	50	174336	2784	709484	222778	42569	21475	56532	1453708	1815908	1,151	97,661	1,054	1,132	97,689	1,038	1,142	97,675	1,046	99,862	415,071	195,291	826109	57789	3917,72	430
Case 5 - No waiting 1	0	150	100	0	0	69829	1365	347949	109256	20876	2853	58090	0	210440	2,841	46,693	2,696	2,833	46,532	2,686	2,837	46,612	2,691	52,141	,---	0,000	3048625	59381	0	57
Case 5 - No waiting 2	0	140	100	0	0	70887	1462	372643	117010	22358	3055	58186	0	220006	3,054	50,225	2,900	3,011	49,470	2,856	3,032	49,848	2,878	55,758	,---	0,000	3048625	59479	0	61
Case 5 - No waiting 3	0	130	100	0	0	71131	1571	400284	125689	24017	3282	58253	0	230660	3,249	53,530	3,090	3,246	53,433	3,085	3,248	53,482	3,088	59,817	,---	0,000	3048625	59548	0	66
Case 5 - No waiting 4	0	120	100	0	0	71859	1701	433616	136155	26016	3555	58320	0	243488	3,509	57,862	3,340	3,512	57,877	3,341	3,510	57,869	3,341	64,720	,---	0,000	3048625	59616	0	71
Case 5 - No waiting 5	0	110	100	0	0	72829	1856	472943	148504	28376	3878	58416	0	258648	3,819	63,043	3,640	3,816	62,984	3,636	3,817	63,013	3,638	70,469	,---	0,000	3048625	59714	0	78
Case 5 - No waiting 6	0	100	100	0	0	73856	2040	519892	163246	31193	4263	58484	0	276681	4,186	69,220	3,996	4,184	69,158	3,993	4,185	69,189	3,994	77,368	,---	0,000	3048625	59783	0,05	85
Case 5 - No waiting 7	0	90	100	0	0	75056	2267	577816	181434	34668	4738	58575	1583	300524	4,634	76,793	4,433	4,638	76,766	4,432	4,636	76,779	4,433	85,848	,---	0,002	3048625	59876	3,1	95
Case 5 - No waiting 8	0	80	100	0	0	76887	2545	648442	203610	38906	5317	58642	111833	437857	5,181	86,098	4,961	5,177	86,032	4,954	5,179	86,065	4,958	96,202	15,882	0,116	3048625	59945	59,45	106
Case 5 - No waiting 9	0	70	100	0	0	78833	2704	688989	216342	41339	5650	57051	355916	695317	2,639	94,038	2,501	2,668	93,955	2,523	2,654	93,996	2,512	99,162	107,745	1,507	3048625	58319	117,833	113
Case 5 - No waiting 10	0	60	100	0	0	80979	2738	697830	219118	41869	5722	56258	376750	718471	1,536	96,557	1,429	1,521	96,527	1,415	1,529	96,542	1,422	99,492	274,131	7,911	3048625	57508	233,067	114
Case 5 - No waiting 11	0	50	100	0	0	85318	2764	704333	221160	42260	5775	56472	384958	729451	1,309	97,095	1,210	1,308	97,052	1,207	1,309	97,074	1,208	99,590	341,263	21,311	3048625	57726	505,583	116
Case 5 - No waiting 12	0	40	100	0	0	90955	2801	713784	224128	42827	5853	57074	387541	736450	1,214	97,353	1,116	1,211	97,328	1,114	1,212	97,340	1,115	99,668	367,497	42,494	3048625	58343	958,283	117
Case 5 - No waiting 13	0	30	100	0	0	99771	2742	698643	219373	41918	5729	55794	382625	724039	1,181	97,471	1,083	1,183	97,436	1,086	1,182	97,454	1,084	99,720	387,440	78,099	3048625	57034	1631,32	115
Case 5 - No waiting 14	0	20	100	0	0	118081	2677	682079	214172	40924	5593	54410	383208	716446	1,154	97,588	1,057	1,159	97,558	1,062	1,157	97,573	1,060	99,789	386,911	149,610	3048625	55619	2923,1	112
Case 5 - No waiting 15	0	10	100	0	0	172202	2632	670697	210599	40241	5500	53430	390875	718456	1,123	97,707	1,026	1,123	97,697	1,025	1,123	97,702	1,026	99,851	378,395	365,547	3048625	54617	6798,45	110
Case 6 - No waiting 1	0	150	0	50	50	69943	248	63384	19902	3803	2902	29350	0	65742	3,005	9,017	2,881	2,646	7,794	2,537	2,826	8,405	2,709	13,940	,---	0,000	273021	30002	0	58
Case 6 - No waiting 2	0	140	0	50	50	70356	265	67763	21277	4065	3107	29341	0	67572	3,218	9,649	3,087	2,831	8,327	2,716	3,024	8,988	2,902	14,914	,---	0,000	272609	29993	0	62
Case 6 - No waiting 3	0	130	0	50	50	71092	286	72873	22882	4372	3345	29352	0	69737	3,461	10,368	3,323	3,044	8,955	2,923	3,253	9,661	3,123	16,037	,---	0,000	272284	30005	0	67
Case 6 - No waiting 4	0	120	0	50	50	71767	311	79289	24896	4757	3625	29387	0	72463	3,747	11,256	3,599	3,291	9,746	3,161	3,519	10,501	3,380	17,400	,---	0,000	273383	30040	0	73
Case 6 - No waiting 5	0	110	0	50	50	72699	338	86281	27092	5176	3953	29409	0	75435	4,078	12,111	3,921	3,584	10,723	3,445	3,831	11,417	3,683	18,931	,---	0,000	272828	30063	0	79
Case 6 - No waiting 6	0	100	0	50	50	73743	371	94623	29711	5677	4341	29407	0	78940	4,478	13,252	4,308	3,931	11,790	3,782	4,204	12,521	4,045	20,770	,---	0,000	272419	30060	0	87
Case 6 - No waiting 7	0	90	0	50	50	75027	413	105328	33073	6319	4819	30867	0	85368	4,984	14,789	4,797	4,350	13,099	4,185	4,667	13,944	4,491	23,102	,---	0,000	286806	31553	0	96
Case 6 - No waiting 8	0	80	0	50	50	76512	469	119646	37569	7178	5420	49661	0	116384	5,965	18,065	5,724	4,618	13,771	4,430	5,291	15,918	5,077	26,286	,---	0,000	465848	50765	0	108
Case 6 - No waiting 9	0	70	0	50	50	78037	529	134795	42325	8087	6174	58450	0	134521	6,131	18,456	5,880	5,945	17,450	5,696	6,038	17,953	5,788	29,779	,---	0,000	545596	59749	0	123
Case 6 - No waiting 10	0	60	0	50	50	81621	619	157808	49551	9468	7208	58671	0	144456	6,957	20,821	6,675	7,071	21,048	6,789	7,014	20,935	6,732	34,681	,---	0,000	548915	59974	0	144
Case 6 - No waiting 11	0	50	0	50	50	84868	741	188986	59341	11339	8624	58782	0	157681	8,338	24,952	8,014	8,387	25,094	8,063	8,363	25,023	8,039	41,425	,---	0,000	548352	60088	0	172
Case 6 - No waiting 12	0	40	0	50	50	90227	930	237092	74446	14225	10794	58897	83	178079	10,472	31,184	10,080	10,392	31,476	10,005	10,432	31,330	10,042	51,804	1,806	0,000	550032	60206	1,083	216
Case 6 - No waiting 13	0	30	0	50	50	99049	1227	312634	98167	18758	14330	58899	8041	217830	13,812	41,307	13,324	13,780	41,318	13,289	13,796	41,313	13,307	68,415	7,644	0,052	545944	60208	58,333	287
Case 6 - No waiting 14	0	20	0	50	50	118503	1841	469096	147296	28145	21495	58943	181416	456944	15,482	61,835	14,931	15,384	62,054	14,837	15,433	61,945	14,884	92,262	17,230	0,647	546292	60253	323,567	430
Case 6 - No waiting 15	0	10	0	50	50	172342	2734	696712	218767	41802	31995	56139	2111125	2478544	1,648	96,647	1,536	1,692	96,538	1,580	1,670	96,593	1,558	99,820	323,879	66,002	545937	57387	1629,88	640

