MASTER

Global supply chain planning in a make-to-order environment

Hendriks, S.C.P.

Award date:
2020

Eindhoven University of Technology
Department of Industrial Engineering and Innovation Sciences
Operations, Planning, Accountancy and Control Research Group

Global Supply Chain Planning in a Make-to-Order Environment

Project at Vanderlande Industries B.V.

Sanne Hendriks - 0854004

Committee members:
Prof.dr.ir. I.J.B.F. (Ivo) Adan - TU/e
Dr. Z. (Zümbül) Atan - TU/e
Dr. ir. Q.V. (Vinh) Dang - TU/e
G. (Gilbert) Schapendonk - Vanderlande
ir. J.F. (Jelte) Van Gils - Vanderlande

Version 1.0

Eindhoven, December 15, 2019

Abstract

Creating a Supply Chain Planning in multi-project, Make-to-Order environment is a complex problem. This problem includes both the costs and time of production and transportation to satisfy a resource capacity and lead time restriction. Four methods are used to solve the problem: The current allocation method, the FCFS policy, an exact solution by Gurobi and a Genetic algorithm (GA). This research contributes to literature because both the model and GA solution design were not found in literature yet. For small solutions, the GA is able to obtain the optimal solution. For larger size problems, this comparison was not possible. However, the GA outperforms both the Current allocation method and the FCFS policy.

Management Summary

This research models and analyses a Supply Chain Planning in a multi-project environment. It is tested with a case study provided by Vanderlande Industries B.V. (Vanderlande).

Problem statement
Vanderlande is marketleader in 'Value-added logistic process automation' and is active in two sectors: Airports and Warehousing Parcel (WP). Examples are Schiphol Airport and Albert Heijn, respectively. This project focuses on the Supply Chain planning, which includes the manufacturing and transportation of the different items to the customer. In the Supply Chain planning (SC Planning), the core decisions are when and where to produce every item while keeping a multi-project overview. Vanderlande has a network of factories around the world, which each different costs to produce items. At this moment, allocation decisions are made by default or human insight. This research aims at redesigning this planning by taking the costs of manufacturing and distribution into account in the global multi-project environment. The following research question is defined:

How can items be allocated to global production facilities to create a cost efficient Supply Chain Planning (SCP) in a multi-project environment?

Vanderlande has a project based approach. A project p is split up into activities a, which consists of the items i. Production and transportation is planned on item level. To provide unique labels to every item to be order, the SC planning will plan with i, a, p which refers to item i, activity a and project p.

Analysis
The desired allocation method is driven by costs and should satisfy two types of constraints: the time and capacity constraints. This method is defined by a mathematical linear program model (LP) with the objective to minimise the costs. These costs include production, transportation, waiting and underload costs, where underload costs define unused capacity in Vanderlande factories. This model includes two decisions: Where to produce and when to start production. To assure the feasibility of the model, an extra supplier with infinite capacity is included for every production region.

Multiple allocation strategies are included in the result comparison, the Current method, Gurobi (an optimization program), the Genetic Algorithm (GA) and the First-Come First-Served (FCFS) policy. For a project with only 109 items to be allocated, an exact solution is found by Gurobi. For larger size problems, 517, 1165 and 3225 items respectively, Gurobi was not able to solve the problem. Therefore, the remaining three strategies are compared. For all three scenarios, the GA outperforms the Current method and the FCFS policy.
A Genetic Algorithm (GA) is designed to solve the allocation problem. A GA aims to find the global optimal solution. A GA is based on evolution theory and uses the concept of genetic structure, chromosomes. Each chromosome consists of different genes, which each define

a unique i, a, p (item, activity, project). Both a supplier and start production time are assigned to every gene (i, a, p). With the supplier and assigned production time, the costs of the chromosome can be calculated. The objective is to minimise these costs. The model will have 330 iterations, named generations, to improve the solution and decrease the total costs; this number is defined by a design of experiments. Multiple steps are included for going from one generation to another. These steps include: Elitist selection, Crossover, Random generation, Mutation and Local search. Of the last generation, the allocation solution with the lowest costs is given as advice and will therefore be used in the result comparison.

There are two main differences between the Current allocation method and the GA allocation. In the current method, allocating to a Vanderlande factory is preferred over subcontractors and production is restricted to the region of the project. These restrictions are relaxed in the GA. The largest cost savings can be accounted to relaxing the production region. The GA shows that for projects in the Europe (EU) region, on average, 50% should be produced in the AsiaPacific (AP) region. For projects in the AP region, it is more cost-efficient to produce around 30% of the items in the EU region. As a result of assigning to different production regions, the costs in the objective are differently distributed. In the Current method, almost all costs are derived from production costs. Although relatively more transportation costs are incurred in the GA, this increase insignificant compared to the total savings.

Recommendations
For Vanderlande, this research gives both insight in their allocation costs and provides a more cost efficient allocation method. The designed Genetic Algorithm (GA) provides a more cost efficient allocation method for Vanderlande compared to the Current allocation method. Although the costs of the FCFS policy are higher than the GA, it does provide quick insights in the cost-efficient production regions.

Furthermore, the quality of the output is highly dependent on the quality of the input variables for all allocation methods. Specifically for the variables that are time dependent, these must be updated on a regular basis for the model to work.

Academic relevance
It seems that this research defines a new scheduling model. This model includes both production and transportation, looks at multiple production locations, both internal and external suppliers, with each a separate resource capacity. The objective of this model is to minimize the costs in a multi-project and Make-to-Order environment. No papers were found that include all these aspects of the problem.

Furthermore, the application of a Genetic Algorithm (GA) to an allocation problem, at least this complex, was not yet found in literature. Multiple articles were found where a GA is applied to scheduling a single machine, or a Traveling Salesman Problem (TSP). However, applying a GA to an allocation problem brings new challenges and not all steps in creating new generations with TSP are possible in an allocation problem.

The model in this report was extended with a consolidation option. In this extension, a new decision variable is defined: When to start transportation. By including this decision, items going to the same customer can be consolidated in the same container. In future research, this could also be included in the solution design. This will make the solution more realistic and will potentially further reduce the Supply Chain costs.

