Bachelor Thesis

Redesigning the service Supply Chain Network for ASML in the United States

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Preface

Dear reader,

In front of you lies my bachelor thesis report on "Redesigning the service Supply Chain Network for ASML in the United States" conducted for ASML within the Industrial Engineering and Management program of the University of Twente.

I want to use this moment and thank the people involved in the excellent organization of the thesis. ASML has made it a greatly pleasant experience to work for them from the first minute onwards. The intake interview with my manager and supervisor was not only informative but also kind, friendly, and progressive. I want to thank my manager Sjang Selen for giving me more responsibility within the department than I could have hoped for, and for being supportive throughout the entire duration of the thesis regarding the content and work atmosphere. Most of all, I would like to thank my supervisor Piotr Zajaczkowski for excellent guidance and appreciate the dedication and effort from him. The sharp advice from Piotr and the motivation to discuss aspects of my study excessively were crucial to finish this assignment with satisfactory results. Further, I would like to thank the entire team in the US and the Netherlands, and everyone involved who provided required information quickly and allowed for conducting my research without disruption.

Furthermore, I would like to thank my university supervisor Dr. Matthieu van der Heijden for the great supervision. Matthieu constantly challenged me to think a step further and ensure good readability even when dealing with complex content. He guided me towards finding good answers and great results throughout the entirety of this research assignment. I would also like to thank Dr. Engin Topan for offering support and inspiring me to pursue the Supply Chain Management path not only during the thesis but also during the entire Industrial Engineering and Management program.

Finally, I want to thank all friends and family members that supported me in one way or another on this journey. The support I received ranges from proof-reading documents to long and meaningful discussions, allowing me to gain insight into other perspectives and ultimately adding on top of the academic learning experience.

Moritz Wagner

Munich,
27.08.2022

Management summary

ASML is a Dutch company providing lithography machines for semiconductor companies all over the world. ASML also provides service material for their machines for all global customers. This study is concerned with ASML's service Supply Chain Network in the United States. High service level requirements and large distances to ship material in combination with a rapidly growing customer base create challenges for ASML to achieve the targeted service level Agreements. Therefore, this research investigates alternative Supply Chain Network Designs to improve service levels at optimal cost for ASML in the United States.

The research approach is to determine the optimal Supply Chain Network Design through modeling different Networks which allows to predict the service level and cost performance. The model is built based on historical data ranging from January of 2021 until December 2021. The used data includes transportation costs, lead time performance of third-party logistics providers, material availability indicators, and customer demand. To predict the performance of a Network Design, the input parameters in terms of warehouse locations, shipment routes, customer and material allocation are required. The model predicts the service levels for all US customers in terms of Delivery Response Time (DRT), which represents the percentage of shipments that are on time according to the agreed lead time targets, and Downtime Waiting for Material (DWM), which indicates the percentage of time a machine cannot operate while waiting for service materials. The cost performance is measured in annual domestic and international transportation cost excluding replenishment flows.

ASML currently assigns a local warehouse for each customer that can supply material within one hour. The local warehouses satisfy almost X% of all demand for the two core Business Lines EUV and DUV. The remaining X% of demand is supplied from the central warehouses outside of the US in X, or, if sufficient material is available, from another customer's local warehouse.

Simulating the current network yields an average demand volume weighted DWM performance for EUV and DUV of X% and X%, DRT performance of X% and X%, and total annual transportation cost of X million USD. The simulated performance matches reality accurately as the performance indicators deviate by a maximum of X%. Changing the material allocation drastically, e.g., by supplying a majority of material from one location to all customers, resulted in significantly worse performances caused by increased lead times and higher costs. Changing the supplying warehouse for material that is not available locally, however, allows for a slight performance improvement. Supplying all non-available material from the closest large warehouse yields an EUV and DUV performance of X% and X% for DWM, X% and X% for DRT, and total annual transportation cost of X million USD. The large warehouses in the US network are namely USX, USX, USX and USX, which have the capability to supply materials to multiple customer locations. Additional cost savings of X million USD annually can be achieved by consolidating all return flows at said large warehouses instead of shipping returns directly from the local warehouses to the Global Distribution Center in X. The research further shows that using the third-party logistics provider F2 more than F1 allows for better performance regarding US domestic shipments. F2 offers faster shipments with lower prices for routes longer than X miles and for all routes when shipments weigh between X and Xkg. Using only F2 results in X hours less total waiting time and X million USD transportation cost savings in comparison to using only F1. In comparison to the current distribution, using only F2 would result in X hours less total waiting time and X million USD transportation cost savings. This translates into a X% better waiting time and X% better cost performance.

In case material shortages become a bigger problem for the US supply in the future, the Supply Chain Network should be prepared to handle the impact. Material shortage for the US supply means that for some materials, so-called critical materials, only one item is available for all US customers. The model predicts an optimization opportunity for the material allocation of critical material to show the optimal coping strategy. Supplying critical material from the central US warehouse USX improves EUV

and DUV performances by 1.9% and 0.2% for DWM, 0.2% and 0.4% for DRT, and X million USD cost savings in comparison to the current system if only 2% of all materials become critical. Due to USX being close to major customer sites, the performance is significantly better than supplying critical material from any central US warehouse.

Therefore, it is recommended that ASML keeps the existing warehouse infrastructure with one Local Warehouse for each customer, and the Global Distribution Centers supplying material that is required to be available for all global customers. ASML should implement supplying material that is not available locally from the large warehouses USX, USX, USX, and USX. It is further recommended to supply critical material from USX to all US customers in the future. Additionally, consolidating all return flows at the mentioned large warehouses allows for operational optimization through cost savings.

To implement the optimized Supply Chain Network regarding material allocation and return consolidation, ASML needs to validate the findings within the Customer Supply Chain Management Department on a material level. Through simulating the proposed infrastructure and strategic decision, they can optimize the stocking strategy and validate the predicted impact in practice. Therefore, a pilot project to change the Network Design for only a few customers can be used that aims at validating the theoretical findings in practice. Furthermore, the precise inventory level impact should be used by the warehousing team to determine the possible investment cost if expanding the large warehouses is necessary to supply critical material in the future.

The validation on a material level including stocking strategy and investment costs through the Customer Supply Chain Management and Warehousing team also covers the main limitation of this research. The research was conducted on a strategic and tactical level without in-depth simulation of individual SKUs. Thus, the expected inventory levels of each SKU are unknown which limits the insights into performance improvements especially regarding holding cost. Furthermore, allocating critical material in the US can have a global impact as less material may be available for customers in other regions. Hence, the research is limited to the US region without considering global impact. Lastly, the mathematical model limits the sequence to determine which warehouse should supply material. Thus, the simulation automatically supplies material from the Global Distribution Center once the first and second prioritized warehouse does not have the material in stock. In reality, the system checks the material availability at all US warehouses and only then supplies it from the Global Distribution Centers. This limitation is not significant as the material availability in the US is over X%, however, may become more critical in the future.

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Glossary of terms

3PL	Third-party logistic provider
APPS	Applications (ASML product)
BL	Business Line
BX	Bucket, X = {1, 2, 3}
CX	Customer, X = {1, 2, 3, …}
CAPEX	Capital Expenditures
CDC	Central Distribution Center
CSCM	Customer Supply Chain Management
CWH	Central Warehouse
DRT	Delivery Response Time
DTWP	Downtime Waiting for Part
DUV	Deep Ultraviolet
DWM	Downtime Waiting for Material
EUV	Extreme Ultraviolet
FMA	Field Material Availability
FO	Field Office
GDC	Global Distribution Center
GF&E	Goods Flow and Excellence
IB	Install Base
LSO	Logistics service Operations
LT	Leadtime
LWH	Local Warehouse
MPS	ASML product
MRQ	Main Research Question
SX	Shipment priority, X = {1, 2, 4}
SC(N)	Supply Chain Network
SERV OPEX	service Operating expenditures
SL(A)	service level (Agreement)
SQ	Sub Question
TMS	Transportation Management System

1. Introduction

This chapter provides a general introduction to the contents of the research assignment. In the following sections, the commissioning company will be introduced (1.1), the problems leading to the research explained (1.2.), the core problem to be focused on will be shown and quantified (1.3.), the research questions that lead to answering the problem will be introduced (1.4.), and the research design including research activities and the scope will be described (1.5.).

1.1. Commissioning company

ASML Holding B.V. is a Dutch company, founded in 1984, with its Headquarters located in Veldhoven, North Brabant. ASML supplies market-leading companies like Intel and Samsung with machines to manufacture chips and is the market leader in its own domain, the semiconductor stepper industry (The Economist, 2020). With more than 32,000 employees and 60 locations worldwide, according to Forbes' Global 2000 list 2021, ASML is among the top three largest publicly traded companies in the Netherlands and 250 globally (Forbes et al., 2021).

ASML sells innovative machines that enable their customer to produce computer chips with exceptional precision, even in high volumes. The current top-notch machines are the Extreme Ultraviolet lithography machines (EUV). ASML's second product line, the Deep Ultraviolet lithography machines (DUV), are high-tech and represents the majority of demand today. Even though DUV and EUV machines dictate the market, many customers still use the previous machines, the MPS and APPS, in their factories.

ASML structured its organization around its four product lines, *EUV*, *DUV*, *MPS,* and *APPS,* by assigning individual business units, so-called Business Lines (BLs), to each product line. The Logistics service Operations department (LSO), for which this research assignment is being conducted, is responsible for planning the service operations globally. This includes storing and transporting spare parts and tools worldwide for all customers and BLs. Within LSO, spare parts and tools are referred to as materials and treated as one entity since they use the same Supply Chain.

1.2. Problem identification

ASML distinguishes between two types of service level Agreements (SLAs): internal and customer commitments. The relevant internal commitment for the LSO department is measured in Delivery Response Time (DRT) for materials, which includes parts and tools. The DRT is often also referred to as lead time (LT). The customer commitment varies per product and customer. However, most customer commitments are measured in Down Time Waiting for Part (DTWP) or Down Time Waiting for Material (DWM). The DTWP and DWM serve as performance indicators for the Supply Chain Network (SCN). They are calculated as percentage of the time a machine cannot run while waiting for material in relation to the total time the machine should be running. The DRT is used as an internal planning metric for Supply Chain Management and depicts the time it takes ASML to deliver material to its customers. This planning metric is used for aligning the expectations within departments. This way, e.g., new agreements with customers should be in line with expected LT performance. As Figure 1 shows, the LT refers to the timespan from ASML starting to process an order, internally called *picklist*, to the customer receiving the order, internally called *goods received*.

Figure 1: Lead time calculation

Every SKU is categorized into three buckets per Business Line according to their importance. The DRT target for DUV Bucket 1 material is X hours, Bucket 2 material is X hours, and Bucket 3 material is X hours, as table 1 shows. The DRT commitments and the SKUs per Bucket are fixed for all customers. This translates to different shipment routes per Bucket, as Figure 2 shows. Bucket 1 material, indicated in green, is shipped directly from a local warehouse to the customer. Bucket 2 material is either supplied directly from the Local Warehouse or first sent from another warehouse within the country to the local warehouse (domestic shipment route), and then to the customer as indicated in orange. Bucket 3 material, indicated in blue, is first shipped from a global distribution center to the local warehouse, and then to the customer.

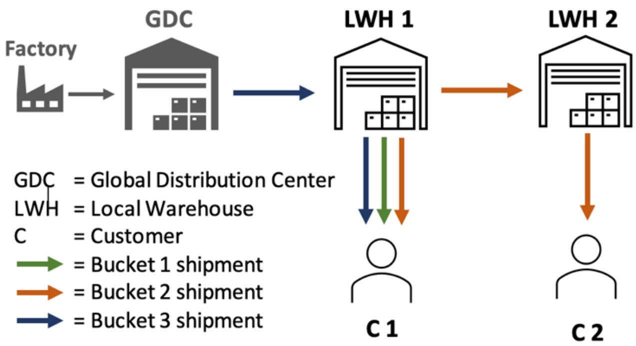

Figure 2: Supply Chain DUV

Bucket	DRT target DUV	Supplying from
Bucket 1	X hours	X
Bucket 2	X hours	X
Bucket 3	X hours	X

Table 1: DRT goals and implications DUV

The MPS DRT targets are structured similarly to the DUV DRT targets. The Bucket 2 and 3 commitments are the same as for the DUV BL. However, the DRT commitment for MPS Bucket 1 material is X hours instead of X hours for DUV. Therefore, MPS Bucket 1 and Bucket 2 materials are transported from a central location to the customer as Figure 3 shows. Even though some service tools may be supplied from the Local Warehouses, tools and parts will hereafter be treated equally in the Supply Chain. Table 2 summarizes the DRT targets for the MPS BL.

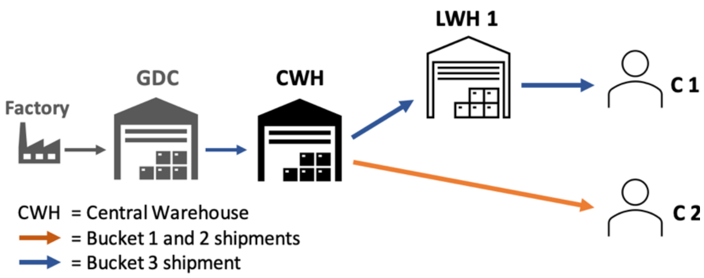

Figure 3: Supply Chain MPS

Bucket	DRT target MPS and APPS	Supplying from
Bucket 1	X hours	X
Bucket 2	X hours	X
Bucket 3	X hours	X

Table 2: DRT goals and implications MPS

ASML observes challenges to meet the DRT commitments for Bucket 2 shipments in the US (domestic shipments). Currently, only X% of domestic routes, which are shipments between one local warehouse to another (Figure 2, orange route), achieve a mean LT below X hours (using CI of 95%). ASML further expects the DRT performance to worsen in the future, based on two trends. For one, the Customer Supply Chain Management department (CSCM) has drafted new DRT commitments for the upcoming EUV products. This draft indicates that future EUV DRT commitments will merge EUV Bucket 1 and 2 targets by promising LTs of X hours. Even though the Bucket 1 target is loosened compared to the X-hours DUV target, this is expected to be a massive challenge since the current DUV DRT commitment for Bucket 2 material is only X hours. Table 3 shows the DRT targets for EUV. For two, the Customer Supply Chain Management Field Office in the US (CSCM FO US) expects to sell X new EUV and DUV systems, increasing the number of machines by X% until 2025. Since the LSO department is responsible for service operations, the increase in machines is translated to a X% expected increase in total part movement by using an average part movement per machine and multiplying with the number of new machines. This increase suggests a significantly higher demand for service operations, further challenging network performance.

Bucket	DRT target EUV	Supplying from
Bucket 1	X hours	To be determined
Bucket 2	X hours	To be determined
Bucket 3	X hours	To be determined

Table 3: DRT goals and implications EUV

ASML's expectation not to meet future SLAs led to conducting this research assignment and represents the action problem. Through my research, I discovered underlying issues that cause the action problem.

As Figure 4 shows, the high losses due to short breakdowns and the necessity of special, large, and expensive parts to repair machines lead to customers demanding short LTs. The short LT requirements then set high standards for DRT commitments (norm). The large distances between customers in the US and the weak performance of transportation companies are the main drivers for not meeting the DRT commitments (reality). The two problems' root cause is the suboptimal warehouse locations and distribution strategy. This root cause also leads to ASML not being able to supply new customer locations fast enough.

The *warehouse location and distribution strategy* includes the number of warehouses, their location, which customers are supplied by specific warehouses, and which materials are allocated to specific warehouses. The material and customer allocation is summarized as distribution strategy since this research is on a strategic level, and thus, does not investigate the allocation of specific SKUs to warehouses and customers but rather the allocation of material buckets. The current network setup allocates one local warehouse to each customer which holds all Bucket 1 material for that customer. These warehouses also hold additional Bucket 2 inventory, which may be supplied to any domestic customer. Therefore, no specific secondary customers are assigned to the local warehouse, and no stock pooling regions are set according to the current setup. This causes large distances to ship materials all over the US and large distances to cover for transportation contractors that pick Bucket 2 items up anywhere in the US before shipping them to their distribution center and then delivering them to another ASML warehouse in the US. Lastly, renting local warehouses close to the customers' factories decreases ASML's capability to supply new customer locations without adapting their network setup.