Name	Elapse time or volume filled	Mean arrival	Reas-sign big parts	Reas-sign mid parts	Reas-sign small parts	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total main-tenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	%	%	%	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Case 7 - No waiting 1	0	150	0	100	0	69807	454	115900	36392	6954	2897	29330	0	85352	3,000	16,346	2,877	2,646	14,410	2,536	2,823	15,378	2,706	20,907	,---	0,000	500000	29982	0	58
Case 7 - No waiting 2	0	140	0	100	0	70212	487	124133	38977	7448	3103	29343	0	88654	3,210	17,501	3,080	2,831	15,425	2,715	3,020	16,463	2,897	22,381	,---	0,000	500000	29995	0	62
Case 7 - No waiting 3	0	130	0	100	0	70937	524	133633	41960	8018	3340	29360	0	92466	3,452	18,834	3,315	3,043	16,592	2,920	3,247	17,713	3,117	24,078	,---	0,000	500000	30012	0	67
Case 7 - No waiting 4	0	120	0	100	0	71649	568	144900	45498	8694	3622	29413	0	97033	3,735	20,394	3,589	3,290	17,949	3,159	3,513	19,172	3,374	26,058	,---	0,000	500000	30067	0	72
Case 7 - No waiting 5	0	110	0	100	0	72582	619	157800	49549	9468	3945	29415	0	102182	4,064	22,204	3,908	3,582	19,550	3,441	3,823	20,877	3,674	28,374	,---	0,000	500000	30069	0	79
Case 7 - No waiting 6	0	100	0	100	0	73578	680	173266	54405	10396	4331	29406	0	108342	4,462	24,398	4,294	3,929	21,462	3,777	4,196	22,930	4,036	31,161	,---	0,000	500000	30060	0	87
Case 7 - No waiting 7	0	90	0	100	0	74859	755	192533	60455	11552	4813	33757	0	121830	4,844	26,471	4,659	4,499	24,560	4,323	4,671	25,516	4,491	34,678	,---	0,000	575000	34507	0	96
Case 7 - No waiting 8	0	80	0	100	0	76503	848	216133	67865	12968	5403	56472	0	161533	5,611	30,560	5,379	4,959	26,974	4,747	5,285	28,767	5,063	39,115	,---	0,000	966667	57727	0	108
Case 7 - No waiting 9	0	70	0	100	0	78558	966	246300	77338	14778	6157	58537	0	176323	6,025	32,834	5,779	5,997	32,668	5,750	6,011	32,751	5,764	44,526	,---	0,000	1000000	59838	0	123
Case 7 - No waiting 10	0	60	0	100	0	81661	1127	287300	90212	17238	7182	58736	0	192948	6,956	37,953	6,680	7,000	38,190	6,721	6,978	38,072	6,701	51,750	,---	0,000	1000000	60041	0	144
Case 7 - No waiting 11	0	50	0	100	0	84871	1348	343600	107890	20616	8590	58837	0	215546	8,339	45,552	8,017	8,301	45,355	7,982	8,320	45,453	8,000	61,773	,---	0,000	1000000	60144	0,017	172
Case 7 - No waiting 12	0	40	0	100	0	90697	1688	430066	135040	25804	10751	58908	375	250516	10,389	56,834	10,003	10,388	56,812	9,999	10,388	56,823	10,001	77,212	3,401	0,002	1000000	60217	4,267	215
Case 7 - No waiting 13	0	30	0	100	0	99812	2239	570533	179147	34232	14263	58910	165625	471814	11,043	75,394	10,644	11,102	75,366	10,691	11,073	75,380	10,668	97,121	18,932	0,545	1000000	60219	247,95	285
Case 7 - No waiting 14	0	20	0	100	0	118839	2711	690833	216921	41450	17270	55829	1136708	1486790	1,764	96,334	1,648	1,772	96,286	1,656	1,768	96,310	1,652	99,730	264,110	20,090	1000000	57070	600,867	345
Case 7 - No waiting 15	0	10	0	100	0	173551	2764	704366	221171	42262	17609	56180	1192833	1548782	1,183	97,594	1,088	1,189	97,575	1,090	1,186	97,585	1,089	99,859	411,593	229,055	1000000	57428	4510,42	352
Case 8 - No waiting 1	0	150	0	0	100	69877	44	11326	3556	679	2909	29348	0	46277	3,015	1,598	2,890	2,650	1,406	2,541	2,832	1,502	2,716	7,050	,---	0,000	48668	30001	0	58
Case 8 - No waiting 2	0	140	0	0	100	70417	47	12124	3807	727	3114	29357	0	46791	3,224	1,710	3,092	2,834	1,504	2,720	3,029	1,607	2,906	7,543	,---	0,000	48668	30009	0	62
Case 8 - No waiting 3	0	130	0	0	100	71216	51	13059	4100	783	3354	29373	0	47402	3,469	1,841	3,330	3,048	1,619	2,928	3,259	1,730	3,129	8,117	,---	0,000	48668	30025	0	67
Case 8 - No waiting 4	0	120	0	0	100	71870	55	14129	4436	847	3629	29366	0	48069	3,755	1,994	3,605	3,294	1,751	3,166	3,525	1,872	3,386	8,783	,---	0,000	48668	30019	0	73
Case 8 - No waiting 5	0	110	0	0	100	72860	60	15405	4837	924	3956	29396	0	48913	4,085	2,171	3,925	3,588	1,908	3,450	3,836	2,039	3,688	9,563	,---	0,000	48668	30049	0	79
Case 8 - No waiting 6	0	100	0	0	100	73844	66	16939	5319	1016	4350	29427	0	49923	4,487	2,386	4,315	3,935	2,094	3,786	4,211	2,240	4,051	10,501	,---	0,000	48668	30081	0	87
Case 8 - No waiting 7	0	90	0	0	100	75158	73	18795	5901	1127	4827	29428	0	51094	4,977	2,650	4,791	4,360	2,322	4,198	4,669	2,486	4,494	11,648	,---	0,000	48668	30082	0	97
Case 8 - No waiting 8	0	80	0	0	100	76804	82	21125	6633	1267	5425	29445	0	52586	5,589	2,977	5,382	4,893	2,607	4,714	5,241	2,792	5,048	13,082	,---	0,000	48668	30099	0	109
Case 8 - No waiting 9	0	70	0	0	100	78906	94	24113	7571	1446	6193	29454	0	54484	6,373	3,397	6,143	5,579	2,975	5,379	5,976	3,186	5,761	14,923	,---	0,000	48668	30109	0	124
Case 8 - No waiting 10	0	60	0	0	100	81787	110	28113	8827	1686	7220	29476	0	57037	7,420	3,958	7,157	6,497	3,465	6,266	6,958	3,712	6,712	17,382	,---	0,000	48668	30131	0	144
Case 8 - No waiting 11	0	50	0	0	100	85552	132	33717	10587	2023	8660	29508	0	60615	8,878	4,738	8,568	7,786	4,155	7,513	8,332	4,447	8,040	20,819	,---	0,000	48668	30164	0	173
Case 8 - No waiting 12	0	40	0	0	100	91097	165	42071	13210	2524	10805	35372	0	73704	11,091	5,921	10,706	9,716	5,185	9,375	10,403	5,553	10,040	25,996	,---	0,000	58402	36158	0	216
Case 8 - No waiting 13	0	30	0	0	100	99655	219	56049	17599	3362	14395	58852	0	113828	14,193	7,569	13,686	13,605	7,256	13,120	13,899	7,412	13,403	34,715	,---	0,000	97336	60160	0	288
Case 8 - No waiting 14	0	20	0	0	100	119096	329	84052	26392	5043	21588	59018	0	131714	20,748	11,076	20,027	20,770	11,094	20,059	20,759	11,085	20,043	51,887	,---	0,000	97336	60329	0,55	432
Case 8 - No waiting 15	0	10	0	0	100	172026	656	167336	52543	10040	42979	59103	41	184409	35,950	21,981	34,759	35,965	22,094	34,775	35,958	22,037	34,767	92,762	6,098	0,468	97336	60416	662,2	860