List of Variables

Variable	Explanation
P	Set of Projects
A	Set of Activities
A_p	Set of Activities in Project p
I	Set of Items
I_a	Set of Items in Activity a
S	Set of Suppliers
$ad_{i,a,p}$	Arrival date per Item i in Activity a in Project p
$dd_{i,a,p}$	Due date per Item i in Activity a in Project p
T	Time horizon in weeks
PT_i	Production Time per Item i (weeks)
$pc_{i,s}$	Production Cost per Item i per Supplier s
C^p	Total Production Cost
$Q_{i,a,p}$	Demand of Item i in Activity a in Project p
h_i	Holding Cost per Item i per week
C^w	Total Waiting cost
V_i	Volume per Item i. Number of Items per Container
$tc_{s,p}$	Set of Transportation Costs Supplier s to Project p
C^t	Total Transportation Cost
$TT_{s,p}$	Set of Transportation Times from Supplier s to Project p
K	Set of Resource Types
$RC_{s,k,t}$	Number of Hours available per Resource Type k per Supplier s per week
$R_{i,a,p,k}$	Number of Hours required for Item i in Activity a in Project p per Resource Type k
$RB_{s,k,t}$	Number of Hours to Break-Even per Resource Type k per Supplier s per week (Only filled for Vanderlande factories)
$U_{s,k,t}$	Number of Underload hours per Resource Type k at Supplier s during Week t
RC_s	Hourly Resource Cost per Supplier s
C^u	Total Underload Cost

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Chapter 1

Introduction

This project is commissioned by Vanderlande Industries B.V., referred to as Vanderlande from this point. First, this chapter will give a short description of Vanderlande and its products. Then the main process that projects go through within Vanderlande will be discussed and some general information will be provided that is required throughout the project. Afterwards, the problem will be elaborated within Vanderlande and in the literature. Then the scope of the project is set and the research questions will be defined. Lastly, the structure of the report will be given.

1.1 Company profile

Vanderlande is market leader in 'value-added logistic process automation' (Vanderlande, 2019). The company distinguishes two Business Units (BUs), namely airports, and warehousing & parcel (W&P). The business units describe the sectors in which they operate and can therefore easily be separated. They generally follow the same processes, but have different customers and systems. Both BUs design and provide systems to perform the distribution of products for their customers in their sectors. For example, at Schiphol airport, BU Airports delivered the baggage handling system and for Albert Heijn, BU W&P provided the inbound, outbound, storage and palletization installations. Every customer order is handled as a project within Vanderlande, since for every order a customer specific system is designed. For every customer order, a project team is composed that is responsible for that project. They create the project planning and cooperate with other departments involved, to ensure a smooth process.

The departments that are represented in the project team and that are relevant for this research are Sales, Engineering, Sourcing, and Supply Chain. The Sales department is responsible for identifying new customers and providing new projects. To be able to sell a new project, the Sales department already defines a first design for the system. The Engineering department takes the system design from the Sales department and further specifies the design; the only thing that they do not specify are the exact items. Several characteristics such as the speed of a conveyor belt will influence the items to be chosen, but do not adapt the lay-out of the design, this will be done by the SC department. The Sourcing department is involved in contacting Vanderlande's suppliers, they maintain a good relationship with custsomers, search for new suppliers and send invoices.

The Supply Chain (SC) department is the main department of interest in this research and it is connected to different aspects of the project planning. The sub-departments involved are Coordination, Planning, Engineering and Ordering. SC Coordinators are the main contact point between the project groups and the other SC sub-department. SC Planning does not operate project specific, but gives advice in the project planning while keeping the other projects' planning in mind. The SC Engineering department is responsible for the specification of the exact items to be ordered. SC Ordering is the department that eventually places the Purchase Orders.

1.2 Process description

This section describes the business processes considered in this report. The first sub-section describes the general process which is followed for every project. Also the item structure at Vanderlande is explained, this is required for the rest of the project and it defines the levels from projects until the items that are ordered.

1.2.1 Main process

Each Business Unit (BU) has Customer centers and Supply centers for the three geographical locations Vanderlande distinguishes: Europe, North America, Asia-Pacific. A Customer center is responsible for all communication with customers and makes a design of the system in the sales phase of a project. When a project is sold, the Supply center in that region will make the engineering (more specified) design and organises production and shipping to the customer location. The project process can be found in Figure 1.1 below.

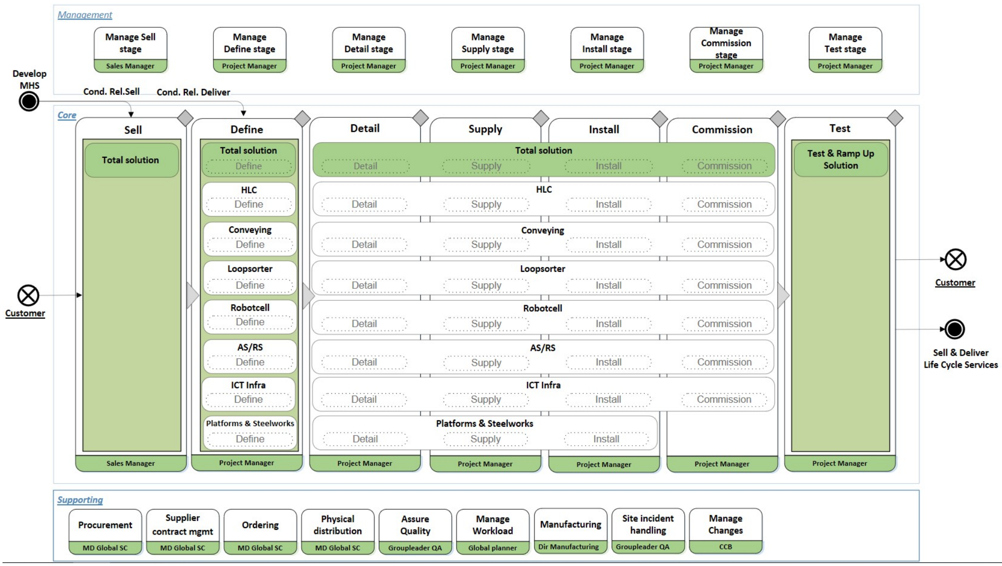


Figure 1.1: Main process at Vanderlande

The project process describes the stages of a project, from acquiring new customers and projects to the delivery of a project, which includes installation and testing at the customer's site. The planning process spreads across three phases of the process: sell, define and detail. During each of these phases, which will be discussed in the following paragraphs, a planning is created or updated. A further elaboration on the current planning process and SC tasks concerning the planning will be given in the next chapter.