The weak performance of transportation companies has been investigated in-depth due to the current capacity problems in transportation. This internal investigation showed that the current contractors' performance was impacted by capacity but using data from 2021 adequately represents the expected performance for the time range of this study. Therefore, the problem still holds, and any analyses on transportation performance and costs only refer to the timeframe after the first quartile of 2021. While there might be an underlying issue of inadequate selection of transportation companies by ASML, the transportation team stated that it is highly unlikely that other contractors would perform better. The 3reason for the weak performance is the distribution strategy in combination with warehouse locations. Due to short notice when requesting transportation and the far distance from warehouses to contractors' distribution centers, the lead times are longer than they advertise.

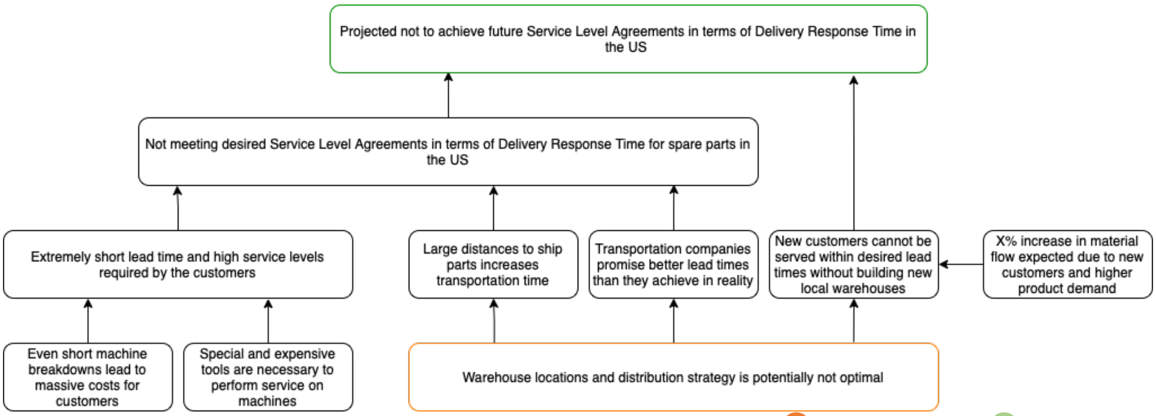

Figure 4: Problem cluster *= Core problem, = Action problem*

1.3. Core problem and measurement

The problem cluster shows four root causes leading to ASML's action problem. It is necessary to select a core problem to solve for this research assignment, which should resolve the action problem. The two leftmost root causes, *short machine breakdowns leading to high costs* and *necessity of special parts to repair machines*, are of mechanical nature. Therefore, neither problem can be solved within the scope of this IEM Bachelor's research assignment and do not qualify as core problems. The rightmost root cause, *expected increase in material flows*, represents the increased demand for ASML products. ASML does not want to jeopardize its future growth by selling fewer products, and thus, this root cause does not qualify as core problem either. Hence, tackling the suboptimal warehouse location and distribution strategy is the reasonable choice as the core problem for this research. Through an optimal warehouse location and distribution strategy, ASML could achieve better LTs, and thus, adjust the reality to meet the norm.

ASMLs norm is to meet X% of the internal DRT commitments, which translates to achieving a LT below the LT target for X% of the shipments. This percentage is measured individually for every customer but includes all buckets. Thus, the KPI DRT represents the percentage of all Bucket 1, 2, and 3 shipments that are delivered within their respective LT target (e.g., for DUV this would be X hours, X hours, and X hours) for a specific customer. Access to the KPI Dashboard is restricted and cannot be accessed yet. However, a previous analysis provides similar data to the KPI DRT and will represent the reality for now. The current reality shows that less than X% of the Bucket 2 shipments achieve the DRT target of X hours. With the expected X% increase in demand until 2025, this discrepancy is expected to increase.

Additionally, the LSO department has the ongoing objective to reduce costs by X% of the sales in the 5-year financial plan. Achieving DRT commitments is the priority for the LSO department, however, changing the Network Design to improve performance needs to align with the corporate cost reduction objective. Therefore, relevant costs need to be considered when tackling the core problem. The relevant costs consist of SERV OPEX and CAPEX. However, due to timely limitations of this research, the problems will not be tackled on a material level. Thus, the SERV OPEX regarding inventory will be out of scope. The CSCM department has indicated that relocating material within the US will not have significant impact on the overall inventory levels, and thus, the neglecting inventory related OPEX will not impact the cost performance conclusions drastically. Furthermore, this study focusses on determining the optimal network design, and thus, the CAPEX are set out of scope. In case the optimal Network Design requires additional facilities or the termination of existing facilities, the implementation plan will include calculating the expected CAPEX as a core step. The transportation costs will represent the core component of the SERV OPEX, covering all domestic and international shipments, which also includes a sensitivity analysis for return flows based on historical return flow data. With the inventory levels being out of scope, the replenishment flows will also not be modelled since CSCM again does not expect drastic changes when relocating inventory within the US.

It is worth noting that the previously introduced external commitments, DTWP and DWM, are important to this research but not used as variables. The DTWP and DWM highly depend on the DRT since they represent the time a machine is down and waiting until material is delivered. Therefore, shorter DRTs can achieve lower DTWP and DWM. However, the DTWP and DWM also depend on the material availability. Thus, the DTWP and DWM will be estimated by the CSCM department using an existing algorithm based on the DRT performance so that the feasibility of alternative Supply Chain Network Designs can be evaluated. The feasibility here refers to that existing customer agreements cannot be changed, and therefore, any alternative Supply Chain Network design should achieve the DTWP and DWM commitments. Table 4 shows the operationalized variables for this research.

Variable	Measurement	Calculation
DRT	Lead Time (hours)	Per shipment, Lead Time in hours from Picklist to Goods receipt
KPI DRT	DRT achievement (%)	Per customer, Percentage of all shipments (regardless of the Bucket) within DRT target. So, for customer Y: $\frac{\sum_{x=1}^{3} Nr\ of\ on\ time\ shipments\ in\ Bucket\ x\ to\ customer\ Y}{Total\ nr\ of\ shipments\ to\ customer\ Y}$
SERV OPEX	Transportation costs (€) Return costs (€)	For all shipments excluding replenishments based on: Mode, Company, Distance Depending on: Consolidation at warehouses, and Mode and distance of transportation

Table 4: Operationalized variables

1.4. Research questions

For ASML to meet its goals, they need to adjust its performance to meet commitments. To achieve this, the identified core problem needs to be solved. This yields the following main research question (MRQ) for this research:

> *MRQ: How can a new Supply Chain Network Design for the Logistics service Operations department improve the Delivery Response Time for ASML in the United States at optimal cost?*

The core decisions for alternative Supply Chain Network Designs are the variables that the LSO department can actively influence. Those variables are the warehouse locations, customer and material allocations, and transportation methods. The customer allocation describes which customers will be served from which warehouse with what priority. The material allocation consists of the Bucket assigned to specific warehouses but does not include specific SKUs (see section 1.5.1 scope). The transportation methods include the mode of transportation, i.e., road or air, and the carrier, i.e., F1 or F2. The improvements of the DRT are measured in time, while the cost performance covers all transportation related SERV OPEX excluding replenishments.

The existing structure and performance need to be investigated to understand whether an alternative network design improves the current setup. Afterward, one can evaluate if alternative network setups achieve the goal of DRT performance meeting DRT commitment. This leads to the first sub-question (SQ):

> *SQ1: What is the qualitative structure and quantitative performance of the current Supply Chain Network Design at ASML in the US?*

For ASML to assess how the current network performance can be improved, they need alternative designs. The alternative Supply Chain Network designs that will be considered to compare to the current setup are hereafter referred to as scenarios. The second sub-question tackles said selection of scenarios:

- *SQ2: What are alternative Supply Chain Network Designs that ASML should consider implementing in the US?*

The next step is to understand the impact of changes in the variables on the identified action problem. The quantitative analysis will show the scenarios' performance scores. This builds the basis for comparing scenarios and recommending the optimal solution. These steps yield the following sub-questions:

- *SQ3: What is the impact of alternative Supply Chain Network Designs on the service level in terms of DRT and Cost performance in terms of SERV OPEX regarding transportation?*
  - *SQ3.1: How do the warehouse locations impact the service levels and Costs?*
  - *SQ3.2: How do the transportation methods impact the service levels and Costs?*
- *SQ4: What Supply Chain Network Design can achieve the desired service level in terms of DRT at optimal cost in terms of SERV OPEX regarding transportation?*

Comparing the scenarios' performance shall provide sufficient information to answer the MRQ. This should further resolve the core problem and all other problems caused by the core problem. The optimal scenarios should be recommended to ASML, and further steps and implications of this research need to be shown. This yields the final sub-question:

- *SQ5: What are the conclusions and recommendations for ASML?*
  - *SQ5.1: What Supply Chain Network Design should ASML implement?*
  - *SQ5.2: What are the necessary steps for ASML to implement the recommended Supply Chain Network Design?*
  - *SQ5.3: How can ASML improve future Network studies?*

Answering the research question by following the five SQs results in the final deliverables, as table 5 shows.

Deliverable	Contents
Dashboard	Visualized SERV OPEX regarding Transportation cost without replenishments, DRT and DWM performance of all simulated scenarios (including the current setup)
Presentation & Report	Recommended SCN Design including: Number of warehouses and locations, Customer and material allocation, and Transportation mode and company
	Recommendations for improving future network studies
	Brief explanation of next steps for implementing the network design and limitations of this research's findings

Table 5: Final deliverables

1.5. Research Design

All stakeholders affected by or impacting the action problem will be introduced in this section. Furthermore, the relevant activities to solve the problem, including a timeline of the stages, are shown. Complementing this overview, the scope is narrowed down and clearly defined. Lastly, the validity and reliability of the research design are touched upon.

1.5.1. Stakeholders

The identified stakeholders, outside of the Logistics Service Operations department (LSO), in the process of answering all research questions are the Customer Supply Chain Management department (CSCM), their US Field Office (CSCM US FO), and LSO departments such as Transportation and Warehousing. CSCM takes care of SLAs with customers and is automatically involved due to the impact of the SCN design on the SLAs. With the SCN massively depending on the warehouse locations and the transportation capabilities of ASML, the two departments Transportation and Warehousing will play a significant role in data gathering and KPI measuring. Lastly, with the CSCM US FO being the problem owner, they are also this project's core stakeholder.

1.5.1. Scope

The research will be conducted on a strategic level and not on a part level. This implies that investigating individual parts' demand and shipping lanes is out of scope. However, the shipment lanes per Bucket and total parts movement per product are on the strategic level and will therefore be investigated throughout this research. The DRT commitments per Bucket serve as inputs for the model and simulation, but it is out of scope to determine whether changing commitments would allow for a step-change in cost and capital performance. Furthermore, the allocation of material, i.e., which Bucket should be stored in which warehouse, lies on a strategic level and is therefore within scope. Allocating specific SKUs to warehouses and including their inventory levels would be on a part level and is, therefore, not within the scope of this assignment.

Before modeling and simulating any changes in the Supply Chain Network Design, historical data, i.e., freight performance in terms of lead times, contracts with transportation companies, and expected part movements, needs to be gathered and analyzed. I will analyze and collect the data provided by the according stakeholders. The general model of how inputs, e.g., lead times and warehouse locations, impact the performance indicators, e.g., DRT performance and transportation SERV OPEX, will be drawn by me. The simulation of transportation SERV OPEX, i.e., the impact of choosing different routes on the transportation costs will also be conducted by me. As indicated in subsection 1.3, the impact of Network Design on the inventory levels and holding costs are out of scope due to time limitation and the expectation of little impact. Due to this research not being on a part and material level, the replenishment flows cannot be modelled accurately. Similarly as with the holding costs, the impact on replenishment costs is expected to be minimal, and thus, the research will focus on the forward flow and return flow related SERV OPEX as the core cost performance indicators. Furthermore, calculating the CAPEX regarding facility investments and termination costs is out of scope, however, will be included in the implementation steps if the optimal Supply Chain Network would require such expenditures. I will create and decide on the scenarios to model, which includes decisions on warehouse locations, primary customers, shipment lanes, and transportation methods. I will also conduct the analysis of the results.

Lastly, it is out of this research's scope to implement a new SCN. This will only be a recommendation to serve the company as a foundation for starting the implementation plan for a new SCN. The implementation plan will also include the advice to validate the findings of this research within the CSCM department through applying their stocking strategy on a part and material level.

1.5.2. Problem solving approach

Figure 5 shows the rough timeline for the different stages. The following paragraphs describe each stage's activities, their purpose, and impacted stakeholders in more detail.

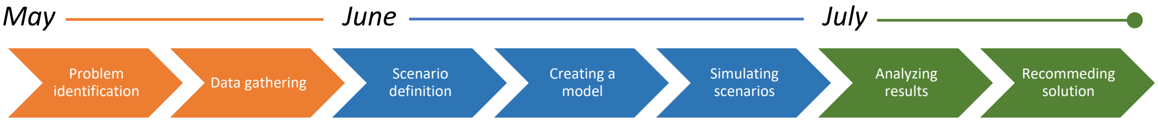

Figure 5: Timeline

The first two stages, *problem identification* and *data gathering*, cover SQ1, *qualitative and quantitative analysis of the current SCN design*. The problem identification stage requires qualitative analysis of the current network to understand the relationship between the stakeholders and their problems or impact. The data gathering stage should be started simultaneously and complements the qualitative analysis through quantifications. In this stage, the relations between problems and impact, as well as their norm and reality, will be quantified. These stages focus on investigating the core cost drivers for transportation SERV OPEX, the current SLs in terms of DRT, DWM, and DTWP, and the freight capabilities, which are the main driver for the DRT. The summarized goal of the first two stages is a quantified core problem that should be approved by the company's project board, an infographic showing the dependencies of the stakeholders, and a presentation consisting of the most critical insights from historical data.

The third stage, *scenario definition*, covers SQ2, *possible SCN designs that ASML should consider*. During this exploratory stage, I will analyze which SCN designs from other companies and literature exist, how they could be adjusted, and what novel designs I could design. Then their compatibility with ASML's prerequisites shall be challenged. Therefore, the main task is to evaluate which network designs could be implemented and should be analyzed further. This stage is crucial due to the limitation of the number of scenarios for the simulation. Simulating complex scenarios is time-consuming and increases the scope of this research massively. Thus, only a select number of scenarios should be simulated in the fifth stage. The decision on which scenarios those will be needs to be well reasoned in this stage. The deliverable of the third stage is a set of scenarios for the SCN design, including the number and location of warehouses, their primary and secondary customers, and the method of transportation.

The fourth stage, *creating a model*, builds upon the third stage's outcome and covers SQ3 regarding the *impact of key variables on the performance indicators*. The key variables to consider are the previously introduced outputs of the third stage (number and location of warehouses, their assigned customers, and the method of transportation). The model created throughout this stage serves as the foundation for the simulation. The dependencies between inputs and outputs need to be understood before quantitatively analyzing the scenarios. Therefore, this stage yields an infographic on the dependencies of variables and measurable outputs. The measurable outputs have yet to be fully defined but will most likely be the key performance indicator SL in terms of DRT, DWM, and DTWP and the cost performance in terms of transportation SERV OPEX.

The fifth and sixth stage, *simulating scenarios and analyzing results*, cover the *quantitative analysis of scenarios* which SQ4. Simulating scenarios is based on the previously designed model. This stage calculates the results for every scenario, which are combinations of alternative warehouse locations, customer and part allocations, and transportation methods. One simulation model will be used to simulate all scenarios so that the results can then be compared. The resulting service levels and cost performances per scenario will be stored as outputs during this analysis. Furthermore, criteria to compare the results will be determined.