Table 9-30: Results of part size simulations - Upper limit - Waiting

Name	Elapse time or volume filled	Mean arrival	Reas-sign big parts	Reas-sign mid parts	Reas-sign small parts	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total main-tenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	%	%	%	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Case 1 - Waiting 1	1	150	5	20	75	69788	195	49901	15669	2994	2894	54373	125	94180	2,956	7,002	2,808	2,823	6,456	2,683	2,889	6,729	2,746	12,364	,---	0,000	411563	55581	0	58
Case 1 - Waiting 2	1	140	5	20	75	70315	210	53608	16833	3216	3097	55276	125	96974	3,132	7,223	2,978	3,049	7,227	2,902	3,090	7,225	2,940	13,255	,---	0,000	425279	56505	0	62
Case 1 - Waiting 3	1	130	5	20	75	70976	227	57930	18190	3475	3333	56425	125	100358	3,355	7,691	3,191	3,276	7,902	3,120	3,315	7,797	3,156	14,268	,---	0,000	431626	57679	0	67
Case 1 - Waiting 4	1	120	5	20	75	71798	243	61933	19447	3715	3610	56512	125	102248	3,631	8,273	3,458	3,527	8,353	3,365	3,579	8,313	3,411	15,304	,---	0,000	428196	57768	0	72
Case 1 - Waiting 5	1	110	5	20	75	72729	264	67338	21144	4040	3936	56493	125	104570	3,947	8,944	3,764	3,847	9,142	3,673	3,897	9,043	3,718	16,658	,---	0,000	424504	57748	0	79
Case 1 - Waiting 6	1	100	5	20	75	73722	290	73914	23209	4434	4330	57710	125	109046	4,316	9,744	4,121	4,223	10,036	4,037	4,269	9,890	4,079	18,238	,---	0,000	423104	58992	0	87
Case 1 - Waiting 7	1	90	5	20	75	74907	321	81975	25740	4918	4808	57842	250	112840	4,843	11,126	4,633	4,603	10,748	4,402	4,723	10,937	4,518	20,178	0,222	0,000	425781	59127	0,05	96
Case 1 - Waiting 8	1	80	5	20	75	77025	356	90817	28516	5449	5386	58273	166	117217	5,405	12,618	5,176	5,170	11,647	4,952	5,288	12,133	5,064	22,484	,---	0,000	425787	59568	0,2	108
Case 1 - Waiting 9	1	70	5	20	75	78643	410	104498	32812	6269	6170	58465	291	123499	5,922	13,805	5,679	6,136	14,012	5,887	6,029	13,908	5,783	25,720	5,591	0,001	425552	59765	0,767	123
Case 1 - Waiting 10	1	60	5	20	75	81116	475	121044	38007	7262	7172	58608	625	131212	7,015	16,543	6,739	6,954	15,608	6,672	6,984	16,075	6,705	29,765	12,796	0,004	423290	59910	1,933	143
Case 1 - Waiting 11	1	50	5	20	75	85308	568	144893	45496	8693	8638	58737	1875	143019	8,434	19,301	8,109	8,284	19,098	7,963	8,359	19,200	8,036	35,594	18,947	0,011	422198	60042	4,717	173
Case 1 - Waiting 12	1	40	5	20	75	90648	714	182003	57149	10920	10783	58758	4708	161905	10,430	24,441	10,042	10,295	23,772	9,913	10,362	24,107	9,978	44,447	19,772	0,031	423489	60064	13,233	216
Case 1 - Waiting 13	1	30	5	20	75	100102	950	242078	76012	14524	14354	58884	19583	202987	13,369	32,367	12,896	13,316	31,625	12,842	13,342	31,996	12,869	58,208	14,565	0,118	423146	60193	68	287
Case 1 - Waiting 14	1	20	5	20	75	118203	1454	370460	116324	22227	21423	58934	169416	407970	16,445	48,994	15,868	16,379	48,860	15,798	16,412	48,927	15,833	81,172	20,082	0,635	434238	60243	271,15	428
Case 1 - Waiting 15	1	10	5	20	75	174711	2607	664453	208638	39867	39685	57207	2210416	2574883	4,520	90,362	4,318	4,448	90,519	4,251	4,484	90,441	4,285	99,209	105,318	10,793	420700	58478	852,967	794
Case 2 - Waiting 1	1	150	33	33	33	69530	634	161614	50746	9696	2880	57670	1000	141218	2,954	22,229	2,805	2,815	21,377	2,667	2,885	21,803	2,736	27,424	,---	0,000	1408773	58952	0	58
Case 2 - Waiting 2	1	140	33	33	33	70683	683	174257	54716	10455	3087	57979	1125	146691	3,078	23,789	2,924	3,067	23,009	2,912	3,073	23,399	2,918	29,389	,---	0,000	1416890	59268	0	62
Case 2 - Waiting 3	1	130	33	33	33	71111	730	186227	58475	11173	3320	58087	1250	151669	3,293	25,459	3,131	3,296	24,461	3,135	3,294	24,960	3,133	31,387	,---	0,000	1405777	59378	0	66
Case 2 - Waiting 4	1	120	33	33	33	72036	794	202519	63591	12151	3589	58056	1250	157990	3,555	27,462	3,384	3,558	26,832	3,390	3,556	27,147	3,387	34,091	,---	0,000	1413811	59346	0	72
Case 2 - Waiting 5	1	110	33	33	33	72939	871	221999	69707	13319	3918	58212	1250	165812	3,867	29,947	3,687	3,868	29,413	3,690	3,868	29,680	3,688	37,236	,---	0,000	1419710	59505	0	78
Case 2 - Waiting 6	1	100	33	33	33	73898	958	244302	76711	14658	4310	58413	1250	174814	4,229	32,814	4,039	4,238	32,284	4,049	4,234	32,549	4,044	40,827	,---	0,000	1419517	59711	0,017	86
Case 2 - Waiting 7	1	90	33	33	33	75245	1028	262019	82274	15721	4775	58235	1250	181667	4,679	35,621	4,476	4,714	34,428	4,508	4,697	35,025	4,492	44,213	2,096	0,000	1376986	59529	0,583	96