Selling process

New projects originate from a Customer center; their job is to approach (new) customers, make a sales design and an offer. Both during the selling phase and the two following phases a tactical planning is created. This planning defines the time horizon for each department, including the

SC department. The tactical planning created during the selling phase is very important, since it defines the deadlines and the budget for the SC department. The selling phase consists of 4 stages:

1. Lead: Potential new customer projects are identified.
2. Pre-bid: The leads are analysed and options with an expected business opportunity continue to the next phase.
3. Bid: A sales design, planning and price quotation are created and offered to the customer.
4. Closing: If the offer is accepted by the customer, the project is handed over to a Supply center.

As can be seen in the stages above, an initial planning is created in the third stage. This is a very crucial stage in the planning process, since several characteristics are defined during this stage, such as project deadlines, the budget, production regions and the general items included in the design. This phase ends when the project is either won or lost. If won, the project continues to the next stage: Define.

Define process
When a project is sold, the Sales department in the Customer center hands it over to the Engineering department in the Supply center. The Engineering department defines a physical and functional design and a project plan. The physical design describes the layout of the system and includes the equipment used. The functional design is a list of specifications for system performance which is based on the customer's requirements. The two designs will show whether the specifications can be satisfied with standard Vanderlande equipment or whether special developments are required. From all this information, a project plan can be concluded which includes the planning to develop the physical design, and the budget for the SC department to execute their stage of the project. This stage is concluded with a last check before the designs and project plan are frozen and the next stage can start.

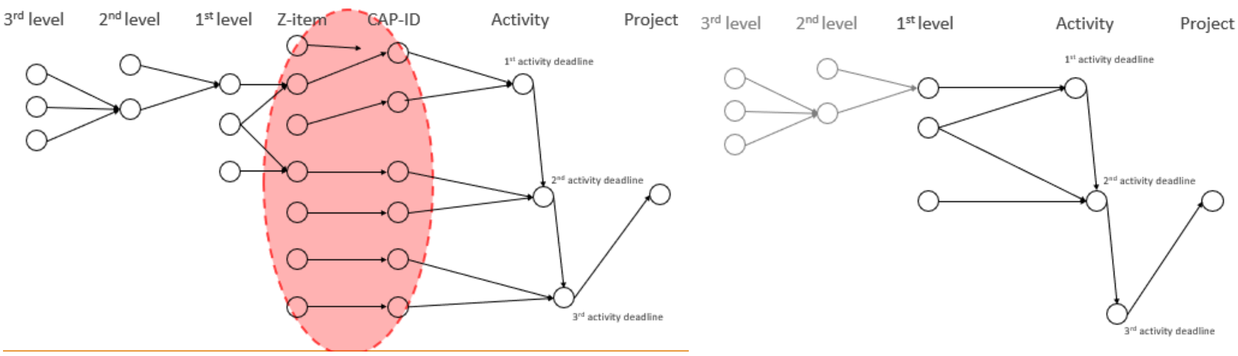
Detail process
The detail stage takes the documents from the Define stage and further specifies the system design. Some characteristics of the system are determined at this stage such as for example speed of a conveyor to achieve the throughput required. These last characteristics determine the exact items to be ordered by the Operational Buyer in the SC department.

1.2.2 Item Structure

The item structure within Vanderlande is a unique structure and will occur throughout the rest of the research. Every system sold by Vanderlande starts with a **project**; the project defines the whole system design. To make this project manageable, it is divided into smaller areas with similar characteristics; these smaller areas are named **activities**. An example of an activity is the check-in area at an airport, which includes the desks and the first meters of conveyor belt. Activities also define a precedence relation for starting installation and therefore the deadlines for the SC department. Looking a layer deeper, an activity consists of several items that are included in the design.

During the Sales phase these items are specified with **CAP-items** in the CAP calculation tool. This could, for example, represent a meter conveyor belt. In the Supply Chain department, these CAP-items are substituted by **z-items**. A z-item almost corresponds to a CAP-item, except that they distinguish in-house production from subcontracting or purchasing. z-items can be defined as a parent-item and consists of components. The exact components and specifications are still unknown at this moment; for example, two motors can have a different power. The most common specifications are used in the calculation of a z-item.

The **component** level is the lowest level and consists of three sub-levels. The **1st level** components are the components included in the z-item and are built up of **2nd and 3rd** level sub-components. However, these sub-components are not included in the planning. An overview of the whole structure is given in Figure 1.2a below.



(a) Item structure during Sales phase

(b) Item structure after Sales phase

Figure 1.2: Item structures at Vanderlande

When the project is sold, all 1st level components must be specified and the CAP-IDs and z-items are removed from the dependency structure, because eventually 1st level items will be ordered. The structure after the sales phase is depicted in Figure 1.2b. The 2nd and 3rd level sub-components have been blurred, since these are part of the 1st level component, but not explicitly defined in the order specifications.

1.3 Problem statement

When making a planning, project planners cooperate with Engineering, Supply Chain and 3rd parties. They assign each of these parties a certain lead time with start and finish dates per activity. For Supply Chain, which is the scope of this project, the start date is when the specifications are finished by Engineering and the finish date is when installation starts at site. This gives a lead time in which all items must be manufactured and shipped. To achieve this, the items should be allocated to a Vanderlande factory or subcontractor such that both the budget and lead time are not exceeded.

Within the department it is questioned whether the quality of decision-making is achieving its full potential with the current approach. Although costs are recorded during the selling phase in the process to determine the customer's bid and the budget for SC, they are not directly considered in the allocation process. It is therefore expected that the majority of items is allocated cost-inefficiently. If adding costs as a factor of the decision-making process improves the allocation of products, it can either increase the competitiveness by being able to offer a lower bid, or increase the profit margin of Vanderlande.

1.4 Scheduling in literature

The literature defines the SC planning problem as encountered in this project as a scheduling problem and can be applied to both production and transportation scheduling [3]. Scheduling literature aims to link products to machines and/or transportation modes to achieve the objective set while satisfying the constraints. Some articles combine the two aspects, however; most research is limited to either production or transportation. The majority of articles defines an optimization model to solve the scheduling problem. The most common objectives in scheduling problems are minimizing costs or time, where time can imply e.g. lead time, idle time and tardiness. For the constraints, the due date is an important recurring parameter since it determines the on-time service percentage of the schedule [2][3][7]. Also the precedence constraints between items or activities are usually included in the model [2][3].