The last stage, *recommending a solution*, covers SQ5. In this section, the previously gained results of the quantitative analysis will be used to assess which scenario is optimal. Therefore, the performance scores need to be investigated and compared. A possible trade-off between cost and performance needs to be investigated and valued to evaluate the optimal scenario. In other words, I need to derive if changing the network design to improve performance and possibly increase cost is better than keeping the current network design or if there is a scenario that can improve both performance and cost. Ultimately, a recommendation on the optimal scenario based on well-reasoned arguments will be provided to the problem owner as the final deliverable. To improve the transparency of my research, the limitations of the analysis and possibly further necessary investigations will also be explained for this deliverable.

1.5.3. Validity

Achieving *internal validity* is extremely important for this research design. The results can only be meaningful if the cause-effect relationship is complete and correct. Therefore, the internal validity of the research model will be ensured by simulating the current model with the same inputs as the new models and then comparing the results with the actual measured performance of the current system. For this comparison, a simple statistical test on the means of two independent samples will provide sufficient insight. Additionally, investigating a variable's changes in performance individually and comparing the change to the expected change based on SQ4 will ensure a high internal validity.

With high internal validity, achieving a high *external validity* is difficult. The SCNs of different companies may operate differently, and thus, other factors affect the performance of those SCNs depending on the organizational structure. Therefore, the findings may not be readily generalizable. Nevertheless, the general approach of how to conduct research into improving SCNs and especially the selection of stakeholders and factors influencing the performance is at least similar for the entire research population. Therefore, the high internal validity compromises the external validity, however, the theory is still generalizable to some degree.

1.5.4. Reliability

Testing the reliability of this research is simple, and most parts are implicitly reliable. The simulation aspect of the research calculates the performance measures based on the changing inputs of the SCN design. Since this simulation is simply calculating outputs based on specific inputs (testing) while the formulas to calculate said outputs do not change, running the simulation multiple times (retesting) will not yield different results. A possible issue could be that the formulas calculate the wrong values, however, this falls under validity rather than reliability. The initial data gathering on the current SCN highly depends on the information provided by the stakeholders. It might very well be that the stakeholders would describe the SCN differently when asked again after a few months. Nevertheless, it is highly likely that they would not change the 9escryiption within a few days or weeks. Moreover, the information used to model and investigate the current SCN is also based on facts and files from the organization, which, when used again, would always result in the same gathered data, and hence, ensure high reliability.

1.6. Conclusion

ASML sells products and provides service (materials) for companies in the semiconductor industry. Due to the challenge to achieve the desired service levels, this research aims at determining the optimal Supply Chain Network for the service Supply Chain. Through modeling the service Supply Chain, various Network Designs will be simulated, analyzed, and compared to evaluate whether a performance or cost improvement is possible for the service Operations in the United States. The research focusses on the two main Business Lines, EUV and DUV, and models the lead time performance for all twelve US customer locations. Due to the high complexity, the inventory strategy on a material level is not included but rather a material availability indication is used. Furthermore, the cost performance only covers the transportation component of the SERV OPEX but does not consider CAPEX. Since material relocation within the US is not expected to have a great impact on the replenishments and inventory levels by the CSCM department, both aspects are out of scope for this research. To determine the optimal network design, possible cost benefits through return consolidation will be investigated through a sensitivity analysis. ASML will ultimately receive a comparison of multiple scenarios based on the Delivery Response Time (DRT) and Downtime Waiting for Material (DWM) performance as well as the total annual transportation costs excluding replenishments. Moreover, recommendations for future Network studies will be provided next to an implementation plan of the optimal Supply Chain Network Design.

2. Research question 1 | current performance

Chapter 2 aims to answer the subquestion *SQ1: What is the qualitative structure and quantitative performance of the current Supply Chain Network Design at ASML in the US?*

The part of the supply chain relevant to this assignment is the service supply chain. The service supply chain network consists of four core elements: Customers, warehouses, transportation, and demand. Each element will be further explained and connected throughout this section.

2.1. Customers

ASML has four main customers in the US, namely Intel, Samsung, Micron, and Global Foundries. Each customer may have multiple locations distributed over the entire country. Therefore, the current supply chain network has nine customer locations to serve. The current customer locations are spread throughout the US; however, they show an important pattern. All sites are located toward the country's borders, resulting in X locations on the X area. ASML further expects to acquire new customers and new locations for existing customers. Therefore, X additional locations will have to be served by 2025, which will also be located toward the country's borders. X of the new locations are located in X and X in the X area. The exact customer locations are further listed in Figure 11 in the following warehouses section.

2.2. Warehouses

Due to current contractual agreements, each customer location has one assigned local warehouse within a X-hour driving distance, as shown in Figure 6. In rare exceptions, one warehouse may be used to serve X customers, which currently is only the case in X instances: X. All warehouses that hold material to satisfy demand and are therefore relevant to this assignment are rented or leased through ASML. The warehouses are managed in close collaboration between ASML and third-party logistics providers (3PLs). ASML also owns a central hub not assigned to a specific customer. The only warehouses outside of the US that are still relevant for the supply chain network design of the US are Global Distribution Centers (GDCs) that supply material to the warehouses in the US. With providing X% of all international shipments, the X main GDCs are located in X.

X

Figure 6: Warehouses and customers

2.3. Transportation

ASML works with X third-party logistic providers (3PLs) for transportation within the US, namely F1 and F2. Domestic transportation in the US includes delivering material from warehouses to customers but also transporting material from one warehouse to another US warehouse. The latter aspect is used for stock rebalancing in case the inventory is lower than the desired safety stock but another US warehouse has sufficient inventory, the material is sent to increase inventory to the safety stock level. ASML uses the X forwarders F2 and F3 for international shipments to US warehouses. The forwarders control and manage international shipments, so ASML has little influence on the used routes. Nevertheless, it is clear that the forwarders use air transportation to ship orders to the US. At which airport they enter the country and whether they use additional air transport or trucking to get to the destination is up to the forwarders. Within the US, the 3PL use a combination of trucking and air transportation depending on the desired performance and type of shipment. Overall, X% of the total shipments are international shipments from the GDCs, and X% domestic shipments within the US.

2.3.1. Domestic 3PL F1

F1 distinguishes between three types of shipments: Parcel, Heavy Weight, and Freight. Any shipment below X kg is considered a parcel, while any shipment above X kg is heavy weight. Large and heavy materials that require special equipment are called Freight. F1 picks up any parcel and heavy-weight items from the warehouses every day at a set time, while freight shipments need to be requested individually. The pick-ups of regular shipments from ASML's warehouses are on a fixed time, and ASML needs to indicate before said time which number of shipments they want to have delivered. This time is called cutoff time and varies per location.

For each type of shipment, F1 offers different service levels. If better performance in terms of shorter shipment duration is required, the costs per shipment will increase. Due to the short lead time requirements, ASML only uses the best service level offered by F1 to satisfy customer demand. For replenishments and return flows, they choose longer shipment durations to save costs. The best offering is called F1 X for parcels and heavy weight. This service level promises delivery at the destination at X when requested before the cutoff time. For Freight, the same service level applies; however, the cutoff and pick-up times are earlier than for parcels and heavy weight. It is crucial to understand that F1's service level promises are rather advertisements than contractual service level agreements. Even though it is in F1's best interest to achieve the promised lead times to maintain customers and achieve a high customer satisfaction, they cannot be held accountable if they exceed the promised shipment duration.

F1's cutoff times vary per location but are, on average, at X o'clock. The latest delivery time also varies slightly per destination but is, on average, at X o'clock when choosing the fastest service level X. This allows for a shipment duration time span between X to X hours depending on the time of request. When assuming a normal distribution, the average promised lead time is then X hours. Since ASML desires faster deliveries, they only request services from F1 on the day of the cutoff time to decrease the average expected transportation time to X hours. However, practice shows that the average transportation time when using F1 as the forwarding agent is still X hours on average. Furthermore, the percentage of shipments that arrive within X hours after requesting shipping is only X% on average. At the same time, ASML desires this percentage to be X%, as will be explained in the Performance section later.

2.3.2. Domestic 3PL F2

F2 does not distinguish by type of shipment but always provides the fastest service possible. All shipments with F2 need to be requested individually before F2 picks them up as fast as possible and ships them with the next available plane or truck. Therefore, F2's service is expected to be faster on average but also more costly. ASML achieves an average domestic lead time of X hours, which is well within the targeted DRT. However, the percentage of individual shipments that arrive on time is only X%, which underperforms ASML's target of X%.

2.3.3. Shipment policies

ASML's general policy is to use F1 for all shipments when possible due to the lower rates compared to F2. However, when shipments need to be requested after F1's cutoff time, F2 is used for fast delivery. To determine which service level to choose, shipments are classified into three categories: emergency, priority, and routine shipments. For material requests from customers, the emergency category (S4) is chosen. This means that all Bucket 1, Bucket 2, and Bucket 3 material that is requested from the customer will be shipped as an emergency shipment with the S4 category. This allows for faster lead time but also increases the total transportation costs. Any replenishment, stock balancing, and return flows are categorized as priority (S2) or routine (S1). It is unclear which methodology is in place to distinguish when to use S1 or S2 shipments. Since there is no tactical difference in choosing them, the LSO team advised to use the same percentage of S1 and S2 shipments that we observe in reality for all instances where it is necessary throughout this research. Data from 2021 shows that X% of the shipments are S4, X% S2, and X% S1. Even though we see fewer S4 than S1 and S2 shipments, ASML focuses on good performance for their customers, which translates into focusing on the performance of S4 shipments as they are covering all demand. S1 and S2 shipments do not need to be on time as strictly as S4 shipments since they are only replenishments, returns, and stock rebalancing shipments.

S4 shipments are of the highest priority and, thus, are always shipped using the best available service level of the shipping agent. The best available service level is categorized according to the lead time performance. Therefore, the S4 shipments are being shipped with the fasted lead time possible even though the costs for the best available service level are also highest. In practice, this means that any requests before the F1 cutoff times are shipped using F1 X. Any requests after the F1 cutoff times are shipped using F2's X.

2.4. Systems and demand

As previously explained, ASML has four individual business lines (BLs), however for this study the MPS and APPS BL are combined as they show significantly less demand resulting in three lines, namely "EUV", "DUV", and "MPS and APPS". As Figure 7 shows, the number of installed MPS and APPS products, so-called install bases (IBs) are expected to stay roughly the same in the US until 2025. The number of EUV and DUV systems is expected to increase significantly.

Figure 7: Systems 2021 vs. 2025

When a machine breaks down, it is often unclear which exact material is necessary to repair it. Therefore, multiple parts may be requested and need to be at the customer's fab as soon as possible. The total movement of parts over the course of a year is considered the demand for the service supply chain network. The newer machines are built in a more complex structure which has two implications for the service demand. For one, the uncertainty which part is necessary to repair the machine is higher, and for two, the machines break down more often. This results in a higher average total part movement for newer machines, as Figure 12 shows.

Multiplying the number of machines per customer location with the average demand per machine yields each location's total demand. Due to the low part movement of MPS and APPS and lower service level agreements, the focus lies on the DUV and EUV install bases. The comparison of demand from 2022 to 2025, as Figure 8 shows, depicts the shift towards the X within the US.

Figure 8: Total part movement 2021 vs. 2025

2.5. Material flows

Even though material flows differ per business line (BL), all material is categorized into the three previously introduced buckets. The bucket agreements are made on a BL level and directly with the customers. This means that for each BL and customer, a specific set of materials is assigned to each bucket. Based on these agreements, the material in different buckets of different BLs follow different routes to reach the customer.

2.5.1. EUV material flows

For the new EUV machines, the previous bucket 1 and bucket 2 will be combined (cf. Figure 6 in section 1.2). Any material in either bucket is supposed to be available within predefined regions. ASML expects X EUV customer locations in the US by 2025. Based on the performance commitment to deliver any Bucket 1 or Bucket 2 material within X hours, ASML determined X regions to serve customer locations, as Figure 9 shows. Any Bucket 1 or Bucket 2 material for the customer location needs to be available at any warehouse within that region. In practice, for all regions except R3, both Bucket 1 and Bucket 2 materials must be available directly at the local warehouse since no other local warehouse is within the region. For the customer locations in X and X, any Bucket 1 or Bucket 2 material should either be available in X or X to be served to any of the X customer locations. Bucket 1 and Bucket 2 material is directly shipped from the local warehouse to the customer without consolidating in or channeling through another facility.

Figure 9: Reporting regions EUV

Identically to all other business lines, Bucket 3 material is stored at GDCs in X and, when needed, shipped directly from there to the local warehouse and then to the customer.

2.5.2. DUV material flows

DUV Bucket 1 material is, per definition, available to the customer within X hours after request. Therefore, all DUV Bucket 1 material is stored in Local warehouses directly at the customer. Bucket 2 material may be sourced from any other facility within the country as long as it is available within X hours. In practice, Bucket 2 material can then be shipped from a local warehouse at another customer location to the local warehouse of the requesting customer location and then to the customer. Bucket 3 material is shipped identically to the previously explained EUV Bucket 3 material.

2.5.3. MPS material flows

MPS and APPS show the lowest demand in terms of annual parts movement, and breakdowns of these machines are not nearly as costly as with the newer DUV and EUV machines. Therefore, all Bucket 1 and Bucket 2 materials may be supplied from any location within the country as long as it is available within X hours. This means that no local warehouses are necessary to store material for the MPS BL. Thus, the local warehouses are only used for newer machines, and a central hub in X provides all Bucket 1 and Bucket 2 materials for MPS customers. After requesting material, the materials are shipped from the central hub to the local warehouse at the customer and then to the customer. Bucket 3 material is shipped identically to the previously explained EUV and DUV Bucket 3 material.

2.5.4. Return flows

As mentioned before, at the time of a machine breakdown, it is often unknown which exact material is necessary to repair the system. Therefore, customers order more material than necessary and return any unused material after the repair as well as used, or broken, materials. These materials need to be shipped back, which is summarized as return flow. All unused materials will be shipped back to the Local Warehouse or GDC that supplied the material in the first place. All used or broken materials need to be shipped back to the GDC in X. All return material are shipped with the S1 and S2 service level which are cheaper with longer lead times than the S4 service level category. The returns of used or broken materials are consolidated at the local warehouse before being shipped overseas with the exception that all MPS material is consolidated at the USX warehouse. To avoid overflow, all warehouse ship returns after 3 weeks on average even though the container utilization may be low.

2.5.5. Replenishments

Replenishments concern filling up warehouses when the safety stock levels are below a set threshold. The replenishment material can be shipped from the GDCs but also rebalanced within the US through sharing stock among Local Warehouses. All replenishments are shipped with the service level category S1 and S2 which are cheaper due to longer lead time promises by the third-party logistics providers. According to CSCM, the stocking strategy will not be greatly impacted when changing the Supply Chain Network within the given boundaries as will be discussed in the third chapter. With the lack of information on inventory levels, the replenishment flow will also not be included in the research.

However, international shipments cost almost the same price regardless of the destination warehouse in the US. In combination with the indication that the inventory levels will not be greatly affected, this implies that the replenishment shipment costs will not differ significantly when changing the customer and material allocation.

2.6. Performance indicators

As described in the first chapter, ASML uses two categories of performance indicators: Internal and customer commitments. The customer commitments vary per BL and customer, while the internal performance indicator is the Delivery Response Time (DRT). The customer commitment is mainly measured in DWM or DTWP, which indicate the percentage of time a machine is not running while waiting for material or parts. The range of current DWM for EUV is between X and X%, while the range of DTWP for DUV is between X and X%. Assuming that a machine is supposed to run the entire year, the target uptime would be X hours. This implies that the strictest agreement of X% DTWP only allows for a total annual waiting time of X hours. The least strict agreement of X% DWM allows for a total waiting time of X hours per year. The reason for less strict DWM agreements being applied for the new EUV machines is that the total part movement is significantly higher than for any other BL. Therefore, longer total waiting times are inevitable and represented in the commitment. The total part movement for DUV machines is lower, resulting in stricter DTWP commitments with the customers. Nevertheless, both total waiting times are low. Even the seemingly long X hours would only allow for X orderlines when assuming a lead time of X hours. Therefore, these commitments dictate short lead times and warehouse locations close to the customers.