Case 2 - Waiting 8	1	80	33	33	33	76489	1157	294975	92622	17698	5373	58497	4958	198649	5,373	39,715	5,147	5,140	38,767	4,919	5,256	39,241	5,033	49,530	8,853	0,009	1378738	59797	7,75	107
Case 2 - Waiting 9	1	70	33	33	33	78292	1310	333765	104802	20025	6140	58572	18625	227690	5,942	45,252	5,699	6,031	43,441	5,785	5,987	44,347	5,742	56,075	17,684	0,042	1365037	59874	20,383	123
Case 2 - Waiting 10	1	60	33	33	33	80708	1538	392063	123107	23523	7141	58677	44416	276427	6,888	52,325	6,613	6,742	51,682	6,472	6,815	52,003	6,542	65,361	26,657	0,118	1378163	59981	37,7	143
Case 2 - Waiting 11	1	50	33	33	33	84866	1820	463838	145645	27830	8538	58628	117791	377976	7,507	62,381	7,213	7,481	60,781	7,182	7,494	61,581	7,197	76,272	31,451	0,284	1362244	59931	76,867	171
Case 2 - Waiting 12	1	40	33	33	33	90769	2252	573804	180174	34428	10579	58385	338375	641404	6,885	77,143	6,608	6,954	75,889	6,679	6,920	76,516	6,644	90,079	49,350	0,931	1360209	59683	156,983	212
Case 2 - Waiting 13	1	30	33	33	33	100048	2682	683336	214567	41000	12516	56553	778041	1121530	2,554	93,974	2,415	2,491	94,119	2,355	2,523	94,047	2,385	98,954	180,969	6,932	1373358	57809	306,15	250
Case 2 - Waiting 14	1	20	33	33	33	118792	2734	696574	218724	41794	13228	55831	883541	1231731	1,301	97,165	1,200	1,321	97,049	1,220	1,311	97,107	1,210	99,628	380,346	63,352	1344045	57072	1311,07	265
Case 2 - Waiting 15	1	10	33	33	33	173853	2753	701550	220286	42093	14038	55971	957166	1308213	1,122	97,633	1,029	1,115	97,623	1,020	1,118	97,628	1,024	99,771	423,708	265,809	1269622	57215	5061,92	281
Case 3 - Waiting 1	1	150	50	50	0	70041	909	231600	72722	13896	2875	58007	2250	169087	2,962	31,854	2,810	2,765	30,320	2,624	2,864	31,087	2,717	36,668	,---	0,000	2019805	59296	0	58
Case 3 - Waiting 2	1	140	50	50	0	70643	970	247181	77615	14830	3074	58018	2458	175336	3,046	32,928	2,893	3,071	33,387	2,914	3,058	33,157	2,903	39,119	,---	0,000	2014398	59307	0	61
Case 3 - Waiting 3	1	130	50	50	0	71226	1037	264434	83032	15866	3309	58085	2458	182112	3,228	34,960	3,070	3,338	35,916	3,174	3,283	35,438	3,122	41,843	,---	0,000	2003267	59375	0	66
Case 3 - Waiting 4	1	120	50	50	0	72021	1134	289022	90752	17341	3585	58297	2458	191869	3,510	38,192	3,342	3,571	38,986	3,399	3,540	38,589	3,371	45,500	,---	0,000	2019022	59593	0	72
Case 3 - Waiting 5	1	110	50	50	0	72859	1233	314352	98706	18861	3906	58292	2458	201656	3,827	41,614	3,649	3,877	42,337	3,696	3,852	41,976	3,672	49,500	,---	0,000	2016440	59588	0	78
Case 3 - Waiting 6	1	100	50	50	0	73909	1357	345925	108620	20755	4303	58368	2541	214045	4,203	45,630	4,013	4,258	46,629	4,066	4,230	46,130	4,039	54,400	0,485	0,000	2012975	59665	0,067	86
Case 3 - Waiting 7	1	90	50	50	0	74836	1519	387131	121559	23227	4765	58429	3208	230666	4,688	51,104	4,482	4,658	52,023	4,454	4,673	51,564	4,468	60,705	4,405	0,001	2033402	59728	1,9	95
Case 3 - Waiting 8	1	80	50	50	0	77014	1711	435988	136900	26159	5365	58572	17166	263688	5,368	59,667	5,142	5,117	56,207	4,896	5,243	57,937	5,019	68,199	9,734	0,022	2035145	59874	18,567	107
Case 3 - Waiting 9	1	70	50	50	0	78935	1931	492016	154493	29521	6103	58591	78791	347031	5,966	66,111	5,723	5,850	64,603	5,610	5,908	65,357	5,666	76,932	22,022	0,129	2018698	59893	50,083	122
Case 3 - Waiting 10	1	60	50	50	0	81212	2267	577806	181431	34668	7100	58634	194375	495754	6,076	77,373	5,825	6,022	76,026	5,777	6,049	76,700	5,801	88,550	37,075	0,402	2038275	59937	92,45	142
Case 3 - Waiting 11	1	50	50	50	0	85533	2614	665993	209121	39959	8265	58064	448500	783267	4,103	89,575	3,914	4,133	88,994	3,947	4,118	89,285	3,931	97,334	76,246	1,415	2019118	59355	157,65	165
Case 3 - Waiting 12	1	40	50	50	0	91122	2703	688809	216286	41328	8573	55777	561416	901974	1,648	96,242	1,536	1,703	95,989	1,589	1,675	96,115	1,562	99,353	275,224	11,066	2014155	57016	313,433	171
Case 3 - Waiting 13	1	30	50	50	0	100229	2741	698379	219291	41902	8703	55922	576458	920918	1,277	97,216	1,177	1,254	97,182	1,155	1,266	97,199	1,166	99,631	381,529	43,644	2012147	57164	908,183	174
Case 3 - Waiting 14	1	20	50	50	0	118151	2753	701594	220300	42095	8874	55970	601791	947689	1,121	97,602	1,028	1,125	97,525	1,032	1,123	97,564	1,030	99,717	413,357	113,106	1982891	57214	2190,55	177
Case 3 - Waiting 15	1	10	50	50	0	173820	2771	706167	221736	42370	9227	56224	644041	992341	1,063	97,767	0.,971	1,057	97,743	0.,964	1,060	97,755	0.,967	99,783	431,105	324,875	1921139	57473	6156,2	185