Li, H. et al. [3] limit the paper to production scheduling. They assume a Make-to-Order environment, where they receive orders. Once these orders are received, the demand of items is deterministic. The model aims to assign these items to resources for production. Every resource type has a maximum capacity which cannot be exceeded. A maximum capacity, however, is only defined for inhouse production, which they distinguish from subcontracting. Luh, P.B. [4] does not produce items, but performs tasks. They make use of a structure that defines projects, with orders with tasks to perform. For every task, certain resources are required. The model designed assigns tasks to resources and apply a capacity constraint in this assignment. The objective is to maximize the on-time completion time and does not include the costs of the task. Porselvi, S. [5] combines production and transportation scheduling. The resource capacity in the model defines a number of machines available for production and the transportation costs are calculated per item and increase linearly. The objective is to minimize the costs, which consists of production, distribution, inventory and backorder costs. However, the assumption that material costs are fixed and therefore not included in the model might not be reasonable if the machines are situated at different locations, or when there are multiple suppliers for the same type of product. Guo, Z.X.[2] distinguishes different production locations as well as resources in a department within a location. Transportation time is incorporated in the production time and therefore linearly increases per product produced. This corresponds to the transportation calculation from Porselvi, S. [5]. An assumption made by Guo, Z.X. [2] is that each department can only perform one Production Order (PO) at a time. Since they define a department as a part of a production facility, this might be a valid assumption to simplify the scheduling problem. Ertogral, K. et al. [1] define two separate models, of which one addresses a production schedule and the other a distribution schedule. The production model produces to stock and sets a resource capacity. The distribution model determines a route that visits pick-up and drop-off locations with a fixed start and finish location. Both models have the objective to minimize the costs incurred.

In Table 1.1 below, an overview is given of the model aspects that are included in each article as described above. The aspects looked at are the main characteristics for the problem situation at Vanderlande.

Reference	**Make-to-Order**	**Production**	**Transport-ation**	**Cost objective**	**Resource capacity**	**Multiple production locations**
Li, H. (2013) [3]	X	X		X	X	
Luh, P.B. et al. (1999) [4]	X	X			X	
Guo, Z.X. (2013) [2]	X	X	X		X	X
Porselvi, S. (2018) [5]	X	X	X	X		
Ertogral, K. et al. (1998) [1]		X	(X)	X	X	X

Table 1.1: Overview of corresponding aspects in literature

Although all articles above describe a part of the scheduling problem faced in this report, they all neglect an aspect that is of influence when planning globally in a Make-to-Order setting. Li, H. [3] fails to include the impact of having several locations globally by not including material and transportation cost. Luh, P.b. [4] restricts planning to time and resources and hereby neglects to include costs at all, also the transportation section is missing. Although Porselvi, S. [5] does include transportation, they neglect the difficulties of the global production process by assuming all products originate from one production facility. Even though Guo, Z.X. [2] includes both production and transportation into their scheduling, they neglect the importance of costs in their model. Ertogral, K. [1] seems to tick the important aspects, but not assuming a Make-to-Order environment has an enormous impact on both the production and transportation planning, which makes the exact models unsuitable for the current situation.

1.5 Scope

An important question to answer before starting the design is: What should be modeled and what is the purpose of the model? This will have significant impact on both the environment of the model and the method of solving the problem. This section will look into the scope of the process, its variables, constraints, and assumptions.

This research focuses on the second phase where a tactical planning is made, the define phase. In this phase, the exact specification of items are not yet known. The planning is therefore based on the Bill of Material (BOM) of the z-items. The model will include both steps in the supply phase in the model in terms of cost and time. These steps are manufacturing and transportation to the customer. The parameters that are currently used in the Vanderlande Supply Chain planning process will re-occur in this project, mainly as constraints. These parameters include the supply plan, capacity/workload and the start- and finish dates of the activities. A supplier preference, which is used as a default supplier will be left out of the scope. The main reason for this, is that it is expected that new default options can be established from the output of the model. In addition, to make the model useable in a steady-state business situation, the products that have already been ordered must be fixed as the supplier cannot be changed in real-time.

1.6 Research goal/question

Currently, all allocation decisions are made by default or human interaction. To achieve an understanding of the costs of manufacturing and distribution the following Research Question is defined:

How can items be allocated to global production facilities to create a cost efficient Supply Chain Planning (SCP) in a multi-project environment?

In addition several sub-questions are defined to provide guidance throughout the project.

1. How does Vanderlande currently allocate its items to production facilities?
2. What model can be used to determine the cost of an allocation planning that is suitable to the Vanderlande environment?
   (a) What are the costs involved?
   (b) To what restrictions must the planning conform?
   (c) What method can be used to minimize the costs by allocating items to production facilities?
3. What are the benefits of using this model to allocate the items compared to the current situation at Vanderlande?
   (a) How different is the allocation to the current situation? Can different strategies be observed?

Chapter 2

Current situation

This chapter describes the current planning process at Vanderlande. First a general description of the process is given. Next, the functions involved in the process by the Supply Chain department are elaborated on. Lastly, the decisions made during this process will be further discussed.

2.1 Planning

A planning at Vanderlande is divided into three parts, Engineering, Supply and Installation. During the engineering period, the exact item specification is made, which is the input for the supply period. The supply period is the responsibility of the SC department and includes the manufacturing and transportation of the items to the customer. Once this is finished, the installation (executed by third parties) can start.

Each planning is originally defined by the project planner who confirms this with the stakeholders of each period in the planning. The main stakeholders include the Engineering department, the Supply Chain (SC) department and the third parties, since these are responsible for the three parts of the planning. The supply planning, which is the scope of this research, is created during the three phases of the main process: in the selling, define and detail phase. The first two phases define a tactical planning, where the items are not specified yet, but represented by z-items. During these two phases, some decisions are made regarding the allocation and therefore lead time of the items. The planning at this point, for example, usually defines the supply area (Europe, North America, Asia-Pacific) of manufacturing. Deviations from the default allocation are recorded in a supply plan by the SC Engineer.

In the detail phase, the specifications are created by the SC Engineer and released. The exact item numbers are now fixed and can be allocated to a supplier; this can be a Vanderlande factory or a subcontractor. The specification list can then be transferred into a Purchase Order (PO) or Factory Order (FO), if the production is allocated to a subcontractor or Vanderlande factory respectively. An Operational Buyer creates the PO (and FO), by combining a supplier preference from sourcing on top of the input from all stakeholders mentioned before. An overview of the stakeholders and the information they provide can be found in Figure 2.1 below.