The internal DRT commitments respect the material buckets introduced in the first chapter. The DRT performance represents a combination of material availability and freight capability. Generally, the DRT performance indicates the percentage of shipments that are delivered on time. Any shipment is considered on time if it is delivered within the desired DRT of its Bucket. Since no material can be delivered within X hours if it is not available at the local warehouse, the shipment will automatically be late. Therefore, even if the freight performance is optimal, but the material is not available, the DRT performance decreases. Thus, the DRT performance depends on material availability and freight performance.

An interesting dynamic we see in practice is the combination of different agreements. While the DRT performance would allow simply keeping all material that is assigned to a bucket in the warehouses that are designed to hold material in that bucket, the strict uptime commitments do not allow for that. The uptime commitments push towards a larger percentage of material being available within X hours, which results in a discrepancy between bucket distribution in theory versus reality, as Figure 10 shows.

Figure 10: Material per Bucket

2.7. Performance

The supply chain network performance can be separated into two main categories, cost performance and service level performance. The cost performance covers all costs related to the supply chain network setup, while the service level performance includes all internal and customer commitments.

2.7.1. Cost performance

Cost performance for the service supply chain in the US is not an existing KPI within ASML. Therefore, precise data is hardly accessible, and the cost performance can only be estimated using a common understanding of cost factors impacting the supply chain infrastructure. Hence, it is not accurate to evaluate the absolute cost performance of the current supply chain network. Nevertheless, to analyze the cost performance when evaluating whether a different network setup can improve the current structure, the relative performance will be accurately compared. The costs, covering transportation

SERV OPEX, will be estimated by simulating the network setup. The cost performance results may not accurately represent the real costs, however, the simulation will always estimate cost performance the same way for any simulated network structure. Thus, the cost performance according to the simulation of alternative supply chain network designs can be accurately compared later on.

2.7.2. Service level performance

The service level performance is measured in three main indicators, the DRT, DWM, and DTWP, as previously introduced. The DRT can be calculated individually for every bucket and, thus, varies per customer, system, and bucket. The DWM and DTWP do not take buckets into account and are, therefore, subject only to customer and system. Since the DWM and DTWP represent the downtime of a machine, ASML refers to these measurements as uptime commitments.

DRT performance

The DRT performance is measured as a total per customer location and business line which represents all Buckets of all materials for each customer. The DRT performance can be investigated further using the on-time delivery information on a shipment level. For Bucket 1, the shipments are not logged in the internal Transportation Management System (TMS), and thus, the DRT performance for Bucket 1 cannot be tracked. Nevertheless, according to CSCM US FO, a X% DRT can be assumed for bucket 1. For Bucket 2, all domestic shipments need to be considered, and for Bucket 3, all international shipments. The bucket 2 DRT performance in 2021 is X%, with an average lead time of X hours. This performance can further be split up per shipping agent and flavor whereas flavor stands for the type of shipment depending on the weight class. As Figure 11 shows, F1 has a significantly worse performance than F2, and ASML can only achieve its X% DRT performance for Bucket 2 by shipping most orders with F2. This goes against the objective of minimizing cost as F2 charges higher rates than F1, which is the preferred shipping agent. To summarize, the Bucket 2 DRT performance is X% which underperforms the target of X%.

Figure 11: DRT performance per shipping agent bucket 2

The Bucket 3 DRT performance is similar to Bucket 2, as Figure 12 shows. The goal of X% on-time deliveries is not met, with the current performance being only X%. The average lead time of X hours is well within the target of X hours, however, X% of the shipments take longer than X hours. This depicts precisely the problem ASML faces; lead times exceed the targeted duration causing an underperformance of service levels.

Figure 12: DRT performance bucket 3

The DRT performance has not been measured for all customers, but the data from 2022 provides insight into a handful of customer-specific DRT performances. As Figure 13 shows, the DRT performance is lower than the target of X% for three out of four customer locations.

Figure 13: DRT performance

There is a clear difference between the calculated overall DRT performance and the available data for customer-specific DRT performance. There are two reasons to explain that discrepancy. One, the large percentage of material being supported in Bucket 1 can increase the overall performance significantly. Through supporting almost all material at local warehouses and shipping them on time directly to the customer evens out the overall weak performance for bucket 2 and bucket 3 material. Two, the sites for which DRT performance is available are easily accessible sites with large warehouses. Therefore, USX, USX, and USX are expected to have a better performance than most other customer locations in the US.

Uptime performance

Currently, X uptime commitments are in place with ASML's customers in the US. The uptime commitments vary per system and are, in rare cases, mixing business lines. The only reason for mixing uptime agreements among business lines is in case a machine uses additional systems to perform better, called APPS. In this case, even though APPS are generally summarized in the MPS and APPS business line, the delivery performance of APPS system for DUV or EUV systems are included in the DUV or EUV uptime commitment. Overall, ASML aims at achieving all uptime commitments due to penalties when underperforming. As Figure 14 shows, with X out of X commitments, ASML underperforms in almost X% of its uptime commitments. Especially the DWM performance for the EUV system at USX shows a massive underperformance with more than X times as much downtime as targeted. On the other hand, ASML often achieves significantly lower downtime than targeted as for example the EUV USX performance shows. Overall, the uptime performance is often better than desired, however, underperforming almost X% of the promised service levels deviates from ASML's target to meet all commitments.

Figure 14: Customer commitment and performance

2.8. Conclusion

To summarize, ASML sells products from four different Business Lines (BLs) in the US, namely EUV, DUV, MPS and APPS. There are X customer locations spread across the country that need to be served. For each BL, the service materials, which include parts and tools, are categorized into three Buckets, B1, B2, and B3. Each Bucket has a specified Delivery Response Time (DRT) according to their priority. ASML's commitment is to deliver X% of all materials within the specified DRT. This generally pushes to supply B1 material from a local warehouse, B2 material from a domestic warehouse, and B3 material from a Global Distribution Center (GDC). Additionally to the DRT, the service performance is measured in Downtime Waiting For Material (DWM). The DWM commitments range between X% and X% depending on the customer and BL. Due to the tight DWM commitments, ASML is forced to keep achieving short lead times. Especially the EUV machines have a high demand, and thus, need material faster to achieve the DWM commitments which pushes ASML to store a significant number of B2 material at the local warehouses. The MPS and APPS demand is the lowest which is why both B1 and B2 material can be served from one central hub in the US to still achieve the service level agreements. For EUV and DUV, ASML uses 12 warehouses which each supply material to one customer. Currently, ASML cannot achieve at least one of their DWM commitments for X customer locations in the US which is why ASML seeks to improve the network design especially regarding the EUV and DUV service level performance.

3. Literature review

This section aims at answering the subquestion SQ2: *What are alternative Supply Chain Network Designs that ASML should consider implementing in the US?*

To answer this question, literature shall be reviewed to gain an understanding of required structural decisions for supply chain network designs and deep-diving into existing supply chain network structures. Through integration of the theory, a few relevant supply chain network designs for ASML's prerequisites should be found.

3.1. Decisions for SC networks

Farahani et al. (2014) explain design choices for supply chain networks on different organizational levels. Among others, decisions have to be made on a strategic and tactical level. Strategic decisions consist of structural choices that build up the infrastructure of a network, while tactical decisions are focused on the methodology when building up the network structure in practice. The introduced strategic decisions cover mainly facilities and third-party collaboration. Therefore, the main strategic decisions are the number, location, and capacity of facilities and the number and capacity of providers a company is working with. To use a supply chain network, given the strategic choices, tactical choices need to be made. The tactical choices mainly include transportation and inventory. Therefore, decisions on transportation flows and modes, as well as inventory volume or management, fall under tactical choices.

Altekin et al. (2017) discuss similar choices but explains tactical choices in further detail. They also cover the number and location of facilities but introduce two core types of facilities: Distribution Centers and Warehouses. They also go further than introducing transportation flow on a high level and discuss precise aspects connected to said choice. Transportation flow focuses on assigning suppliers and vendors to specific facilities. They recognize that such lower-level decisions may increase the complexity of theoretical network structures, especially when modeling them. Therefore, they advise simplifying flows for modeling network structures. Different parts or SKUs with identical flows through the supply chain shall be modeled as one flow. This, however, is only possible when the different parts do not have specific requirements or boundaries that jeopardize the holistic supply chain model. The integration of theory section will evaluate the dynamic of this aspect for ASML's position.

Saxena and Yadav (2019) go one level lower on the location decision for facilities and discuss how the optimal warehouse location should be determined. It is crucial to start with customer locations and demand as they drive the boundaries for warehouse locations. Different warehouse locations can be modeled using the customer locations and demand to then apply a cost-based optimization that yields the optimal decision. For said optimization model, however, some prerequisites such as capacity and operating cost need to be known or collected.

Kerbache (2019) lays down relevant cost factors for the optimization of supply chain networks. These cost factors cover both fixed and flexible costs. The fixed facility costs, for example, represent any investments into new locations when necessary but also the cost of closing existing facilities such as distribution centers and warehouses. Running costs such as production, inventory, and transportation are crucial to consider when optimizing a network since any design choice impacts these variables. The production costs depend on the tactical decision of where to produce which material. The inventory costs are impacted by the decision on the number and location of warehouses. The transportation costs correlate with the tactical decision on the transportation mode and flows.

Kerbache (2019) also discusses the relation between performance requirements and network design choices, specifically in the United States. She states that the decision on the number of distribution centers depends on the required or desired end-to-end lead time. In the United States, a lead time target of one day requires roughly 13 distribution centers. A lead time of 5 days requires 2 DCs, and a lead time of 1 week only 1 DC. This is also important to keep in mind as the number of facilities impacts the cost, and using these two aspects, the performance will be in a tradeoff with costs.

Arivalagan (2019) describes the main drivers for choosing a good warehouse location. While some variables, such as the distance to customers and transportation availability, are straightforward and overlap with the previously introduced literature, two novel variables stand out. They mention the availability of labor and the quality of available transportation as crucial factors for determining the optimal warehouse location. Now, the availability of labor is especially important when opening a new greenfield location but may be less important when transferring an existing location. Therefore, these aspects also highly depend on a company's starting position. The quality of transportation is an interesting factor. Especially for companies that require special transport, e.g., transporting dangerous goods, this is a highly important decision variable. Opposite to other factors that are tradeoffs, this can actually be an exclusion criterion since no company with special transportation requirements should choose a location where transporting their goods cannot be supported.

3.2. Resulting network designs

Arivalagan (2019) presents two core designs for distribution networks, Centralized and non-centralized setups. A centralized setup consists of one location that holds most competencies and inventory, which can be supplied to customers directly. A non-centralized setup includes multiple, most likely smaller, locations that all hold inventory and competencies. Customers can then be supplied from and serviced by locations close by.

Schönleben et al. (2015) further split these two types of networks by the methodology for transporting material. They argue that in any service network, a key decision is whether customers shall drop off and pick up material to service at the location or if the servicing company should provide pick up and drop off. Using this differentiation, they present four core combinations for service and distribution networks:

- Centralized with transportation by company,
- Centralized with transportation by customer,
- Non-centralized with transportation by company,
- Non-centralized with transportation by customer.

Kerbache (2019) goes one level lower and presents five network designs including tactical decisions for material flows. The manufacturer storage with direct shipping network does not use any warehouses or distribution centers for material flow but ships all material directly from the plant to customers. The in-transit merge network ships the material from the plant to a storage facility and uses carriers to deliver to the customers. The distributor storage with carrier delivery is similar to the in-transit merge network but in-houses the distribution center. Therefore, the company owns and manages the distribution centers from which the material is delivered to the customers instead of shifting ownership to a third party. The distributor storage with last-mile delivery uses the same network structure but delivers material for multiple customers in one go instead of shipping material for each customer individually from the distribution center. The manufacturer or distributor storage with customer pick-up requires the customer to pick up their order from the storage facility instead of delivering the material. The storage facility may be outsourced to a third party or managed by the manufacturer.

Altekin et al. (2017) also investigated different network designs on the same level as Kerbache (2019), resulting in three specific network designs for service supply chains. One, the supplier ships material to a distribution center from which the material is shipped to warehouses. The material is then delivered to customers from the warehouse location using trucking. Two, the supplier ships to the distribution center from which the material is directly delivered to the customer through trucking. Three, instead of trucking the material from distribution center to customer, other means of transportation such as air transport or parcel shipping can be utilized.

3.3. Integration of theory for specific ASML case

A unique prerequisite of ASML's service supply chain are the different performance requirements regarding the lead times between X hours and X hours for the three buckets. Using Kerbache's indication for the number of DCs in the US, material that needs to be delivered within one day require 13 DCs, while other material that may take up to 3 days will need significantly less. The insight of Kerbache shows that the existing local warehouses are essential to achieving the desired performance level and centralizing bucket 1 material is not feasible. However, for bucket 2 and bucket 3 material, centralizing the network structure can be investigated.

The high complexity of shipping large and heavy goods excludes any network designs that require customers to pick up material at ASML facilities. Since ASML does not want to insource the transportation capability, the only viable decision is to continue the partnership with 3PLs. Therefore, a network setup is necessary that allows for collaboration with a 3PL.

Based on these requirements, only few introduced network setups are viable as an alternative to the current structure:

- Fully decentralized network
  Storing the material of all buckets directly at the customer locations to achieve minimal lead times, and replenishing material directly from global distribution centers
- Partially centralized (Bucket 2 material at one warehouse)
  Storing the material of bucket 1 directly at the customer locations, storing bucket 2 in a US warehouse, and supplying bucket 3 from global distribution centers
- Partially centralized (Bucket 2 and Bucket 3 material at one warehouse)
  Storing the material of bucket 1 directly at the customer locations, storing bucket 2 and bucket 3 in a US warehouse that supplies all customer locations

To determine the optimal network setup, the tradeoff between cost and lead time performance needs to be evaluated, as the literature discussed. For partially centralized network designs, the central US warehouse needs less material to achieve the desired safety stock and, thus, improve inventory costs. It needs to be evaluated whether the saving in inventory costs outweigh the investment costs in a new location and the loss in performance. Furthermore, the location of said central warehouse needs to be identified using various variables into account. One main decision will be if investing in a new location will pay off or if expanding an existing local warehouse to become the central warehouse is better. As mentioned in multiple publications, the capacity, fixed and running costs, and performance of possible locations need to be considered to make this decision.

After making the strategic decisions on the network infrastructure, the tactical choices need to be set to compare the current network setup with alternative designs. The tactical choices are limited for ASML, especially regarding the mode of transportation. LSO indicated that they do not want to inhouse the transportation capability but continue their collaboration with the 3PL. Therefore, the mode of transportation is out of scope. However, the material flow for transportation can be adjusted and needs to be set when defining alternative network setups.