Name	Elapse time or volume filled	Mean arrival	Reas-sign big parts	Reas-sign mid parts	Reas-sign small parts	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total main-tenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	%	%	%	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Case 4 - Waiting 1	1	150	50	0	50	70101	702	179056	56223	10743	2883	58004	1583	148772	2,957	24,524	2,805	2,785	23,548	2,643	2,871	24,036	2,724	29,631	,---	0,000	1561044	59293	0	58
Case 4 - Waiting 2	1	140	50	0	50	70715	750	191233	60047	11474	3080	57991	1833	153757	3,043	25,452	2,890	3,087	25,886	2,930	3,065	25,669	2,910	31,644	,---	0,000	1559689	59280	0	62
Case 4 - Waiting 3	1	130	50	0	50	71235	795	202573	63607	12154	3314	58057	1833	158319	3,222	26,916	3,065	3,355	27,404	3,191	3,289	27,160	3,128	33,577	,---	0,000	1536639	59347	0	66
Case 4 - Waiting 4	1	120	50	0	50	71997	866	220862	69350	13251	3590	58208	1833	165636	3,503	29,252	3,336	3,594	29,817	3,423	3,549	29,535	3,380	36,463	,---	0,000	1544887	59501	0	72
Case 4 - Waiting 5	1	110	50	0	50	72742	947	241301	75768	14478	3912	58252	1833	173663	3,817	31,874	3,641	3,901	32,613	3,720	3,859	32,243	3,680	39,783	,---	0,000	1549296	59547	0	78
Case 4 - Waiting 6	1	100	50	0	50	73753	1041	265279	83297	15916	4310	58343	1875	183191	4,191	34,893	4,004	4,282	35,867	4,090	4,237	35,380	4,047	43,664	0,286	0,000	1544080	59640	0,033	86
Case 4 - Waiting 7	1	90	50	0	50	75039	1160	295752	92866	17745	4784	58433	2250	195556	4,712	39,071	4,507	4,672	39,723	4,465	4,692	39,397	4,486	48,575	3,125	0,001	1550195	59731	1,517	96
Case 4 - Waiting 8	1	80	50	0	50	76452	1336	340489	106913	20429	5384	58531	13250	224018	5,294	46,566	5,069	5,233	43,994	5,011	5,263	45,280	5,040	55,584	10,683	0,019	1586119	59831	14,867	108
Case 4 - Waiting 9	1	70	50	0	50	79340	1496	381287	119724	22877	6135	58580	45291	272134	6,020	50,980	5,775	5,890	50,346	5,649	5,955	50,663	5,712	62,330	23,920	0,087	1560115	59881	30,833	123
Case 4 - Waiting 10	1	60	50	0	50	81892	1781	453765	142482	27225	7139	58567	101000	355937	6,624	60,155	6,362	6,511	60,449	6,248	6,568	60,302	6,305	73,174	34,670	0,231	1596507	59869	56,85	143
Case 4 - Waiting 11	1	50	50	0	50	84931	2067	526769	165405	31606	8505	58545	212625	496203	6,571	70,477	6,302	6,438	69,592	6,177	6,505	70,035	6,240	82,779	44,296	0,514	1556229	59846	98,017	170
Case 4 - Waiting 12	1	40	50	0	50	91453	2522	642630	201785	38557	10242	57711	514500	842034	4,526	86,794	4,323	4,268	86,625	4,075	4,397	86,709	4,199	95,305	91,734	2,050	1576314	58994	186,367	205
Case 4 - Waiting 13	1	30	50	0	50	100020	2709	690359	216772	41421	11737	56209	754125	1099003	1,846	95,636	1,730	1,820	95,540	1,701	1,833	95,588	1,715	99,136	272,680	14,020	1500596	57458	403,117	235
Case 4 - Waiting 14	1	20	50	0	50	118005	2750	700743	220033	42044	14682	56150	983500	1335127	1,303	97,150	1,202	1,283	97,118	1,183	1,293	97,134	1,192	99,619	365,763	53,818	1223803	57398	1164,57	294
Case 4 - Waiting 15	1	10	50	0	50	173768	2773	706684	221898	42401	21312	56327	1440958	1801674	1,122	97,646	1,027	1,104	97,647	1,010	1,113	97,646	1,018	99,777	420,101	196,015	829320	57579	3904,17	426
Case 5 - Waiting 1	1	150	100	0	0	69983	1365	347949	109256	20876	2853	57949	3125	213377	2,999	49,287	2,845	2,690	44,168	2,550	2,845	46,728	2,698	52,270	,---	0,000	3048625	59237	0	57
Case 5 - Waiting 2	1	140	100	0	0	70605	1462	372643	117010	22358	3055	58185	3166	223172	3,098	50,972	2,943	2,964	48,719	2,813	3,031	49,845	2,878	55,754	,---	0,000	3048625	59478	0	61
Case 5 - Waiting 3	1	130	100	0	0	71069	1572	400589	125785	24035	3285	58262	3166	233955	3,261	53,713	3,101	3,236	53,316	3,078	3,248	53,515	3,089	59,852	,---	0,000	3048625	59557	0	66
Case 5 - Waiting 4	1	120	100	0	0	71801	1701	433616	136155	26016	3555	58341	3166	246683	3,512	57,907	3,343	3,503	57,791	3,336	3,507	57,849	3,340	64,696	,---	0,000	3048625	59637	0	71
Case 5 - Waiting 5	1	110	100	0	0	72829	1855	472740	148440	28364	3876	58420	3166	261742	3,819	63,043	3,640	3,808	62,921	3,632	3,813	62,982	3,636	70,431	,---	0,000	3048625	59719	0	78
Case 5 - Waiting 6	1	100	100	0	0	73685	2039	519688	163182	31181	4261	58498	3375	279998	4,185	69,209	3,995	4,177	69,083	3,988	4,181	69,146	3,992	77,318	,---	0,000	3048625	59798	0,25	85
Case 5 - Waiting 7	1	90	100	0	0	74962	2269	578222	181561	34693	4741	58584	6708	305818	4,641	76,888	4,439	4,636	76,752	4,431	4,638	76,820	4,435	85,893	6,062	0,004	3048625	59886	5,983	95