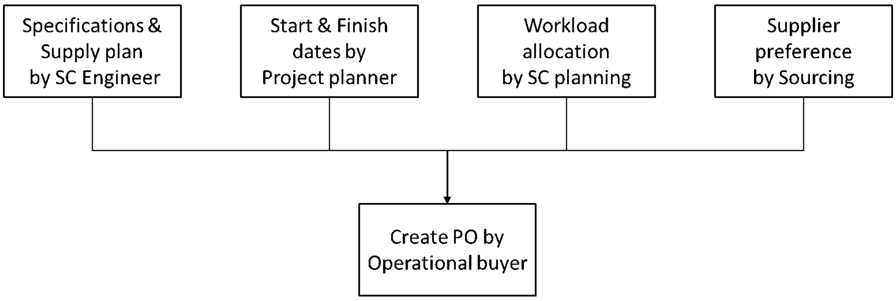


Figure 2.1: Information flow for creating a Purchase Order

2.2 Supply Chain

When zooming in on the Supply Chain (SC) timeline of the project planning, the department is involved in the manufacturing and transportation of the items to site. This part of the planning is only regulated by the project planner on a high level, essentially a start and finish date for each activity. Since SC planning does not operate project specific, aspects from a factory view can be taken into account. The item allocation is based on supplier availability, workload capacity in factories and the workload per item. Workload per item is defined as the number of hours it takes to manufacture an item. The workload allocation is coordinated by SC Planning. They have a Workload Allocation Tool (W.A.T.) used to monitor the workload in Vanderlande's and several subcontractors' factories. This tool aggregates information from all projects within Vanderlande.

The SC department makes many decisions regarding the allocation of items. The paragraphs below describe the current situation in terms of decisions that are made, by human interference, automatically and the business rules included in the Workload Allocation Tooling (W.A.T.).

Automatic and Human decisions
Vanderlande has set up several rules regarding the manufacturing allocation that are generally followed. Each item has a default supplier to which it is allocated if possible. This default supplier is dependent on the project, since it is always in the same geographical region as the customer, this is defined as a Supply Chain Center (SCC). Items can in fact only be allocated to suppliers in the same SCC, unless the supply plan (deviations from default) states otherwise.

If there are no deviations in the supply plan, the SCC is fixed. Items can be allocated to other suppliers in the same SCC, which is usually the case when the maximum workload of the default supplier is exceeded.

In addition, the tactical planning, which is the focus of this research, is based on z-items. These z-items have a Bill of Material (BOM) that consists of actual specification items. These items represent the items that will eventually be determined in the specification and might differ.

W.A.T. decisions
The Workload Allocation Tooling (W.A.T.) applies several extra rules to determine and display the workload. Since the planning is currently only limited by a start and finish date, an activity lead time and start date must be determined. The lead time of an activity is based on the equipment with the longest lead time in that activity. For each equipment type a standard lead time is determined. For the start date there are two options: On the actual start date or the

number of weeks in the lead time before the finish date. These are referred to as an early and a late finish respectively.

In the W.A.T., allocation does not happen on item level but on allocation group level. An allocation group is a category of items with the same characteristics in their production process, and therefore are very likely to have the same supplier options. This design choice is made to limit the information expressed by the W.A.T..

Chapter 3

Conceptual Model

3.1 Desired situation

The goal of Vanderlande is to gain insights in their decision making process within Supply Chain planning. It is expected that more information on different aspects of the process might improve the allocation decision. Currently, the decision is based on the workload that is assigned to the suppliers. This will shift to a cost-based decision. Cost of production, transportation, waiting and under capacity are the new aspects that will be added to improve the decision making process. The new objective in the allocation decision will be to minimize these costs. The workload on which the decision is currently made, will be incorporated as a constraint.

The current allocation decision restricts allocations to be made within Supply Chain Centers (SCCs). This implies that if a project is located in SCC Europe, all production must be allocated to suppliers in SCC Europe. This restriction will be discarded in the new situation and the effect of this will be analysed in the results (Chapter 5). Figure 3.1 shows the old situation (left) and the new situation (right), where the dotted lines define the extra options in the new situation. In addition, the current default supplier will be neglected in the allocation of an item. A default supplier is a huge limitation of the options and might not be the most cost-efficient choice. It is also expected that new (cost-efficient) default allocations will appear from the model.

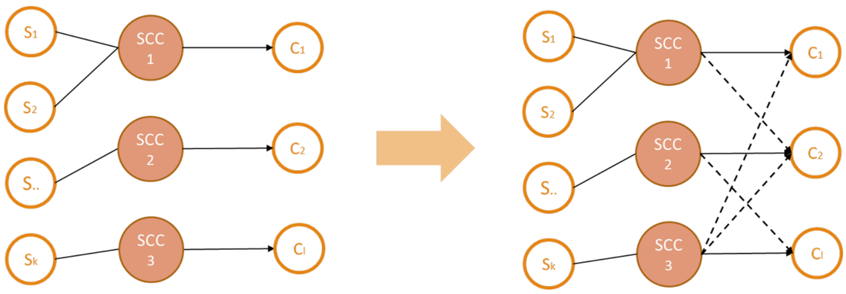


Figure 3.1: SCC restriction VS No SCC restriction

3.2 Situation description

The aim of this research is to find a method to allocate items to a supplier, to produce within the given lead time for the lowest costs. A simplified version of this situation is visualised in Figure 3.2 below. A project (p) is divided into activities (a_p), which includes items (i_a); this combination (i, a, p) is unique and is also used for allocation. The suppliers (S) are grouped geographically into the three Supply Chain Centers ($SCCs$), since only Europe, North America and Asia Pacific have production facilities. From these SCCs, different transportation routes take the items to the destination region (D) of the customer (C). These SCCs have an impact on the allocation decision; not every SCC can transport to every destination, because currently not every transportation route is available.

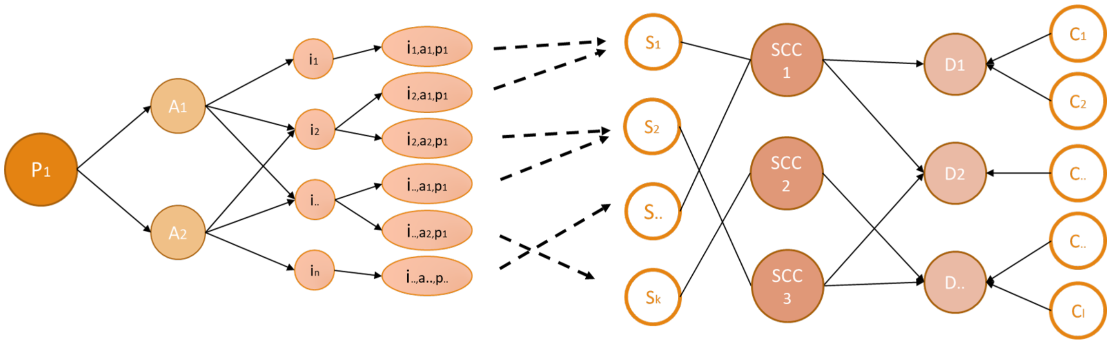


Figure 3.2: Problem situation

The main decision that has to be made is the allocation of items to suppliers. However, many aspects need to be taken into account when making this decision. These aspects include transportation time and costs, the different resource types, the workload and capacity in factories, the lead time and the actual costs made as a result of the allocation decision. Each aspect will be further elaborated on in the following paragraphs.