The design choices for the network setup can subsequently be split into three levels being the warehouse infrastructure, the forward flow routes, and the return flow routes. For the warehouse infrastructure, three types of warehouses can be considered: Customer-specific warehouses, Country warehouses serving multiple customers within a country, and Global Distribution Centers (GDCs) to serve customers in multiple countries. This yields the following possible warehouse infrastructures:

- Only customer-specific warehouses
- Customer-specific warehouses, and a GDC
- Customer-specific warehouses, a country warehouse, and a GDC
- Customer-specific warehouses of which one also serves as the country warehouse, and a GDC
- A country warehouse, and a GDC
- Only a country warehouse
- Only a GDC

Since ASML's performance requirement is to deliver some materials (X% of Bucket 1 material) to all customers within X hours, the warehouse infrastructure requires one customer-specific local warehouse (LWH) for each of the X customers. Furthermore, due to high investment costs and long-term contracts with logistics providers, an additional greenfield country warehouse is deemed as not feasible by the CSCM department. Lastly, due to the low availability of some material, a part of the demand (all Bucket 3 material) always needs to be stored in the GDCs to be available to all global customers. The location of the X LWHs and the GDCs are set by the pre-existing infrastructure as explained in the first section. However, X LWHs are large enough and have suitable transportation connections to serve as the CWH. Therefore, the feasible infrastructure with X LWHs of which one serves as a CWH, can be split up into two different options with either USX or USX as the CWH. Hence, the following three warehouse infrastructures are possible:

I) X LWHs, and GDCs in X
II) X LWHs of which USX serves as the CWH, and GDCs in X
III) X LWHs of which USX serves as the CWH, and GDCs in X

Based on this selection of possible warehouse infrastructures, the number of strategic forward flow choices is limited. The strategic forward flow choices are concerning customer and material allocation, and thus, describe which type of warehouse holds which material bucket for which customer. Using the same prerequisite as before, that some material (bucket 1 material) needs to be supplied to each customer within X hours, each local warehouse will have one customer assigned for which it holds all available Bucket 1 material. However, the strategic forward flow choices should also describe which warehouse shall supply Bucket 1 material in case it is not available at the local warehouse due to material shortage or too little safety stock. Furthermore, Bucket 3 material needs to be available to all global customers and therefore needs to be stored in the GDCs in X. Lastly, X large local warehouses can store more material and could therefore qualify to support other local warehouse in case of material shortages. These X LWHs are namely USX, USX, …. This allows for the following material allocation possibilities:

1) B2 is stored at the LWHs
2) B2 is stored at the CWH
3) B2 is stored at the GDCs

Additionally, a supplying priority should be set that determines which warehouse should supply material that is not available at the Local warehouse. Even though it would be possible that the GDCs supply material that is not available, this option can be ruled out. The GDCs will always supply material that is not available elsewhere and therefore serves as the last resort in all design choices. Therefore, prioritizing the GDC over other warehouses to supply material will only result in worse performance and higher costs since the GDCs require international shipping. This allows for the following network choices regarding supplying priority:

A) Any other LWH in the country (at random)
B) The LWH with the shortest expected lead time
C) The closest large warehouse according to Figure 15
D) The CWH

Figure 15: Warehouse clusters

Lastly, the return flow can be handled in different ways which in turn forms the last dimension of possible supply chain network designs for ASML. The return flow can be consolidated in different locations before ultimately arriving at the GDC. For this assignment, it can be assumed that the return flows end at the GDC even though in reality some returns may be sent from the GDC to a factory. However, due to the high complexity and limited time, this flow is not in scope and the assumption holds that all return material will be sent to the GDC. This yields the following possibilities for return flow handling:

a) Returns are sent from LWH directly to the GDCs
b) Returns are consolidated at the large warehouses, see Figure 15, and then sent to the GDCs
c) Returns are consolidated at the CWH and then sent to the GDCs

Since the return flows are disconnected from the forward flow, the return flow scenarios can be investigated individually. Even though their feasibility depends on the warehouse infrastructure, they are not included in the scenario overview as they have no impact on customer contract performance but only on the cost performance. An optimal solution for the return flow in combination with an optimal solution for the forward flow will yield the holistic optimal network design. It is therefore important to note that it is indeed possible to use a central warehouse either for only return flow, only forward flow, or both.

For the forward flow, the total number of different design choices are defined by the depth of each dimension. The total number of scenarios is therefore three by three by five which is 45. While for the return flow only three design choices are possible. However, not all designs are possible since the dimension build up on the previous dimensions so that e.g. Bucket 2 material can only be stored at the Central warehouse if the warehouse infrastructure includes a central warehouse. Furthermore, the combination of having a central location that does not stock additional material is out of the question for the company. Subsequently, a scenario where a central location supplies material that is not available locally but does not stock additional material will not be included in the investigation. Consequently, the total number of network designs that ASML should consider implementing is 14 which can be seen in Table 6. The total number of possible design choices for the return flows is 3 as mentioned above.

Name / Description	Warehouse infrastructure	Material allocation	Supplying priority
(1A) No CWH	I	1	A
(1B)	I	1	B
(1C)	I	1	C
(1D)	I	3	A
(1E)	I	3	B
(1F)	I	3	C
(2A) CWH US04	II	2	A
(2B)	II	2	B
(2C)	II	2	C
(2D)	II	2	D
(3A) CWH US80	III	2	A
(3B)	III	2	B
(3C)	III	2	C
(3D)	III	2	D

Table 6: Relevant Supply Chain Network Design for Forward Flow

ASML's requirements regarding the mode of transportation restrict the freedom for possible supply chain networks. The forward flow should be supplied as fast as possible for which only air transportation and trucking are used. Trucking is only used when air transportation is not available. The decision between trucking and air transportation is made by the used third-party logistics provider (3PL) which are F1 and F2 for domestic shipments and F1 and F3 for international shipments. The decision variables regarding F1 or F2 for domestic shipments will be investigated later on. However, it should be noted that the international shipments will not be part of this investigation as the focus in on the US network itself. The return flows have no time pressure and should be as cheap as possible. Therefore, trucking is used to transport materials to the closest ports in the US from which onwards maritime transportation is used to transport the returns to the GDCs. To determine which 3PL should be used for the forward flow, a sensitivity analysis will be conducted. Therewith, the tradeoff between faster expected lead times with F2 but lower expected costs with F1 will be investigated after conducting the analysis on the best strategic network design choices. This helps to limit the number of scenarios to simulate to the aforementioned 14 scenarios and yet allows ASML to understand the implications on performance of working with specific 3PL.

3.4. Conclusion

To summarize, Supply Chain Networks (SCNs) depend on the desired service levels and possible infrastructure within a country. To deliver materials to customers all over the US within a day, X distribution centers are required according to the analyzed literature. For ASML, the core strategic decision is whether to centralize parts of the supply or to decentralize them. The supply of Bucket 1 material needs to stay in the Local Warehouses as the required DRT is within X hours while Bucket 3 needs to stay in the Global Distribution Center to be available to all global customers. Only Bucket 2 may be supplied from a centralized location or even the GDC which allows for various SCNs. The only feasible centralized locations are USX and USX due to their capability of storing a large number of stock and having fast lead times to all warehouses. Furthermore, materials that are not available locally, e.g., due to low safety stock or material shortage, need to be supplied from a different location according to a set preference. This allows for three additional SCN design choices, namely supplying them from the centralized warehouse, the local warehouse with the fastest expected lead time, or one of the four largest US warehouses. Additionally, consolidating return flows can yield operational benefits such as cost savings which is adding three further possibilities to the SCN. ASML can choose not to consolidate returns, consolidate them at the central warehouse, or consolidate them at the four largest US warehouses. This results in 14 possible SCNs that shall be analyzed next to a sensitivity analysis regarding the optimal solution for return consolidation.

4. Research question 3 | Model

In this section, the impact of alternative Supply Chain Network Designs on the service level and Cost performance will be modeled. Therefore, the impact of the two main variables, the warehouses and transportation, will be analyzed and mathematically depicted.

4.1. Transportation

The transportation aspect covers the lead times and costs that arise when shipping material. These two parameters depend on the used forwarder as they have different lead times and prices, the weight of the shipment as heavier shipments cost more and take longer to be shipped, and the origin and destination of the shipment. These variables are fixed and not subject to change for different scenarios, which makes them input variables as table 7 shows. The decision variable for which a sensitivity analysis will be conducted is the percentage of time a specific forwarder is used. This decision is always made in the warehouse that orders the shipment, the origin. Therefore, the decision variable is a percentage that varies for every origin but does not depend on the destination of a shipment as table 8 shows.

Variable	Definition
FWH	Warehouse from which material is transported
TWH	Warehouse to which material is transported
F	Forwarder = F1, F2, F3
w	Shipment weight in kg
P(w)	Probability that a shipment weighs w kg
Cv(F,w,FWH, TWH)	Variable costs per kg if a shipment weighs w kg and is shipped with forwarder F from warehouse “FWH” to warehouse “TWH”
Cf(F,w, FWH, TWH)	Fixed costs per shipment if a shipment weighs w kg and is shipped with forwarder f from warehouse “FWH” to warehouse “TWH”
LT(F, w, FWH, TWH)	Lead time if shipment that weighs w kg is shipped with forwarder F from warehouse “FWH” to warehouse “TWH”

Table 7: Input variables transportation

Variable	Definition
K(F, FWH)	Percentage of shipments from warehouse FWH that are shipped with forwarder F

Table 8: Decision variables transportation

Variable	Definition
C_r(FWH, TWH)	Expected transportation cost for route from origin FWH to destination TWH
$LT_{expected}$(FWH, TWH)	Expected lead time for route from origin FWH to destination TWH

Table 9: Output variables transportation

Using the input and decision variable for the model, we can calculate the expected lead time for every route. The lead time (LT) from the origin warehouse (FWH) to the destination warehouse (TWH) takes into account the probability that a shipment has a specific weight (P(w)), the probability that this shipment is shipped with a specific forwarder (P(F,FWH)), and the lead time for the specific route when using this forwarder for a shipment of that weight (LT(F,w,FWH,TWH)). Since the formula is using percentages for the weight and used forwarder, the occurring lead times need to be summed up resulting in the calculation of formula 1.

$$LT_{expected}(FWH,TWH) = \sum_F \sum_w K(F,FWH) * P(w) * LT(F,w,FWH,TWH)$$

Formula 1

The expected transportation costs for each route (C_r(FWH, TWH)) use the same probabilities for weight and forwarder as the lead time formula. However, instead of multiplying the probabilities with the expected lead time, they now have to be multiplied with the fixed and variable costs that occur depending on the forwarder and weight. This yields the following formula 2.

$$C_r(FWH, TWH) = \sum_F \sum_w K(F, FWH) * P(w) * \{C_f(F, w, FWH, TWH) + w * C_v(F, w, FWH, TWH\}$$

Formula 2

For the return flow, the formulas need to be adjusted. The return flow lead time does not count towards any performance measurements and can therefore be disregarded. The transportation costs need to be modeled for which new input and decision variables are required, as table 10 and 11 show. Return shipments that are not consolidated are stored in a container at the local warehouse which is then trucked to the nearest port and shipped to the Netherlands using maritime shipments. This requires the costs per container for trucking to the nearest port and the maritime shipment costs for the last step in the journey. In case material will be consolidated, the material is transported to the consolidation warehouse using F1 where the containers will be filled and transported the same way as without consolidation. Therefore, the domestic F1 transportation costs for returns are required as well. The decision variable shall depict which warehouses will consolidate material from which customers as table 11 shows.

Variable	Definition
TP	Nearest port
M(Cus,TP)	Distance in miles from customer Cus to port TP
C_t	Fixed transportation costs per container per mile for domestic trucking
C_h(Cus,TWH)	Transportation costs for return shipments when using F1 from customer Cus to warehouse TWH per shipment
C_o(TP)	Fixed transportation costs per container for overseas shipping from port TP
R(Cus)	Annual number of returns from customer Cus
S(TWH)	Annual number of container shipments from warehouse TWH

Table 10: Input variables for return flow

Variable	Definition
Con(Cus)	Yields the warehouse at which the return material from customer Cus will be consolidated, yields 0 if no return consolidation is chosen for customer Cus

Table 11: Decision variable for return flow

Variable	Definition
C_{return}(Cus)	Total transportation cost per customer site (Cus) of return material

Table 12: Output variables return flow

If no consolidation takes place, then the total transportation costs are calculated per container. The costs consist of the total trucking costs to the nearest port and the subsequent maritime shipment costs. This yields the following formula 3 where the TWH is the local warehouse at the customer site.

$$C_{return}(Cus) = S(TWH) * \{M(TWH, TP) * C_t + C_o(TP)\}$$

Formula 3

If consolidation is used for return flows, the total costs consist of the transportation costs to the consolidating warehouse and the shipping costs from said warehouse. The transportation costs to the warehouse are according to the F1 rates while using the lowest available service level as fast lead times are not important for the return flow. The rates yield a fixed amount for every route which has to be multiplied with the number of materials which yields the following formula 4.

$$C_{return}(Cus) = R(Cus) * C_h(Cus, Con(Cus))$$

Formula 4

The transportation costs from the consolidating warehouse are calculated identically to when no returns are consolidated and are thus per container. This yields the following formula 5.

$$C_{return}(Con(Cus)) = S(Con(Cus)) * \{M(Con(Cus), TP) * C_t + C_o(TP)\}$$

Formula 5

The total number of container shipments depends on the capacity of the warehouses and the capacity of the container since a container shipment needs to be ordered either if the container is full or if the warehouse cannot store additional return material. Therefore, the number of shipments will be discussed in the following warehousing section.

4.2. Warehousing

The warehousing component builds up on the transportation component and provides the remaining inputs to calculate the overall performance of the supply chain network designs which are summarized in table 13. Each warehouse has an availability of material for every Business line and bucket of material which is the main input parameter. It is crucial to understand that even though the availability is an input parameter, this input may change depending on the network design. For example, if the scenario supplies bucket 2 material from a central warehouse, the availability of bucket 2 at the local warehouses decreases while the availability at the central warehouse increases.

Additionally, each customer shows a total annual demand which impacts the total number of required shipments. The demand can also be divided per business line and bucket and forms another input variable. The number of returns that will be in the supply chain network is not fixed but rather a percentage of the demand. Therefore, the return rate is another input variable. The core decision variable determines the allocation of warehouses to customers as table 14 shows. This allocation defines which warehouse will be used to satisfy customer demand, and further, which warehouse will supply material if the prioritized warehouse does not have the material available.

Variable	Definition
Cus	Customer that demands material
B	The bucket of material (1, 2, 3)
BL	The business line of material (EUV, DUV, MPS and APPS)
D(Cus, BL, B)	Total annual demand of customer cus for material in business line BL and bucket B
A(Prio(Cus,p), BL, B)	Expected availability of material for business line BL and bucket B at warehouse FWH according to historical data

Table 13: Input parameters warehousing

Variable	Definition
Prio(Cus, p)	Indicates which warehouse should supply material if the customer "Cus" demands material. P indicates the priority, i.e., p = 1 indicates the prioritized warehouse, p = 2 indicates the secondary warehouse which supplied material if the prioritized warehouse does not have the material available

Table 14: Decision variables warehousing

Variable	Definition
WT(Cus, BL, B)	Total annual waiting time for customer Cus's machines of Business Line BL for material from Bucket B
DWM(Cus, BL)	Total annual Downtime Waiting for Material for customer Cus's machines of the Business Line BL
LS(Cus, BL, B)	Total number of late delivered shipments to Customer Cus for machines of Business Line BL for material in Bucket B
DRT(Cus, BL, B)	Total annual Delivery Response Time performance for Customer Cus's machines of Business Line BL regarding material in Bucket B

Table 15: Output variables warehousing

With the input and decision variables from the warehousing component and the lead times from the transportation component, it is now possible to create a formula to determine the performance in terms of DRT and DWM. For the DWM performance, the total waiting time needs to be calculated and then divided by the total possible runtime. The total possible annual runtime per machine is simply 24h times 365 days of the year, which is 8760h. The total annual waiting time per machine can be calculated using the total demand multiplied with the expected lead time. The expected lead time depends on the supplying warehouse since closer warehouses can deliver material faster resulting in shorter waiting times. Therefore, we simplify the input parameter for the sake of readability and denote the material availability at the prioritized warehouses as the following formulas 6 to 8 show.

$$A1 = A(Prio(Cus,1),BL,B), \qquad A2 = A(Prio(Cus,2),BL,B), \qquad A3 = A(Prio(Cus,3),BL,B)$$

Formula 6, 7, 8

Following the same principle, we denote the expected lead times for the prioritized warehouses as shown in formulas 9 to 11.

$$LT1 = \sum_F \sum_w P\big(F, Prio(Cus,1)\big) * P(w) * LT(F,w,Prio(Cus,1),TWH)$$
$$LT2 = \sum_F \sum_w P\big(F, Prio(Cus,2)\big) * P(w) * LT(F,w,Prio(Cus,2),TWH)$$
$$LT3 = \sum_F \sum_w P\big(F, Prio(Cus,3)\big) * P(w) * LT(F,w,Prio(Cus,3),TWH)$$