Case 5 - Waiting 8	1	80	100	0	0	77060	2547	649052	203802	38943	5322	58607	153791	480003	5,190	86,259	4,970	5,179	86,134	4,959	5,185	86,196	4,965	96,346	18,417	0,159	3048625	59910	72,45	106
Case 5 - Waiting 9	1	70	100	0	0	78484	2702	688481	216183	41308	5645	57070	364416	703647	2,673	93,931	2,531	2,616	93,857	2,473	2,645	93,894	2,502	99,041	108,763	1,520	3048625	58338	117,75	113
Case 5 - Waiting 10	1	60	100	0	0	81769	2747	699964	219788	41997	5740	56490	379375	722221	1,557	96,500	1,450	1,475	96,517	1,371	1,516	96,508	1,410	99,435	276,512	7,948	3048625	57745	235,1	115
Case 5 - Waiting 11	1	50	100	0	0	84661	2762	703825	221001	42229	5771	56457	384333	728612	1,317	97,073	1,217	1,295	96,984	1,195	1,306	97,029	1,206	99,540	342,101	21,393	3048625	57712	506,75	115
Case 5 - Waiting 12	1	40	100	0	0	90574	2790	710837	223203	42650	5829	56868	395875	743381	1,215	97,347	1,115	1,207	97,235	1,112	1,211	97,291	1,114	99,616	367,352	42,728	3048625	58131	956,467	117
Case 5 - Waiting 13	1	30	100	0	0	99828	2752	701386	220235	42083	5751	56039	389000	731790	1,181	97,463	1,084	1,176	97,355	1,078	1,178	97,409	1,081	99,668	385,215	77,934	3048625	57285	1642,08	115
Case 5 - Waiting 14	1	20	100	0	0	118793	2683	683603	214651	41016	5605	54556	387583	721598	1,154	97,588	1,057	1,154	97,471	1,056	1,154	97,529	1,057	99,740	388,022	150,115	3048625	55768	2943,57	112
Case 5 - Waiting 15	1	10	100	0	0	173991	2642	673238	211396	40394	5520	53662	392333	721195	1,130	97,682	1,031	1,119	97,613	1,022	1,125	97,648	1,026	99,799	381,634	365,980	3048625	54855	6860,3	110
Case 6 - Waiting 1	1	150	0	50	50	69943	247	63181	19838	3790	2896	29312	500	66109	3,004	8,996	2,880	2,646	7,780	2,535	2,825	8,388	2,707	13,920	,---	0,000	272665	29963	0	58
Case 6 - Waiting 2	1	140	0	50	50	70356	265	67759	21276	4065	3106	29360	500	68095	3,216	9,644	3,085	2,830	8,320	2,713	3,023	8,982	2,899	14,904	,---	0,000	272663	30012	0	62
Case 6 - Waiting 3	1	130	0	50	50	71092	285	72733	22838	4364	3340	29337	500	70159	3,458	10,352	3,319	3,045	8,944	2,921	3,251	9,648	3,120	16,019	,---	0,000	272178	29989	0	67
Case 6 - Waiting 4	1	120	0	50	50	71767	311	79252	24885	4755	3624	29401	500	72966	3,744	11,246	3,596	3,291	9,736	3,158	3,517	10,491	3,377	17,385	,---	0,000	273369	30054	0	72
Case 6 - Waiting 5	1	110	0	50	50	72699	338	86201	27067	5172	3948	29405	500	75894	4,075	12,100	3,916	3,583	10,715	3,441	3,829	11,408	3,679	18,915	,---	0,000	272915	30058	0	79
Case 6 - Waiting 6	1	100	0	50	50	73739	370	94399	29641	5663	4338	30342	500	80600	4,505	13,312	4,332	3,909	11,689	3,757	4,207	12,500	4,045	20,752	,---	0,000	280833	31017	0	87
Case 6 - Waiting 7	1	90	0	50	50	74897	416	106084	33310	6365	4820	46305	750	106986	5,257	15,960	5,041	4,145	12,227	3,973	4,701	14,094	4,507	23,302	,---	0,000	433477	47334	0	96
Case 6 - Waiting 8	1	80	0	50	50	75849	463	118084	37078	7085	5398	58358	791	128164	5,457	16,219	5,223	5,130	15,279	4,914	5,293	15,749	5,068	26,110	,---	0,000	546525	59654	0	108
Case 6 - Waiting 9	1	70	0	50	50	78237	526	134205	42140	8052	6161	58565	708	135149	5,966	17,600	5,721	6,058	18,072	5,809	6,012	17,836	5,765	29,613	,---	0,000	545531	59866	0	123
Case 6 - Waiting 10	1	60	0	50	50	81337	617	157229	49370	9433	7206	58698	708	144983	6,965	20,748	6,687	7,049	20,947	6,767	7,007	20,848	6,727	34,582	,---	0,000	546947	60003	0	144
Case 6 - Waiting 11	1	50	0	50	50	84679	738	188191	59092	11291	8613	58768	625	157979	8,395	24,801	8,072	8,311	25,049	7,990	8,353	24,925	8,031	41,309	,---	0,000	547129	60074	0,1	172
Case 6 - Waiting 12	1	40	0	50	50	90860	926	236167	74156	14170	10780	58841	875	178438	10,451	31,247	10,064	10,389	31,228	10,014	10,420	31,238	10,039	51,697	3,968	0,004	548455	60149	8,267	216
Case 6 - Waiting 13	1	30	0	50	50	100090	1220	310915	97627	18654	14360	58899	22666	231842	13,750	41,160	13,259	13,746	41,012	13,256	13,748	41,086	13,258	68,091	9,943	0,121	542087	60208	104,55	287
Case 6 - Waiting 14	1	20	0	50	50	118270	1838	468427	147086	28105	21415	58936	216791	491981	14,570	61,887	14,052	14,564	61,835	14,059	14,567	61,861	14,055	90,483	18,484	0,760	547336	60246	354,1	428
Case 6 - Waiting 15	1	10	0	50	50	172484	2718	692506	217447	41550	31711	55791	2098000	2463097	1,585	96,631	1,477	1,609	96,585	1,500	1,597	96,608	1,489	99,694	328,123	67,648	547606	57031	1639,85	634