Time

Time is a crucial aspect in the SC planning and hard to capture in Figure 3.2 above. In addition to deciding where to produce each item, it must also be decided at what time production should start. Each item has a planned start and finish date, as planned by the project planner. Between these dates the item must be manufactured and shipped to the customer. The decision of a supplier is an important aspect, because it determines the production lead time and transportation time of an item, which determines whether an item can be finished and delivered in time for the finish date.

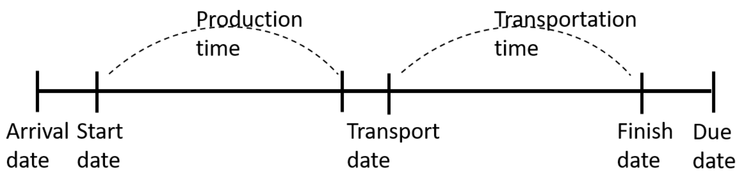


Figure 3.3: Timeline of a project

The whole planning is defined by a discrete time interval, where every time unit represents a week. The time horizon over which the planning is made is based on the arrival and due dates of the projects. Every activity in a project is given a planned start and finish date (arrival and due date in the model) and the model compels all items in activities to be delivered on time. The total planning horizon is therefore from the earliest arrival until the latest due date over all items in activities in all projects (3.1).

$$T = [\min\{ad_{i,a,p}\},\ \ldots,\max\{dd_{i,a,p}\}] \tag{3.1}$$

Transportation
Transportation defines the movement of items from the supplier to the customer. To be able to get an overview of the transportation options, two regions have been defined. These regions are the Supply Chain Centers (SCCs) and Destination regions (D), which represent a category of suppliers and customers respectively. This structure is also visualised in Figure 3.2 above.

Items are transported from the supplier to the customer in containers. A container is used as the standard transportation volume and will therefore be used in the calculation of the transportation costs. The transport can be done via sea or land (rail/road). This will have an impact on the time and costs of the transport. However, the specified transportation mode is not important and will therefore not be included.

Resource types
Items go through several processes in a factory before they are ready for delivery. However, there are too many processes to distinguish them all in the Supply Chain (SC) planning; therefore two types of production processes are defined, Parts and Assembly. Throughout the project these will be referred to as resource types. The employees are also divided into these two areas based on their expertise. Since employees can work on several items during a week, the planning does not require employees but hours of work. The work required for an item is therefore expressed in resource hours.

Capacity and Workload
For every supplier, the available resource hours per week are registered or estimated for Vanderlande factories and subcontractors respectively. The available resource hours define the (expected) available capacity per supplier. This capacity defines for every week the number of resource hours that can be assigned to a supplier per resource type. Each item requires a number of hours per resource type. In addition, the aggregated number of hours assigned to a supplier cannot exceed the capacity constraint. The workload and capacity are already visualised in the Workload Allocation Tooling (W.A.T.) for both resource types (Parts and Assembly). Keeping the workload under the capacity of each supplier is currently a manual task and will be automated in the new solution.

Costs
Minimising the costs is the new objective in the allocation decision and although they have an impact on the situation as shown in Figure 3.2, the costs are not explicitly visualised. The costs consist of manufacturing, transportation, underload and waiting costs. Manufacturing and underload costs are determined by the supplier, where the underload costs define the unused capacity of employees and these costs are only explicitly included for Vanderlande factories. Transportation costs also depend on the choice of supplier, since this defines the origin of the transportation route, and waiting costs are included to aim for delivery as close to the due date as possible. All costs will be further explained in Section 3.3.

3.3 Model formulation

The previous section described the situation that the model will address and the decision that must be made. This section formulates the mathematical model that will give an advice on where to manufacture each item and at what time to start production. The model will be based on the five articles as mentioned in the literature study [1][2][3][4][7]. First, the decision variables will be discussed in subsection 3.3.1. Then, in subsection 3.3.2, the cost calculation will be elaborated. Additionally, subsection 3.3.3 will discuss the constraints of the model and the assumptions made when creating the planning. Subsequently, consolidating items in transportation to the customer is discussed as an addition to the model in subsection 3.3.4. Lastly, the infinite supplier is discussed in subsection 3.3.5, this concept is a measure to guarantee a feasible solution possibility.

3.3.1 Decision variable

In this problem, two decisions must be made: Where to produce the item and when to start production. Both decisions must be made for every item in an activity in a project. The decision variable $X_{i,a,p,s,t}$ defines a 'Yes or No' decision. It has five indices of which the first three (i, a, p) are input variables. The decision to produce item (i, a, p) at supplier s, starting at time t is yes if $X_{i,a,p,s,t}$ is 1 and 0 otherwise (3.2).

$$X_{i,a,p,s,t} \in \{0, 1\} \tag{3.2}$$

To make sure every item is produced, constraint 3.3 is included [3][5]. This forces the model to give every item in an activity in a project, a supplier and start production date.

$$\sum_{t\in T}\sum_{s\in S} X_{i,a,p,s,t} = 1 \qquad \forall i \in I_a, \forall a \in A_p, \forall p \in P \tag{3.3}$$

A visualisation of the time horizon can be found in Figure 3.4 below. It shows the decision for the start date of production, represented by t. The Arrival date ($ad_{i,a,p}$) and Due date ($dd_{i,a,p}$) are item specific. The transport always arrives on the Due date.