Formula 9, 10, 11

As mentioned previously, the third prioritized warehouse will always be the GDC as the last resort with an availability of 100% (A3 = 100%) so that the total waiting time can be calculated by multiplying the demand with the availability to determine the number of materials that will be supplied from each warehouse. The level of granularity is here on a Business Line and Bucket level since EUV machines have significantly more demand than DUV and MPS machines as explained in the first chapter and since the availability of material differs per Bucket. The number of materials supplied from each warehouse will then be multiplied with the expected lead time from said warehouse which yields the following formula 12 for the total waiting time per customer and Business Line (WT(Cus, BL, B)).

$$WT(Cus,BL,B) = D(Cus,BL,B) * (A1 * LT1 + (1 - A1) * A2 * LT2 + (1 - A1) * (1 - A2) * LT3)$$

Formula 12

The total waiting time per Customer and Business Line (WT(Cus,BL)) can be derived by adding the total waiting times of all Buckets and the DWM performance per Customer and Business Line (DWM(Cus,BL)) is the WT(Cus,BL) divided by the total possible runtime. This yields the following formula 13.

$$DWM(Cus,BL) = \sum_B \frac{WT(Cus,BL,B)}{8670h \; * \; (Nr\ of\ machines)}$$

Formula 13

For the DRT performance, the total number of shipments that are late or within the DRT lead time targets is necessary since the DRT performance depicts the number of shipments on time over the total number of shipments. Estimating whether a shipment is expected to be late is more complex because using average expected lead times would not depict reality accurately enough. Hence, the raw lead times for every weight, forwarder, and route (LT(F,w,FWH,TWH)) need to be investigated. If this lead time is longer than the DRT target then we know that the shipment of this specific weight, forwarder, and route will be late. By calculating the probability that a shipment will have exactly these specifications and multiplying with the total demand, we get the total number of shipments that are expected to be late. It is further worth noting that for the DRT performance, material that is not available at the prioritized warehouse counts negatively towards the performance regardless of the achieved lead time. Thus, the total number of late shipments (LS(Cus,BL,B)) also depends on the availability of material since material that is not available automatically counts as late. This part of the late shipments can be calculated as formula 14 indicates.

$$LS(Cus, BL, B) = (1 - A1) * D(Cus, BL, B)$$

Formula 14

For the remaining shipments, we determine whether the lead time for a specific shipment is larger than the DRT target (DRT(Cus,BL,B)). If this is the case, then the number of shipments expected to have these specifications is added to the current total number of late shipments. Since all materials that are not available at the prioritized warehouse are already counted towards the late shipments, this calculation only needs to determine whether the lead time from the prioritized warehouse (Prio(Cus,1)) will be late. This yields formula 15.

$$\text{IF } LT(F, w, Prio(Cus, 1), TWH) > DRT(Cus, BL, B) \text{ THEN}$$
$$LS(Cus, BL, B) += D(Cus, BL, B) * A(Prio(Cus, 1), BL, B) * P\big(F, Prio(Cus, 1)\big) * P(w)$$

Formula 15

The DRT performance per customer and business line can then be derived by adding the late shipments of all buckets and dividing over the sum of all shipments per bucket as formula 16 depicts.

$$DRT(Cus, BL, B) = \sum\nolimits_B \frac{LS(Cus, BL, B)}{D(Cus, BL, B)}$$

Formula 16

For the return flow analysis, additional input parameters are required. The available capacity in the warehouses is estimated using the number of days that returns can be stored before they should be shipped. Furthermore, the capacity of a container in number of parts is required to determine when a container is full and needs to be shipped. These parameters are rough estimations based on historical data since the true values would require an analysis on a deeper level with collaboration of more departments. The estimations and parameters are shown in table 16.

Variable	Definition
LWH	Warehouse
CapD(LWH)	Capacity of the local warehouse in number of days that return flow from the customer can be accumulated before needing to ship
CapContainer	Capacity of a 20ft container in number of parts
r	Return rate in percentage of demand
Rannum(WH)	Total number of return materials at warehouse WH per year
Rsize(BL)	Adjusting factor for the size of material from different business lines

Table 16: Additional input parameter return flow with warehousing

Variable	Definition
R_{daily}(WH)	Expected number of daily return materials coming to warehouse WH
R_{period}(WH)	Expected number of days that a container needs to be shipped from warehouse WH

Table 17: Output variables return flow with warehousing

The capacity of all local warehouses is assumed to be seven days. This means that even if a container is not full after seven days, the returns need to be shipped after seven days because the warehouse does not have more storage space available for return materials. The capacity of a 20ft container is 13.8m^3 which needs to be translated into a number of parts. The average part size is assumed to be X x X x X cm which is X m^3. However, EUV materials are often larger for which a factor (R_{Size}(EUV)) of X is used. Therefore, the capacity of a container is roughly X regular parts for which EUV parts account for X parts. To determine the total number of return containers from every local warehouse, the number of days it takes to fill up one container is required for which we first need the total number of returns per warehouse. The total number of returns per warehouse depends on which customers' returns are consolidated at that warehouse. Therefore, the we use the previous input parameter Con(Cus) which indicates which warehouse consolidates the return of each customer. For each consolidation warehouse, the total returns are calculated using the percentage of return material (r) and multiplying it with the demand of the customer (D(Cus,BL,B)). To adjust for the part size, the demand is also multiplied with the adjusting factor $R_{size}(BL)$. The following formula then yields the total number of return materials for each warehouse $R_{annum}(WH)$ as formula 17 shows.

$$\text{IF } Con(Cus) = WH \text{ THEN } R_{annum}(WH) \mathrel{+}= r * \sum_{BL} \sum_{B} D(Cus, BL, B) * R_{size}(BL)$$

Formula 17

First, we calculate the expected number of return materials per day ($R_{daily}(WH)$) and then divide the capacity of the container by said number. This yields the number days until a container is full for each warehouse ($R_{Days}(WH)$) as formula 18 shows.

$$R_{daily}(WH) = \frac{R_{annum}(WH)}{365days}, \quad R_{Days}(WH) = \frac{CapContainer}{R_{daily}(WH)}$$

Formula 18

If the warehouse can store return materials for less days than it takes until a container is full, the container needs to be shipped more frequently with a lower utilization rate. Therefore, the period after which a container is shipped ($R_{period}(WH)$) is determined using the following formula 19.

$$R_{period}(WH) = Min\{CapD(LWH);\ R_{Days}(WH)\}$$

Formula 19

The total number of annual shipments per customer site (S(WH)) can then be derived using formula 20.

$$S(WH) = \frac{365days}{R_{period}(WH)}$$

Formula 20

This number of container shipments can be used in the previously introduced formula to calculate the return flow transportation costs.

4.3. Validation

The Supply Chain Network model can be validated by using the current setup for all input parameters and compare the model's performance with the performance in reality. The performance is twofold, covering cost performance and customer contract performance. The model needs to match both aspects to be validated. It is important to note that within the given timeframe of this assignment, only information on the forward flow was available but not on the return flow. Therefore, the model can only be validated adequately for the forward flow. However, the warehousing team provided the costs per shipment and validated that the formulas used will provide accurate insights.

4.3.1. Costs

The cost control report for 2021 has data available for transportation costs of roughly X shipments. Since the transportation report shows that over X shipments occurred in 2021, the input for the model was manually adjusted to match the X shipments so that the costs are comparable. The annual forward flow transportation costs in reality are X million Euros while the model predicts annual transportation costs of X million Euros. This represents a deviation of X% which is acceptable and depicts reality accurately. The most plausible explanation for deviating costs is the used weight per shipment. The model uses a probability that a specific weight occurs to calculate the costs per shipment. Since it would be a highly extensive computation to define a probability for every possible weight, e.g. 0.1kg, 0.2kg, etc., the model uses bins of roughly X kg. This results in a slight deviation of the total shipped weight per year ultimately causing the difference in cost between reality and the model.

4.3.2. Performance

The customer contract performance in reality is X on average while the model depicts and average of X. The highest deviation is for the customer site USX, where the model expects outperforming reality of almost X%. However, according to CSCM US FO the bad performance of USX was caused by anomalies due to environmental factors. These anomalies may be fluctuating lead times or material shortage, which cause the performance to fluctuate as well. Overall, the model's performance does not deviate structurally from the performance in reality as the error scores in table 18 show. The mean absolute error, and mean squared error are both within X percentage points while the mean absolute percentage error is X. These are acceptable deviations according to the project owners as the model does not predict anomalies at the moment and the slight deviations will not cause the conclusions of this research to differ significantly.

Error	Calculation	Score
MAE - Mean Absolute Error	$\frac{1}{n}\sum_{i=1}^{n}\lvert x_i - \hat{x}_i\rvert$	X
MSE - Mean Squared Error	$\frac{1}{n}\sum_{i=1}^{n}(\lvert x_i - \hat{x}_i\rvert)^2$	X
MAPE – Mean Absolute Percentage Error	$\frac{1}{n}\sum_{i=1}^{n}\frac{\lvert x_i - \hat{x}_i\rvert}{\hat{x}_i}$	X

Table 18: Error calculation and scores

The model currently does not represent inventory management which also implies that the warehouse sizes and costs are mostly disregarded. This results that in reality the warehouse costs can still influence the optimal decision since the model only allows to draw conclusions from a transportation and service level performance perspective. However, the availability of material at all warehouses is represented by using the average fill rates. Therewith, the impact of non-available material is represented, and thus, the performance scores are matching reality. Additionally, according to CSCM the inventory costs would not change significantly with the current scenarios, but the stock would simply be relocated. A Central Warehouse may reduce the safety stock but due to the high demand, this would not be a significant impact according to CSCM.

4.4. Conclusion

The mathematical model programmed in Excel and VBA uses fixed input parameters and decision variables to calculate the achieved service level and cost performance for different Supply Chain Network Designs. For example, by changing the decision variable regarding the customer and material allocation, the model will predict the performance and cost for this specific Supply Chain Network Design. The performance refers to Delivery Response Time (DRT) and Downtime Waiting for Material (DWM) to understand the impact of different SCNs on the customer service level as introduced in the first chapter. To understand the operational impact the SERV OPEX for transportation costs regarding the forward flow and return flow are also depicted. Even though the inventory management is not represented in the model, ASML does not expect the material allocation to impact the overall warehousing costs and capital to change greatly, and thus, the accuracy of the model was validated by all stakeholders. The motivation behind validating the model without inventory management is that according to CSCM, changing the material allocation to, e.g., a central location does not decrease the necessary stock levels significantly but simply shifts the required space from a local warehouse to the central warehouse.

5. Research question 4 | Analysis of alternative designs

What Supply Chain Network Design can achieve the desired service level in terms of DRT at optimal cost in terms of SERV OPEX?

In this section, the various alternative Supply Chain Network designs will be analyzed and compared according to their service level and cost performance. Furthermore, an analysis will be conducted on the two US 3PL on which one the optimal choices for which routes and shipments.

The 14 designs investigated yield greatly different results regarding service level and cost performance. Comparing all at the same time does not provide an easily understandable overview which is why the scenarios will be split up. Separating the scenarios based on the warehouse infrastructure allows for a comparison of all scenarios that either use no Central Warehouse or USX as the Central Warehouse or USX as the Central Warehouse. With this separation, at most six scenarios need to be compared at the same time. All scenarios will be analyzed based on the average weighted DRT and DWM score as well as the total transportation cost excluding the returns. The return scenarios will be evaluated individually through a sensitivity analysis in the last subsection. For the average weighted scores, the volumes of each customer are considered so that the performance for customers with more machines counts heavier towards the average score than customers with fewer machines. Since the performance of the MPS and APPS business line is not a crucial factor for the decision makers within CSCM US FO, the focus will be on the performance for EUV and DUV. However, the total transportation costs also cover the shipping costs for MPS and APPS materials.

5.1. Scenarios without CWH

The six scenarios without a CWH in the US, 1A through 1F, show a structural difference when changing the supply of Bucket 2 materials. The three scenarios 1A through 1C supply Bucket 2 material from the Local Warehouses and if it is not available from other warehouses within the US. These scenarios achieve an average DRT performance of X% with no fluctuation for EUV and X% with a fluctuation of X percentage points for DUV. Therefore, changing the prioritized warehouse for Bucket 2 material that is not available locally does not impact the DRT performance significantly. However, when shifting the Bucket 2 material from the US and supplying it from the Global Distribution Centers, as scenarios 1D through 1F do, worsens the DRT performance by around 18% for both EUV and DUV. This drastic reduction is quite logical as the Bucket 2 DRT targets of X hours for EUV and X hours for DUV can never be achieved from the GDCs. Similar to the first three scenarios, there is no structural difference when changing the prioritized warehouses that should supply material if it is not available locally.

The Downtime waiting for material (DWM) performance follows the trends of the DRT performance. All scenarios that supply Bucket 2 from the local warehouse show average DWM performances of X% and X% for EUV and DUV, respectively. The reason for the similar performance is the high availability for Bucket 1 and Bucket 2 material at the local warehouses. Over X% of all Bucket 1 material is available at the local warehouses and between X to X% of all Bucket 2 material is also planned to be available locally. This means that for only X to X% of all demand the lead time varies for the different scenarios. Additionally, the scenarios' lead time differences are not large enough to show a significant impact because all scenarios use US warehouses to supply material if it is not available locally. The scenarios 1E through 1F use the GDCs to supply Bucket 2 material which consequently shows a much larger impact. When shifting all Bucket 2 to the GDCs, the lead times increase by over a factor of two resulting in average DWM performance of X% and X% for EUV and DUV.

The transportation costs follow the same pattern as the DWM and DRT performances. Changing the prioritized warehouse for supplying material that is not available locally impacts the cost by less than 1.0%. The total annual transportation costs for the forward flow are X million US Dollars (USD) when Bucket 2 material is supplied from the local warehouses. Shifting Bucket 2 material to the GDCs more than triples the total costs with an annual average of X million USD.

Figure 16: Performance comparison without CWH

Storing Bucket 2 material in the GDC is significantly worse than storing Bucket 2 at the local warehouses regarding both cost and customer contract performance. The best performance can be achieved by supplying Bucket 2 from the local warehouses and supplying material that is not available locally from the closest large warehouse. This scenario will be compared to the best scenarios with other warehouse infrastructures in subsection 5.4.

5.2. Scenarios with CWH USX

The four scenarios supplying all Bucket 2 material from USX as the Central Warehouse, scenarios 2A through 2D, do not show structural differences in the DRT performance when changing the prioritized warehouse for supplying material that is not available at the primary warehouse. The average DRT performance is X% for EUV and X% for DUV with no significant fluctuation. Since the DRT target for Bucket 2 DUV material is X hours and USX can reach almost all sites within X hours it is not surprising that no structural difference is visible. Furthermore, changing the supplying site when material is not available has little impact as explained in the subsection 5.1 due to relatively small deviations in the lead time and small percentage of material that is not available locally.

The performance difference is clearly visible in the DWM scores. The two scenarios 2B and 2C supply material that is not available locally from US warehouses that are close to the customer. This results in an average DWM performance of X% for EUV and X% for DUV. When supplying non-available material from a random US warehouse or the Central Warehouse USX, the DWM performance worsens by over 1.5 percentage points for EUV and 0.5 percentage points for DUV.

The total annual transportation cost of the four scenarios 2A to 2D only differ by 2.0% ranging from X to X million USD. Supplying material from the closest large warehouse if it is not available locally achieves the lowest transportation cost with X million USD, followed by supplying from the Local Warehouse with the shortest lead time (X million USD) and supplying from the Central Warehouse USX (X million USD). Supplying from a random local warehouse within the US yields similar costs to when supplying from USX with also X million USD.

Figure 17: Performance comparison CWH US04

When using USX as the CWH to supply Bucket 2 material, the optimal performance can be achieved by supplying material that is not available locally from the closest large warehouse. This is identical to the optimal scenario without a central warehouse as the previous subsection indicated. Both scenarios will be compared in subsection 5.4.