Name	Elapse time or volume filled	Mean arrival	Reas-sign big parts	Reas-sign mid parts	Reas-sign small parts	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total main-tenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	%	%	%	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Case 7 - Waiting 1	1	150	0	100	0	69807	454	115766	36350	6946	2894	29326	791	86084	2,998	16,331	2,874	2,644	14,394	2,533	2,821	15,362	2,704	20,887	,---	0,000	500000	29978	0	58
Case 7 - Waiting 2	1	140	0	100	0	70212	486	124033	38946	7442	3100	29348	791	89412	3,208	17,484	3,077	2,829	15,410	2,712	3,018	16,447	2,895	22,360	,---	0,000	500000	30001	0	62
Case 7 - Waiting 3	1	130	0	100	0	70937	523	133500	41919	8010	3337	29358	791	93202	3,450	18,816	3,312	3,042	16,577	2,918	3,246	17,696	3,115	24,057	,---	0,000	500000	30010	0	67
Case 7 - Waiting 4	1	120	0	100	0	71649	568	144800	45467	8688	3620	29421	791	97795	3,734	20,374	3,586	3,288	17,933	3,156	3,511	19,153	3,371	26,036	,---	0,000	500000	30074	0	72
Case 7 - Waiting 5	1	110	0	100	0	72582	618	157700	49517	9462	3942	29423	791	102945	4,063	22,184	3,904	3,579	19,532	3,438	3,821	20,858	3,671	28,349	,---	0,000	500000	30077	0	79
Case 7 - Waiting 6	1	100	0	100	0	73609	680	173300	54416	10398	4332	33220	791	114232	4,383	23,928	4,211	4,041	22,048	3,881	4,212	22,988	4,046	31,246	,---	0,000	566667	33959	0	87
Case 7 - Waiting 7	1	90	0	100	0	75042	753	192033	60298	11522	4800	52994	1416	148697	5,100	27,757	4,885	4,319	23,482	4,133	4,710	25,619	4,509	34,838	,---	0,000	908333	54171	0	96
Case 7 - Waiting 8	1	80	0	100	0	76447	844	215033	67520	12902	5375	58455	1333	165072	5,401	29,387	5,172	5,126	27,882	4,907	5,263	28,634	5,040	38,937	,---	0,000	1000000	59754	0	108
Case 7 - Waiting 9	1	70	0	100	0	78739	962	245300	77024	14718	6132	58642	1500	177564	5,957	32,448	5,711	5,988	32,667	5,749	5,972	32,557	5,730	44,260	,---	0,000	1000000	59945	0	123
Case 7 - Waiting 10	1	60	0	100	0	81543	1124	286466	89950	17188	7161	58773	1500	194165	6,965	38,001	6,688	6,946	37,873	6,666	6,955	37,937	6,677	51,569	,---	0,000	1000000	60079	0	143
Case 7 - Waiting 11	1	50	0	100	0	85234	1347	343300	107796	20598	8582	58830	1458	216876	8,304	45,404	7,991	8,312	45,433	7,996	8,308	45,418	7,994	61,720	,---	0,000	1000000	60138	0,233	172
Case 7 - Waiting 12	1	40	0	100	0	90886	1687	429900	134988	25794	10747	58907	4375	254449	10,378	56,809	9,998	10,384	56,793	9,996	10,381	56,801	9,997	77,179	4,591	0,015	1000000	60217	27,817	215
Case 7 - Waiting 13	1	30	0	100	0	99549	2233	569133	178707	34148	14228	58916	184708	490347	9,858	75,234	9,496	9,881	75,139	9,508	9,869	75,187	9,502	94,558	22,446	0,642	1000000	60225	246,667	285
Case 7 - Waiting 14	1	20	0	100	0	118121	2714	691700	217193	41502	17292	55927	1135500	1486058	1,722	96,276	1,606	1,728	96,249	1,616	1,725	96,262	1,611	99,598	266,148	20,169	1000000	57170	603,383	346
Case 7 - Waiting 15	1	10	0	100	0	174575	2759	703033	220752	42182	17575	56104	1190583	1545900	1,156	97,540	1,059	1,161	97,520	1,067	1,158	97,530	1,063	99,751	411,567	229,560	1000000	57351	4508,3	352
Case 8 - Waiting 1	1	150	0	0	100	69877	44	11313	3552	678	2905	29342	0	46260	3,011	1,597	2,887	2,651	1,404	2,539	2,831	1,501	2,713	7,045	,---	0,000	48668	29994	0	58
Case 8 - Waiting 2	1	140	0	0	100	70416	47	12118	3805	727	3112	29369	0	46804	3,220	1,709	3,090	2,835	1,503	2,717	3,027	1,606	2,903	7,537	,---	0,000	48668	30022	0	62
Case 8 - Waiting 3	1	130	0	0	100	71216	51	13043	4095	782	3350	29364	0	47381	3,464	1,840	3,326	3,050	1,618	2,925	3,257	1,729	3,126	8,111	,---	0,000	48668	30017	0	67
Case 8 - Waiting 4	1	120	0	0	100	71870	55	14116	4432	847	3625	29366	0	48061	3,749	1,992	3,602	3,297	1,750	3,163	3,523	1,871	3,383	8,776	,---	0,000	48668	30019	0	73
Case 8 - Waiting 5	1	110	0	0	100	72860	60	15388	4832	923	3952	29392	0	48898	4,079	2,169	3,922	3,589	1,906	3,446	3,834	2,037	3,684	9,556	,---	0,000	48668	30046	0	79
Case 8 - Waiting 6	1	100	0	0	100	73844	66	16926	5314	1015	4347	29431	0	49920	4,481	2,384	4,311	3,937	2,092	3,783	4,209	2,238	4,047	10,494	,---	0,000	48668	30085	0	87
Case 8 - Waiting 7	1	90	0	0	100	75158	73	18782	5897	1126	4824	29435	0	51096	4,973	2,647	4,786	4,361	2,319	4,194	4,667	2,483	4,490	11,640	,---	0,000	48668	30089	0	96
Case 8 - Waiting 8	1	80	0	0	100	76804	82	21105	6627	1266	5420	29444	0	52574	5,584	2,974	5,377	4,894	2,605	4,710	5,239	2,789	5,044	13,073	,---	0,000	48668	30099	0	108
Case 8 - Waiting 9	1	70	0	0	100	78906	94	24097	7566	1445	6189	29462	0	54484	6,369	3,394	6,137	5,579	2,972	5,374	5,974	3,183	5,755	14,912	,---	0,000	48668	30117	0	124
Case 8 - Waiting 10	1	60	0	0	100	81787	110	28091	8820	1685	7215	29480	0	57027	7,414	3,954	7,150	6,494	3,462	6,260	6,954	3,708	6,705	17,368	,---	0,000	48668	30135	0	144
Case 8 - Waiting 11	1	50	0	0	100	85566	132	33697	10581	2021	8655	34854	0	67729	8,948	4,773	8,631	7,735	4,124	7,458	8,342	4,449	8,044	20,835	,---	0,000	57590	35628	0	173
Case 8 - Waiting 12	1	40	0	0	100	90125	165	42042	13201	2522	10798	58742	0	104846	10,825	5,767	10,428	10,097	5,377	9,722	10,461	5,572	10,075	26,108	,---	0,000	97336	60048	0	216
Case 8 - Waiting 13	1	30	0	0	100	100629	219	55919	17558	3355	14362	58908	0	113820	13,775	7,346	13,282	13,930	7,431	13,437	13,853	7,388	13,360	34,601	,---	0,000	97336	60217	0	287
Case 8 - Waiting 14	1	20	0	0	100	118493	329	83975	26368	5038	21568	59040	0	131695	20,636	11,056	19,927	20,694	11,085	19,978	20,665	11,071	19,952	51,688	2,504	0,004	97336	60352	13,633	431
Case 8 - Waiting 15	1	10	0	0	100	174245	659	168057	52769	10083	43164	59083	0	184795	31,175	22,108	30,134	31,170	22,172	30,131	31,173	22,140	30,132	83,445	5,279	0,380	97336	60396	621,6	863
Case 8 Detail - Waiting 1	1	10	0	0	100	174245	659	168057	52769	10083	43164	59083	0.	184795	31,175	22,108	30,134	31,170	22,172	30,131	31,173	22,140	30,132	83,445	5,279	0,380	97336	60396	621,6	863
Case 8 Detail - Waiting 2	1	9	0	0	100	185673	731	186492	58558	11189	47899	59083	125	196550	31,270	24,577	30,227	31,273	24,558	30,222	31,271	24,567	30,225	86,064	5,560	0,464	97336	60396	720,117	958
Case 8 Detail - Waiting 3	1	8	0	0	100	200354	822	209603	65815	12576	53835	59086	375	211382	31,075	27,630	30,028	31,049	27,592	30,007	31,062	27,611	30,017	88,690	6,020	0,593	97336	60399	851,2	1077
Case 8 Detail - Waiting 4	1	7	0	0	100	219627	939	239384	75166	14363	61484	59085	3333	233128	30,128	31,445	29,116	30,120	31,624	29,111	30,124	31,534	29,113	90,772	6,974	0,822	97336	60398	1017,07	1230
Case 8 Detail - Waiting 5	1	6	0	0	100	247909	1095	279127	87645	16747	71691	59076	11666	266520	27,928	36,735	26,988	27,939	36,820	26,997	27,934	36,778	26,992	91,704	8,779	0,227	97336	60389	1206,17	1434
Case 8 Detail - Waiting 6	1	5	0	0	100	287276	1314	334981	105184	20098	86037	59048	38916	328968	25,474	44,165	24,599	25,473	44,155	24,615	25,473	44,160	24,607	94,240	10,053	0,806	97336	60360	1550	1721
Case 8 Detail - Waiting 7	1	4	0	0	100	340491	1640	418022	131259	25081	107365	59044	278583	621015	21,430	55,060	20,694	21,412	55,154	20,681	21,421	55,107	20,687	97,215	11,657	0,823	97336	60356	2090,15	2147
Case 8 Detail - Waiting 8	1	3	0	0	100	431561	2178	554909	174241	33294	142524	58910	1892541	2321149	13,095	73,171	12,620	12,950	73,482	12,477	13,022	73,327	12,549	98,898	20,214	0,696	97336	60220	2855,78	2850
Case 8 Detail - Waiting 9	1	2	0	0	100	611849	2723	693911	217888	41634	178225	56254	11695250	12208004	1,958	96,057	1,836	2,005	95,959	1,883	1,981	96,008	1,859	99,849	235,850	15,362	97336	57504	5343,12	3565