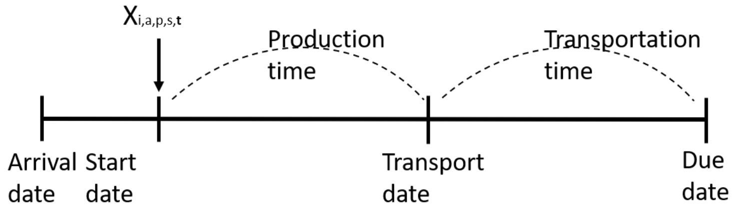


Figure 3.4: Visualisation of the decisions

3.3.2 Cost function

Costs are incurred in several parts of the process, these costs are represented in the cost calculation of the model. These costs include production (C^p), transportation (C^t), waiting (C^w) and underload (C^u). Even though waiting costs are not explicitly incurred in the business processes at Vanderlande, these will be added to the model to aim for a late finish planning. Each of these cost types will be discussed separately in the paragraphs below. The cost function is an addition of the four cost types and the objective is to minimise the costs.

$$Minimise \qquad C = C^p + C^t + C^w + C^u \tag{3.4}$$

Production costs

The production costs define the costs of manufacturing the total quantity of an item within an activity in a project (i, a, p). These incurred costs account for the raw materials, set-up of the production line and the employee hours required for the process. These costs are variable, since they are dependent on the supplier allocation. The production costs therefore have an influence on the objective of minimizing the costs.

$$C^p = \sum_{p \in P} \sum_{a \in A_p} \sum_{i \in I_a} \sum_{s \in S} pc_{i,s} Q_{i,a,p} \sum_{t \in T} X_{i,a,p,s,t} \tag{3.5}$$

In (3.5), $pc_{i,s}$ defines the manufacturing costs of item i for supplier s. $Q_{i,a,p}$ defines the production quantity of item i in activity a in project p. Both variables $pc_{i,s}$ and $Q_{i,a,p}$ are given as input to the model. The decision variable $X_{i,a,p,s,t,\tau}$ is included in 3.5 since it decides the supplier where item i is produced.

Transportation costs

The transportation costs are determined in number of containers required for transportation. These costs include the transportation from the country of the supplier to the country of the customer. The inland costs after arriving in the country of destination are not included in the model since this is a fixed cost that is incurred in all transportation options.

For simplicity, it is currently assumed that transportation costs are only paid for the percentage of the container that is filled. This is a realistic assumption since items might be consolidated into the same container or the container might be further filled by someone else. Besides, performing the calculations with payment for a full container would describe a worst-case situation which is not likely. In addition, calculations with consolidating items within a project were tested; this had little influence on the costs compared to paying the percentage of the container, but took much longer to formulate an allocation decision.

$$C^t = \sum_{p \in P} \sum_{a \in A_p} \sum_{i \in I_a} \sum_{s \in S} \frac{Q_{i,a,p}}{V_i} \cdot tc_{s,p} \sum_{t \in T} X_{i,a,p,s,t} \tag{3.6}$$

The formula above defines the transportation costs for all projects included in the allocation decision. $Q_{i,a,p}$ defines the quantity of the items and V_i defines the volume of those items. $\frac{Q_{i,a,p}}{V_i}$ therefore defines the percentage of the container that is needed for transportation (per i, a, p). This is multiplied by the transportation costs from the supplier (s) to the customer (p). These costs are calculated and summed for every combination of i, a, p.

Waiting costs

Within Vanderlande, no inventory costs are charged if the items are in the warehouse for less than a month. These costs are included as a service to the customer, since most items are there solely for the consolidation of the activity. To improve the quality of the model, waiting costs will be included on a weekly basis. Waiting costs will force the model to apply a late finish strategy, which implies the least amount of waiting time. Since the transportation is always planned to arrive on the due date, waiting can only occur between production and transportation. This is also visualised in Figure 3.5 below.

$$C^w = \sum_{p \in P} \sum_{a \in A_p} \sum_{i \in I_a} \left(\left(dd_{i,a,p} - \sum_{t \in T} \sum_{s \in S} \left((t + TT_{s,p}) \cdot X_{i,a,p,s,t} \right) - PT_i \right) \cdot h_i Q_{i,a,p} \right) \tag{3.7}$$

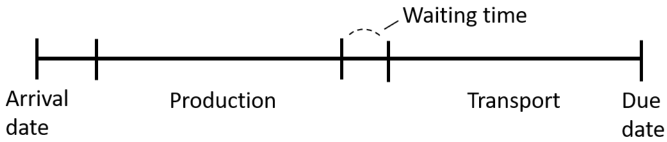


Figure 3.5: Possible waiting time for items

The waiting costs (C^w) define the costs of items being stored between production and transportation. The formula calculates the costs for every i, a, p combination. The time period over which the costs are calculated defines the time between start of production ($t \cdot X_{i,a,p,s,t}$) and the due date ($dd_{i,a,p}$), without the actual production (PT_i) and transportation ($TT_{s,p}$) times.

Underload costs

Underload costs are included in the cost function to account for unassigned capacity, more specifically, the lack of workload for the factory to break-even. The capacity that describes the break-even point of the factory is called the Budget capacity. In addition, Vanderlande has fixed and flexible employees, which limits the maximum capacity of hours that can be assigned. Therefore, in addition to the budget capacity, also a maximum capacity is defined which cannot be exceeded in the planning. Both capacity types are visualised in Figure 3.6 below.

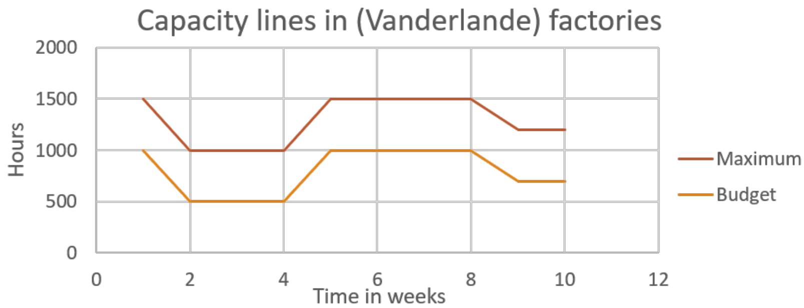


Figure 3.6: Capacity options

The assigned workload is dependent on the items assigned in the planning. Each item is given a production time (PT_i) in weeks, in which all manufacturing steps (resource hours) must be executed. In addition to the parts and assembly steps, some items are purchased that may be required in the assembly step. To account for the purchased items to be delivered, during the first two weeks of the production time (PT_i) no resource hours are required by Vanderlande (or a supplier). This resource division is visualised in Figure 3.7.