5.3. Scenarios with CWH US80

Identically to the scenarios with USX as the CWH, no fluctuation in DRT performance within scenarios 3A through 3D are visible. The average DRT performance with USX as the Central Warehouse supplying all Bucket 2 material is X% for EUV and X% for DUV. This already shows a small difference to the performance of USX which will be analyzed in further detail in the next subsection.

The DWM performance fluctuates by a maximum of 0.8 percentage points for EUV. Supplying non available material from the closest large warehouse or the warehouse with the shortest lead time both score best with X% while the other two scenarios 3A and 3D result in X% DWM for EUV. For DUV, supplying non available material from the CWH scores significantly worse with X% compared to the other three scenarios resulting in X% DWM using scenarios 3B or 3C and X% for scenario 3A.

The annual transportation costs of all four scenarios are highly comparable with an almost neglectable difference of at most 1.0%. Supplying material from the closest large warehouse yields the best cost performance with a total annual cost of X million USD while supplying all material from the CWH USX scores worst with X million USD.

Figure 18: Performance comparison CWH US80

With the third warehouse infrastructure that uses USX as the CWH, supplying all material that is not available locally from the closest large warehouse shows the best performance for DRT, DWM, and costs.

5.4. Comparison of warehouse infrastructures

Determining the optimal scenario requires comparing the best scenarios of each warehouse infrastructure. The three scenarios showing the best performance within their warehouse infrastructure are namely:

1) (1C) Supplying Bucket 1 and Bucket 2 material from Local Warehouse
   If material is not available, then supplied from closest large warehouse
2) (2C) Supplying Bucket 1 from Local Warehouse, and Bucket 2 from Central Warehouse USX
   If material is not available, then supplied from closest large warehouse
3) (3C) Supplying Bucket 1 from Local Warehouse, and Bucket 2 from Central Warehouse USX
   If material is not available, then supplied from closest large warehouse

Scenario 1C scores the highest DRT performance for EUV and DUV with X and X%. Nevertheless, Scenario 2C and 3C are only 0.6 (X%) and 0.2 (X%) percentage points off the EUV performance and 0.2 (X%) and 0.3 (X%) off the DUV DRT performance. Therefore, no structural difference is visible within the DRT performance across all three scenarios. This implies that only the DWM performance may become the main driver for the optimal scenario as the DRT performance does not allow for significant conclusions.

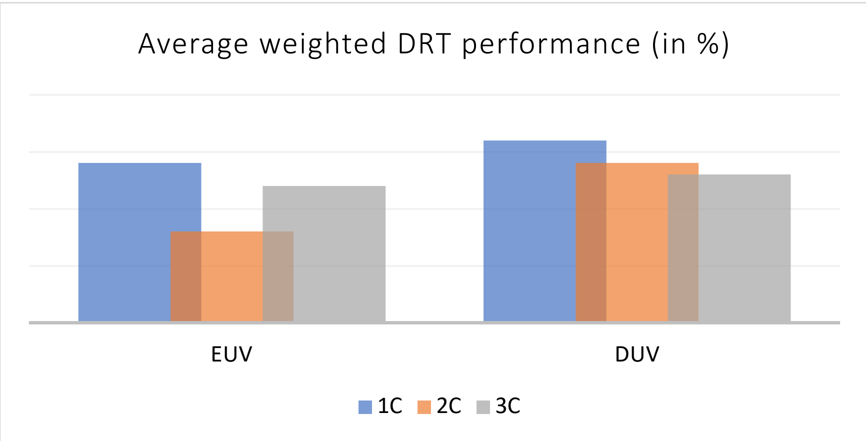

Figure 19: DRT performance comparison

The DWM performance shows clearly that supplying material from the Local Warehouses is necessary to achieve the desired performance. Scenario 1C, that supplies all material from the Local Warehouses, achieves a X% DWM for EUV outperforming Scenario 2C with USX as the Central Warehouse (X%) by 7 percentage points and Scenario 3C (X%) by 9 percentage points. The DUV DWM performance shows a similar trend with less drastic differences. Scenario 2C (X%) and 3C (X%) lack 0.4 and 0.5 percentage points of scenario 1C's X% average weighted DWM performance. The reason for the drastically better lead times when supplying more material from the local warehouses is the extremely short lead time. Even though the DRT targets are achieved when supplying Bucket 2 from the Central warehouse – resulting in similar DRT performances – the lead time and waiting time increase, resulting in a large drop in DWM performance for both business lines. Due to the USX warehouse being close to some of the largest customers in Texas, the average weighted DWM performance is 13% better than the USX performance. This difference is also catalyzed by the fact that USX does not have any customers in close proximity to the warehouse. Therefore, no customer benefits massively from USX supplying material. However, USX does have a good performance to all sites for which it was initially chosen as the prime Central Warehouse location.

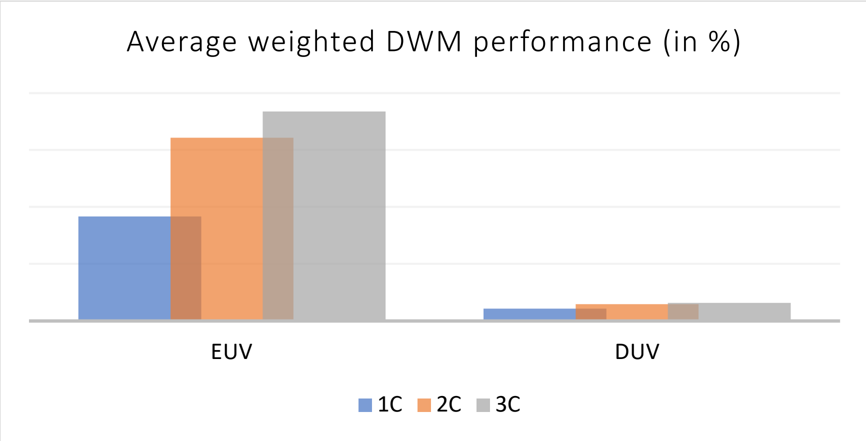

Figure 20: DWM performance comparison

The cost performance of the Central Warehouse scenarios 2C and 3C are similar with a total annual cost of X million USD. Due to the longer distances that shipments need to take and the larger number of domestic shipments when supplying material not from the local warehouse, the total costs are higher than scenario 1C. Supplying all available material from the Local Warehouses, so scenario 1C, results in total annual transportation costs of X million USD. Even though the saving of over X million USD does not include potentially higher replenishment costs, scenario 1C will always be cheaper due to replenishment shipments requiring less service level performance, and thus, being approximately three times cheaper than regular shipments.

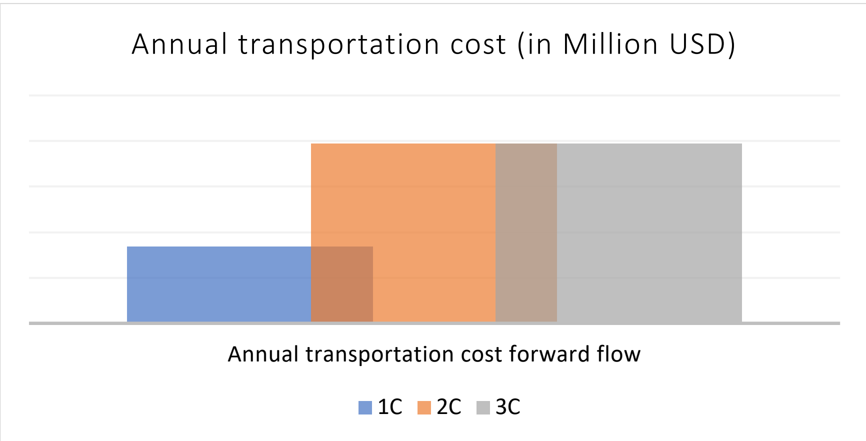

Figure 21: Cost performance comparison

Shifting the supply of Bucket 2 from the local warehouses to a Central Warehouse to achieve higher material availability does not improve the DRT performance. Additionally, the DWM performance worsens significantly which indicates that the current network setup which supplies Bucket 2 from the local warehouses is optimal. Supplying material that is not available locally should always be done from the closest large warehouse as this yields the best performance with all infrastructures. This is different to the current setup where material is supplied from any warehouse based on an algorithm selecting the supplying warehouse. It is interesting to note that CSCM US FO and the Transportation team of LSO have already been drafting a concept to improve the supply which would supply non-available material from the closest large warehouse

5.5. Analysis including possible material shortage

While conducting this research, one environmental factor became more present that may influence the decision making for the Supply Chain Network design drastically. The rising shortage of material in the semiconductor industry makes it difficult for ASML to supply sufficient safety stock for all customers according to CSCM US FO. In the future, ASML expects that a small percentage of material will not be available at multiple locations. Instead, they will plan with having only one part of these so-called critical materials available for all customers in the US. Once the part was needed by a customer, it will be replenished and available again for all customers. Even though the Central Warehouses cannot outperform the current infrastructure with holding as much material at the local warehouses, there might be a benefit of storing critical material in a central location instead of in the GDC. To investigate this impact, we assume that X% of all EUV and DUV material will become critical by 2025 and analyze the performance when supplying these materials from the GDC (1C*), USX (2C*), or USX (3C*). There is no precise estimation on the percentage of critical material in the future but the value was chosen according to the historical range of critical material being between X% and X%. So, instead of supplying all Bucket 2 materials from the Central Warehouse, we will investigate the performance of scenarios with a central warehouse that only supplies critical material while all other material that is not available locally will still be supplied from the closest large warehouse.

The DRT performance only shows minor differences between scenarios 1 to 3 with deviations of around 0.2 and 0.4 percentage points for EUV and DUV. As discussed in the previous subsections, the impact of supplying just X% material from a different location is minimal, and for all Bucket 1 critical material the shorter lead time when supplying them from USX or USX in comparison to the GDC does not count towards the DRT performance. This is owed to the fact that the Bucket 1 DRT target is X hours and exceeding the target by X hours with the CWH or X hours with the GDC does not impact the DRT performance.

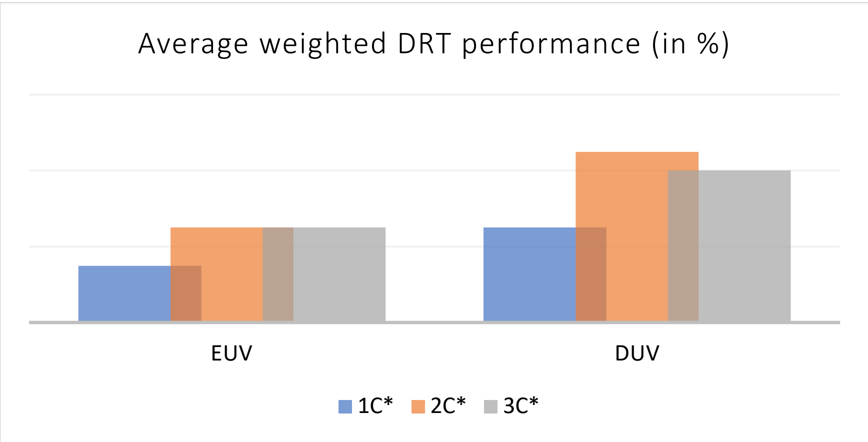

Figure 22: DRT performance comparison

The DWM performance does show structural differences between the scenarios. For EUV, the Central Warehouse scenarios 2C* and 3C* perform over 2 percentage points better yielding a DWM score of X and X% when supplying critical material from USX and USX, respectively. For DUV, both scenarios 2C* and 3C* result in a DWM performance of 0.9% again outperforming scenario 1C* which supplies critical material from the GDCs and achieves a DWM of X%. This shows the clear impact of shortening the lead time for critical material by shifting the inventory into US instead of shipping them internationally from the Global Distribution Centers. Furthermore, holding critical material closer to large customer bases in USX results in a better performance than storing them in USX which has no large EUV or DUV customer close by.

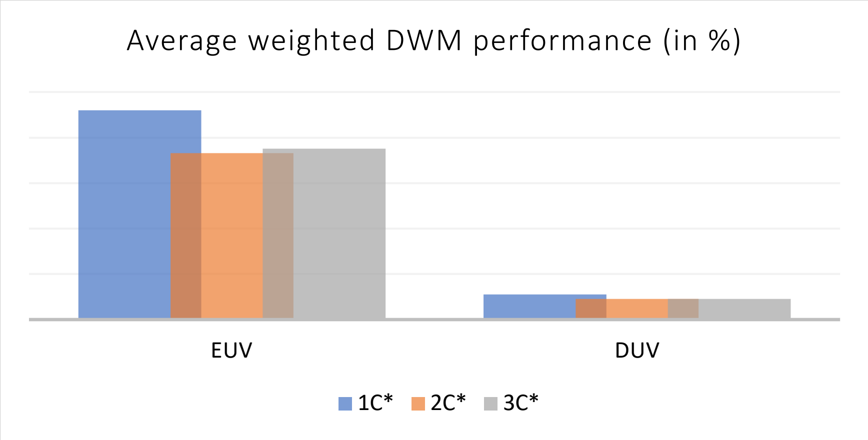

Figure 23: DWM performance comparison

The cost performance shows the same pattern as the customer contract performances. Shipping material international is costly, and thus, supplying material from a Central Warehouse in the US is 14% less expensive. Scenarios 2 and 3 show a total annual transportation cost of X million USD while Scenario 1C* would cost ASML X million USD annually. Nevertheless, the savings of over 1 million USD do not include the additional replenishment costs that occur for scenarios 2C* and 3C*. When supplying critical material from within the US, they need to be replenished internationally. As stated in the previous analyses, replenishment transportation costs are expected to be X% cheaper than forward flow transportation costs which shows that scenarios 2C* and 3C* would still yield a significant cost decrease.

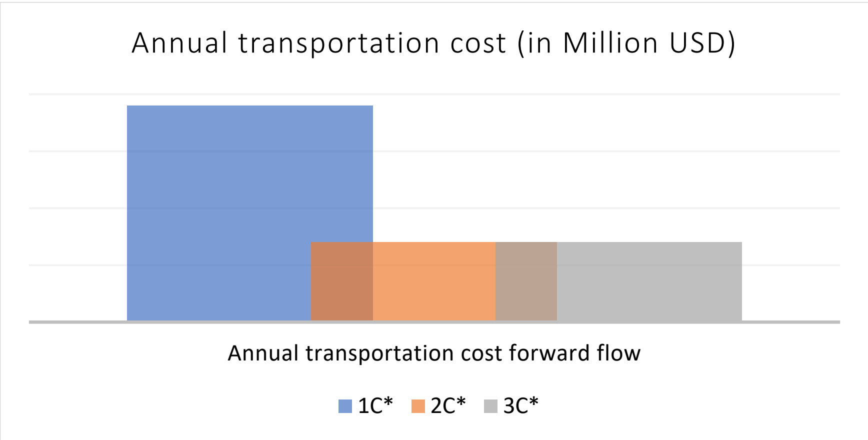

Figure 24: Cost performance comparison

With the increase in critical material, shifting material towards the US and supplying all customers from a central location allows for significantly better cost and service level performance. Storing those materials close to large customers further improves the performance as critical material would be available immediately for the important customer.

5.6. Sensitivity analysis returns

The return flows can be shipped directly from the Local Warehouses to the GDC in X (A), consolidated at a central location (B) or consolidated at multiple locations (C). The central locations to consolidate the return flows are again USX (B1) and USX (B2) as previously for the Central Warehouse scenarios. Scenario C consolidates all returns at the X large warehouses as previously described.

Figure 39 shows that not consolidating the returns (A) results in shipping X container per year due to the small warehouses only being capable of holding return flow materials for a few weeks. Thus, the containers are shipped with a low utilization rate resulting in many shipments and a total annual cost of X million USD. Consolidating material at one central location (B1 and B2) decreases the number of containers to X per year and thus also decrease the costs. Due to USX being a major customer site, less transportation is required when consolidating there in comparison to consolidating all material at USX. Therefore, scenario B1 results in X million USD annual costs outperforming scenario B2 with X million USD. Consolidating all material at the large warehouses increases the total number of container shipments to X per year. However, due to the shorter required distances between the Local Warehouses and the consolidating warehouses, the domestic transportation costs can be drastically decreased. The total annual costs of scenario C are consequently lower with X million USD. This is also due to X major warehouses, USX and USX, being located near the X major ports, X which results in lower container trucking costs per container than in the other scenarios.