Table 9-31: Results of part size simulations - Upper limit summary - No waiting

Name	Elapse time or volume filled	Mean arrival	Reas-sign big parts	Reas-sign mid parts	Reas-sign small parts	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total main-tenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	%	%	%	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Case 1 - No waiting 12	0	40	5	20	75	90275	726	185036	58101	11102	10780	58816	2875	161281	10,376	24,682	9,992	10,347	24,289	9,958	10,361	24,486	9,975	44,822	21,271	0,027	431063	60123	10,333	216
Case 2 - No waiting 8	0	80	33	33	33	76559	1154	294123	92354	17647	5389	58433	2375	195676	5,303	38,643	5,075	5,255	39,697	5,032	5,279	39,170	5,054	49,503	8,648	0,005	1368484	59731	5,033	108
Case 3 - No waiting 7	0	90	50	50	0	75075	1507	384042	120589	23042	4781	58536	375	226837	4,634	50,602	4,430	4,730	51,522	4,521	4,682	51,062	4,476	60,220	1,988	0,001	2011654	59837	0,867	96
Case 4 - No waiting 7	0	90	50	0	50	75201	1154	294224	92386	17653	4795	58438	375	193128	4,673	38,848	4,467	4,736	39,532	4,527	4,705	39,190	4,497	48,391	1,823	0,000	1538840	59736	0,75	96
Case 5 - No waiting 7	0	90	100	0	0	75056	2267	577816	181434	34668	4738	58575	1583	300524	4,634	76,793	4,433	4,638	76,766	4,432	4,636	76,779	4,433	85,848	,---	0,002	3048625	59876	3,1	95
Case 6 - No waiting 12	0	40	0	50	50	90227	930	237092	74446	14225	10794	58897	83	178079	10,472	31,184	10,080	10,392	31,476	10,005	10,432	31,330	10,042	51,804	1,806	0,000	550032	60206	1,083	216
Case 7 - No waiting 12	0	40	0	100	0	90697	1688	430066	135040	25804	10751	58908	375	250516	10,389	56,834	10,003	10,388	56,812	9,999	10,388	56,823	10,001	77,212	3,401	0,002	1000000	60217	4,267	215
Case 8 Detail - No waiting 3	0	8	0	0	100	201283	823	209918	65914	12595	53915	59088	2333	213543	33,943	27,659	32,820	33,973	27,644	32,835	33,958	27,651	32,827	94,437	8,269	0,905	97336	60401	944,6	1078

Table 9-32: Results of part size simulations - Upper limit summary - Waiting

Name	Elapse time or volume filled	Mean arrival	Reas-sign big parts	Reas-sign mid parts	Reas-sign small parts	Total ware-housing cost	Consumed material	Consumed energy	Consumed material cost	Consumed energy cost	Total operator cost	Total main-tenance cost	Total penalty	Total AM cost	Machine setup tracking 1	Machine utili-zation 1	Machine cool down tracking 1	Machine setup tracking 2	Machine utili-zation 2	Machine cool down tracking 2	System setup	System utili-zation	System cool down	Total system utili-zation	Average waiting time in queue	Average number of parts in queue	Average building volume	Machine depre-ciation	Parts in queue total	AM parts out
	Switch	hrs	%	%	%	€	kg	kWh	€	€	€	€	€	€	%	%	%	%	%	%	%	%	%	%	hrs	pcs.	mm³	€	pcs.	pcs.
Case 1 - Waiting 12	1	40	5	20	75	90648	714	182003	57149	10920	10783	58758	4708	161905	10,430	24,441	10,042	10,295	23,772	9,913	10,362	24,107	9,978	44,447	19,772	0,031	423489	60064	13,233	216
Case 2 - Waiting 8	1	80	33	33	33	76489	1157	294975	92622	17698	5373	58497	4958	198649	5,373	39,715	5,147	5,140	38,767	4,919	5,256	39,241	5,033	49,530	8,853	0,009	1378738	59797	7,75	107
Case 3 - Waiting 7	1	90	50	50	0	74836	1519	387131	121559	23227	4765	58429	3208	230666	4,688	51,104	4,482	4,658	52,023	4,454	4,673	51,564	4,468	60,705	4,405	0,001	2033402	59728	1,9	95
Case 4 - Waiting 7	1	90	50	0	50	75039	1160	295752	92866	17745	4784	58433	2250	195556	4,712	39,071	4,507	4,672	39,723	4,465	4,692	39,397	4,486	48,575	3,125	0,001	1550195	59731	1,517	96
Case 5 - Waiting 6	1	100	100	0	0	73685	2039	519688	163182	31181	4261	58498	3375	279998	4,185	69,209	3,995	4,177	69,083	3,988	4,181	69,146	3,992	77,318	,---	0,000	3048625	59798	0,25	85
Case 6 - Waiting 12	1	40	0	50	50	90860	926	236167	74156	14170	10780	58841	875	178438	10,451	31,247	10,064	10,389	31,228	10,014	10,420	31,238	10,039	51,697	3,968	0,004	548455	60149	8,267	216
Case 7 - Waiting 12	1	40	0	100	0	90886	1687	429900	134988	25794	10747	58907	4375	254449	10,378	56,809	9,998	10,384	56,793	9,996	10,381	56,801	9,997	77,179	4,591	0,015	1000000	60217	27,817	215
Case 8 Detail - Waiting 4	1	7	0	0	100	219627	939	239384	75166	14363	61484	59085	3333	233128	30,128	31,445	29,116	30,120	31,624	29,111	30,124	31,534	29,113	90,772	6,974	0,822	97336	60398	1017,07	1230

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1998 – 2001

Dipl.-Ing. (FH), Design engineering

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Dipl.-Wirt.-Ing. (FH), Business engineering

Cologne University of Applied Sciences

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Ph.D., Industrial engineering

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BACKGROUND:	Project engineer BIS Instandhaltung Neuss GmbH Department - Maintenance & Projects 2007 – 2009
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