Consolidating all return flows at the X large warehouses in the US can save up to X million USD annually. However, this is under the assumption that all X warehouses have sufficient capacity to store return flows of multiple customers for at most X weeks or otherwise until a container is full.

Figure 25: Performance comparison return scenarios

5.7. Sensitivity analysis forwarder

In this sensitivity analysis, the performance in terms of lead times and costs of the two third-party logistics providers F1 and F2 will be compared to understand which forwarder should be used for which routes and shipments. To do so, the best available service level is chosen for both forwarders being "X" for F1 and "X" for F2.

Both forwarders use similar pricing strategies for shipments below X pounds (X kg). A fixed rate per shipment is charged based on specific weight ranges. However, F1 adjusts the price per shipment according to the distance between the origin and destination while F2 charges the same price for all deliveries within the US. For shipments above X kg, both forwarders charge per pound (or kilogram) with one main difference. F2 adds a fixed cost per shipment while F1 uses a minimum cost per shipment. For these heavy weight shipments, F1 also adjusts the price per shipment according to the distance between origin and destination. These rates result in an interesting dynamic: Due to F1's distance-based rates, shipments with shorter distance are generally cheaper than F2's fees. Once the distance increases, F2 becomes cheaper than F1. As Figure 26 shows, F2 is cheaper for shipments below X kg once the distance between origin and locations exceeds X miles. For shipments above X kg but below X kg, F2 is cheaper once the distance exceeds X miles. Since ASML's US warehouses and customer locations are spread across the country, the distances are generally large as discussed in the problem statement section. Out of X possible routes, only X routes are shorter than X miles, indicating that F1 is only cheaper for X% of all routes. Figure 27 shows the prices for shipments above X kg. Since both forwarders charge per kilogram, an average weight based on historical data is used for each weight range. As for lighter shipments, F2 is always cheaper than F1 once the distance exceeds X miles. Additionally, shipments with an average weight of X kg are always cheaper when using F2. For possible optimizations in the future, the lower and upper bound of shipments that are always cheaper with F2 can be calculated. This yields that F2 is cheaper for all shipments between X kg and X kg regardless of the distance between origin and destination.

Figure 26: Price comparison F2 and F1 below 70kg

Figure 27: Price comparison F2 and F1 above 70kg

The actual annual performance difference between the forwarders can be analyzed through three scenarios:

i. Using X% F2 and X% F1 as the current data from 2022 shows
ii. Using 100% F2 to evaluate the actual F2 performance
iii. Using 100% F1 to evaluate the actual F1 performance

All three scenarios are simulated using the current baseline with X Local Warehouses, no Central Warehouse, and no critical material. The performance indicators used are the total waiting time in hours as this represents the overall lead time performance of the forwarders, and the total annual transportation costs without taking the return flows into account. As Figure 28 shows, using F2 for all shipments could improve the performance by 1.4% (from X hours to X hours) in comparison to the current baseline and 4.1% (from X hours to X hours) in comparison to the pure F1 performance. Furthermore, the total annual transportation costs of scenario ii yield an 8.7% cost decrease (from X to X million USD) in comparison to today and outperform F1's cost by 32.3% (from X to X million USD), as Figure 29 indicates.

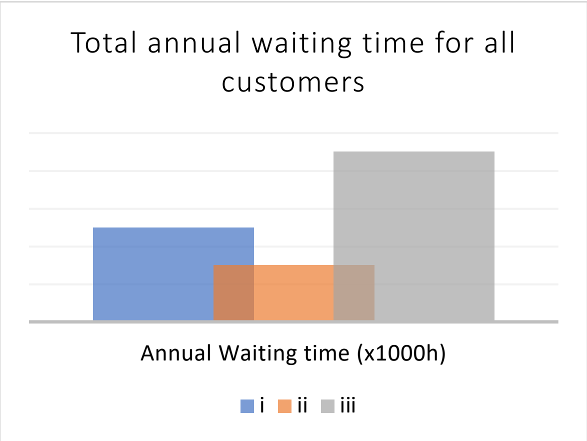

Figure 28: Waiting time comparison

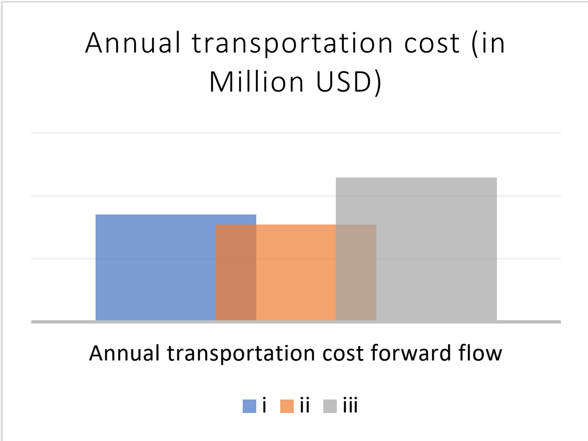

Figure 29: Transportation cost comparison

5.8. Limitations

The limitations of the findings are mainly due to the exclusion of replenishments. The cost savings in reality will not be as drastic as they seem based on the theoretical cost savings provided by the model. Therefore, the validity of the findings' operational impact is limited. Furthermore, the investigated third-party logistics provider will have different lead times depending on the exact time and characteristics of each shipment. So, while the model only takes average lead times into account, in reality the lead times will likely follow a normal distribution. Overall, by not modelling the Supply Chain Network on a part level, it is unclear how much space is required for each shipment. Therefore, the insight into the required capacity for every shipment and also the warehouses is limited. Moreover, the throughput capabilities of transition nodes is not regarded. This means that in reality some airports may not be able to process a large number of incoming goods efficiently. This may result in prolonged lead times or even choosing a different central location to supply material that is closer to airports able to handle a large number of incoming goods efficiently. Lastly, the used rates for F2 and F1 may change if ASML decides to increase or decrease the number of shipments with them. In other words, F2 and F1 may ask for higher or lower prices when settling on contracts with lower or higher number of annual shipments.

5.9. Conclusion

To summarize, shifting Bucket 2 (B2) material from the Local Warehouses (LWH) to a Central Warehouse (CWH) does not impact the DRT performance negatively. The DWM performance gets significantly worse when supplying B2 material from a CWH as the lead times, and thus also the waiting times, increase. Shifting B2 material to the Global Distribution Center (GDC) impacts both the DRT and DWM performance negatively since, e.g., the DRT target of X hours for DUV material cannot be achieved. Moreover, the transportation costs increase as more material needs to be shipped over longer distances and possibly internationally. Therefore, it is optimal to supply the majority of B2 material from the LWHs. All scenarios showed that if material is not available locally supplying it from the closest large LWH yields the best service level and cost performance. However, with increasing critical material, for example due to material shortages, it becomes optimal to store the critical material in a US warehouse that is close to a major customer instead of the GDC or a random CWH. Thus, the service level and cost performance become significantly better when supplying critical material of all Buckets from USX instead of USX or the GDC. The sensitivity analysis on the return flows shows that consolidating all returns at the four large warehouses instead of not consolidating or consolidating at the CWH is optimal regarding the transportation costs. The analysis on the two possible forwarders, F2 and F1, allowed to understand that F2 offers faster shipments and cheaper rates when shipping longer distances. Nevertheless, for distances below X miles, F1 is the best choice to achieve optimal costs if the shipment weighs less than X kg or more than X kg.

6. Research question 5 | Recommendations

In this chapter, the optimal Supply Chain Network Design for ASML in the US will be explained, the next steps to implement said design will be described, and possible improvements for future network studies will complete the recommendations of this research.

6.1. Key conclusions

This research yields five main conclusions that are insightful for the stakeholders of the CSCM and LSO department within ASML.

- Freight performance does not drive underperforming Service Levels

Even though the freight performance, i.e., the achieved transportation times from 3PLs, does impact the Delivery Response Time and Downtime Waiting for Material performance of ASML, it is not the main driver. ASML stores a significant amount of material locally at the customer locations, i.e. X%, to achieve the desired Service Level Agreements. Therefore, the freight performance only impacts a minimal percentage of shipments, i.e., X%.

- Supplying significant volumes of material from a central location is not feasible under current Service Level Agreements

ASML's current Service Level Agreements with customers push ASML to stock over X% of all materials locally at the customers. Even Bucket 2 material that is not required to be stocked at the customer locations is held locally to achieve the low waiting times that customers demand. Increasing the lead times for materials by stocking them centrally in the US would lead to longer lead times with which ASML could never achieve the targeted Downtime Waiting for Material.

- The forwarder F2 is faster and cheaper than F1 on the majority of routes unlike the stakeholders expected

F2 was expected to be significantly more expensive than F1, and thus, was expected to only be used for a minority of shipments. However, the data showed that F1 charges a higher price for over X% of all domestic routes between Local Warehouses. Therefore, the misconception within ASML to use more F1 than F2 should be corrected and F2 should be used for more shipments as the following subsection will explain.

- Rising material shortage will drive the stock allocation decision and challenge achieved Service Levels further

With material shortage ASML can no longer stock those materials locally for every customer but needs to supply all customers from one location. The availability of material decreases, and the lead times increase. This will become a big challenge for ASML as the targeted Service Levels will worsen further. ASML will need to allocate critical material that is impacted by material shortage wisely and analyze the global impact of this allocation as will be further explained in the next subsection.

- Return consolidation should be optimized to achieve operational excellence

Consolidating return material from all customers allows for significant cost improvements. Additionally, when consolidating material at fewer warehouses, many Local Warehouses will then be capable of focusing solely on the forward flow. This may allow for faster process times and managerial improvements in the future. Furthermore, the warehouses that will consolidate return materials can build up the capability to inbound and outbound this material faster through training, again possibly enabling ASML to improve their warehousing processes and save additional costs.

6.2. Supply Chain Network Design ASML should implement

The current service level commitments regarding the EUV and DUV DWM performance require ASML to stock most of the material close to the customer at the Local Warehouses. Beyond stocking Bucket 1 material at the Local Warehouses, most Bucket 2 material also needs to be supplied directly from the Local Warehouses to achieve the desired service levels. Therefore, the Supply Chain Network Design does not require a Central Warehouse for Bucket 2 material. If material is not available locally, it should be supplied from the closest large warehouse to achieve the best DWM and DRT performance. If critical materials, i.e., material of which only one is available for all US customers, increase a Central Location to supply those materials to all customers is beneficial. Locating the materials close to major customers yields the best performance, for which USX is the optimal location. Due to the small demand volume for MPS and APPS and the DRT target for MPS and APPS material being X hours, the current Central Hub USX provides sufficient performance to supply all customers. Thus, the following infrastructure should be implemented:

- One Local Warehouse for each customer serving EUV and DUV Bucket 1 and Bucket 2 material
- One Central Hub (USX) to serve MPS Bucket 1 and Bucket 2 material
- Global Distribution Centers serving Bucket 3 material
- Locally not available material is supplied from the closest large warehouse
- Critical EUV and DUV material is supplied from a local warehouse close to the largest number of install bases, i.e., USX

Regarding the third-party logistics providers, using F2 for all shipments provides the best lead time performance. However, for smaller distances, the lead time volatility loses importance, and the cost performance is of higher importance. With F1 being cheaper for most short distance shipments, the optimal solution is to use F2 for all shipments longer than X miles. Additionally, using F2 for shipments weighing between X kg and X kg adds an additional cost advantage allowing for savings up to X million USD annually. To summarize:

- F2 for all shipments between X kg and X kg
- F2 for all shipments with distance longer than X miles
- F1 for all shipments with distance less than X miles

Consolidating return flow material improves the operational performance by saving significant transportation costs. Instead of consolidating returns at the Local Warehouses individually, consolidating them at the closest large warehouses allows for cost savings of up to X million USD annually. Consolidating return flow material at one Central Location is not beneficial in comparison to consolidating at the closest large warehouses. This adds the following points to the optimal Supply Chain Network Design:

- Consolidating all return flow material at the closest large warehouses

The closest large warehouses are categorized, and each regular warehouse is assigned to one large warehouse as the Figure 30 indicates.

Figure 30: Large warehouses infrastructure

Through implementing the nine recommended aspects of the optimal Supply Chain Network Design, ASML can improve their performance. The Delivery Response Time and Downtime Waiting for Material are mainly impacted when supplying critical material from USX as they could improve by X%. The annual costs can be significantly reduced especially through shipping more shipments with F2 and consolidating returns resulting in annual cost savings of up to X million USD.

6.3. Necessary steps to implement the Supply Chain Network

Before starting the implementation of the proposed Supply Chain Network Design, the cost factors not included in this research need to be validated. Only if they will not exceed the cost savings through the proposed network design, the network should be implemented. Therefore, the CSCM department needs to simulate the new infrastructure including stocking strategy, i.e., inventory levels and true material availability. In this process, the replenishment shipments need to be modeled adequately as well which requires an extensive simulation on a material level.

After knowing the true inventory impact for each warehouse, the warehousing team needs to calculate the possible investment costs of expanding or downsizing locations and the OPEX impact of those changes.

Furthermore, ASML should research the expected percentage of critical material for every Business Line and bucket. The built model can be used to run the scenarios again and understand the real impact of the critical material on each customer, performance measurement, and costs. The impact of storing critical material in the US needs to be evaluated during this step. Storing more material in the US may impact customers in Asia which needs to be considered before implementing the new Network Design.

Since the model provides a theoretically optimal solution but does not take into account anomalies throughout the year, a pilot project can provide true insight into the changes with the new Network Design. Therefore, the new Network Design should be tested with only a few customers for a finite time. The resulting performance can be compared with the historical performance and the current performance to comparable customers to evaluate whether the Network Design is indeed optimal in reality.

Once these two aspects have been validated, material that is not available locally and will in the future be supplied from the closest large warehouse needs to be shipped to those warehouses. The transport management system needs to support employees in the warehouses to automatically select the closest large warehouse to supply those materials so that the network structure will be used in reality.

The Transport Management System should further select F2 and F1 whenever they are optimal as described in the previous subsection. It would possibly be beneficial to contact F2 and negotiate new rates when using their service for a larger percentage of shipments.

6.4. Improvements for future Network studies

ASML could improve three core aspects for future network studies. The following list depicts all three aspects which will be explained in the following paragraphs of this section:

- Build up joint capability to conduct network studies with CSCM and LSO department
- Conduct network design studies on a lower (material) level
- Allow to challenge customer commitments and performance targets

For future Supply Chain Network studies, ASML should build up the capability to collaborate more easily between the CSCM and LSO department. The information flow between CSCM and LSO is crucial to conduct insightful research, e.g., because inventory levels are required to simulate which warehouse has specific material available. Therefore, through collaborating further and being able to access more detailed information on inventory management and stocking strategy, the LSO department could make more reliable Supply Chain Network analyses.

Furthermore, conducting a study on a lower level of detail allows for more certain results. Even though using average probabilities for material availability may represent reality adequately, using information on the demand and inventory of each material can provide better conclusions. For example, knowing the specific demand of each material enables ASML to relocate material with higher demand closer to the customer to improve their performance. Additionally, the return flows could be analyzed more thoroughly with precise information on the material. Knowing the size of each material would allow ASML to use exact capacities for the warehouse and containers while for this research only a generalized estimate is used for all material.

Lastly, allowing for more freedom in the decision-making process could lead to more creative solutions. The boundaries and requirements for new Supply Chain Networks are currently driven by the customer agreements. Thus, any network that will not meet those agreements was deemed infeasible even before simulating its performance, such as a network design moving Bucket 1 material to a Central location. However, such networks may have operational benefits and ASML should consider negotiating lower service levels for lower costs with their customers if a network design can achieve that.

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