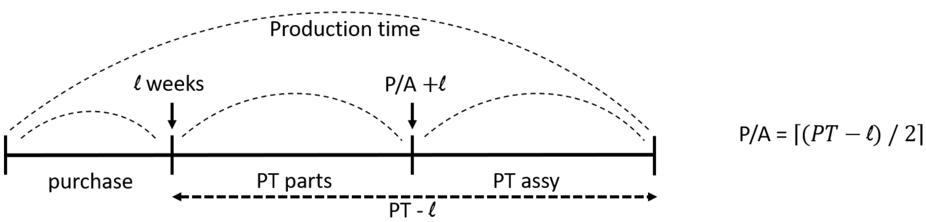


Figure 3.7: Resource split-up

Based on the processes at Vanderlande, the time reserved for Parts and Assembly is divided rather evenly. The split-up between Parts and Assembly in Figure 3.7 defines that; if the total number of weeks is an uneven number, parts production will gain an extra week over assembly. Besides the time horizons also the resource hours follow a uniform distribution for their respective horizons.

The loss for not reaching the budget capacity will be included in the cost function of the model as underload costs. As an estimation, the cost of each hour under the budget capacity is defined as the hourly cost of an employee.

$$\text{Underload} = [\text{Budget capacity - Assigned workload}]^{+}$$

However, this underload function is not linear. To maintain a Linear Problem, the underload function above will be redefined. The formulas below introduce an extra variable $U_{s,k,t}$ which defines the number of underload hours; since costs are attached to this variable, this variable aims to take the smallest value possible. This is either the outcome of (3.8) and (3.9), or 0 as defined in (3.10).

$$U_{s,Parts,t} \geq RB_{s,Parts,t} - \sum_{p \in P} \sum_{a \in A_p} \sum_{i \in I_a} \sum_{z=l}^{min(t,P/A+l)} X_{i,a,p,s,(t-z)} \frac{R_{i,a,p,Parts}}{P/A} \qquad \forall s \in S,\ \forall t \in T \quad (3.8)$$

$$U_{s,Assembly,t} \geq RB_{s,Assembly,t} - \sum_{p \in P} \sum_{a \in A_p} \sum_{i \in I_a} \sum_{z=min(t,P/A+l)}^{min(t,PT_i)} X_{i,a,p,s,(t-z)} \frac{R_{i,a,p,Assembly}}{P/A} \qquad \forall s \in S,\ \forall t \in T \quad (3.9)$$

$$U_{s,k,t} \geq 0 \qquad \forall s \in S,\ \forall k \in K,\ \forall t \in T \qquad U_{s,k,t} \in N \quad (3.10)$$

$$C^u = \sum_{s \in S} \sum_{t \in T} \Big(\sum_{k \in K} (U_{s,k,t}) \cdot RC_s \Big) \quad (3.11)$$

The calculations of the underload hours in (3.8) and (3.9) are similar; each describes a resource type k, Parts and Assembly respectively. These are separated because the resources are required at different moments in the production time. $U_{s,k,t}$ defines the hours under the Budget capacity for every week per supplier. The assigned workload is therefore subtracted from the budget capacity. To calculate the assigned workload per week, for every item (i, a, p) it is checked whether production started z weeks ago [6]. If yes, the workload for that week is added to the supplier's workload. The workload per week is the total workload (parts/assembly) divided by the number of weeks required for that resource type. This provides a uniform distribution over the number of weeks allowed. The underload hours $U_{s,k,t}$ are the Budget capacity subtracted by the assigned workload if the value is positive and zero otherwise. The underload costs (C^u) are a multiplication of the underload hours $U_{s,k,t}$ with the hourly rate of employees RC_s.

3.3.3 Constraints

This subsection will discuss the constraints and assumptions that apply to the model. First every constraint will be explained, followed by the mathematical formulation. The direct assumptions are included in the text below, the indirect assumptions can be found in Appendix A.

The constraints are grouped in two categories according to a common subject. The two categories are processing time and resource capacity. Both categories include multiple constraints based on the environment at Vanderlande. A lot of literature is available on the time constraints of production planning that is suitable to the Vanderlande environment. Even though a lot of research on production scheduling includes a resource capacity, the majority assumes that the production is executed in one time period, whereas the production process of Vanderlande assumes that the hours are spread over multiple weeks. The commonality in resource planning is found in the hospital environment, which will therefore be used in the formulation of the constraints below.

Processing time
The time horizon restriction of every item limits the options of production. Each arrow in (3.8) defines some slack time in the time restriction and corresponds to one of the formulas below. The first arrow defines that production can only start after the arrival date (3.12)[2]. The second arrow defines that both production and transportation must be finished before the due date (3.13).

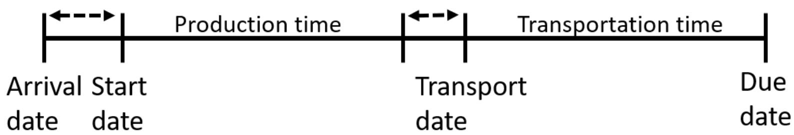


Figure 3.8: Time horizon of project planning

$$\sum_{t\in T}\sum_{s\in S} t \cdot X_{i,a,p,s,t} \geq ad_{i,a,p} \qquad \forall i \in I_a,\ \forall a \in A_p,\ \forall p \in P \qquad (3.12)$$

$$\sum_{t\in T}\sum_{s\in S}(t + TT_{s,p}) \cdot X_{i,a,p,s,t} + PT_i \leq dd_{i,a,p} \qquad \forall i \in I_a,\ \forall a \in A_p,\ \forall p \in P \qquad (3.13)$$

Resource capacity
Vanderlande defines two resource types in the factory, Parts production and Assembly. Both are measured in hours. The capacity is therefore also defined in hours for every supplier on a weekly basis. The supplier capacity therefore defines the maximum available hours per week. The workload is item dependent and follows the distribution as seen in Figure 3.7. The total workload assigned to a supplier cannot exceed its capacity. For each resource, these constraints

are combined in the formulas below.

$$\sum_{p\in P}\sum_{a\in A_p}\sum_{i\in I_a}\sum_{z=l}^{min(t,P/A+l)} X_{i,a,p,s,(t-z)}\frac{R_{i,a,p,Parts}}{P/A} \leq RC_{s,Parts,t} \qquad \forall s\in S,\ t\in T \tag{3.14}$$

$$\sum_{p\in P}\sum_{a\in A_p}\sum_{i\in I_a}\sum_{z=min(t,P/A+l)}^{min(t,PT_i)} X_{i,a,p,s,(t-z)}\frac{R_{i,a,p,Assembly}}{P/A} \leq RC_{s,Assembly,t} \qquad \forall s\in S,\ t\in T \tag{3.15}$$

The formulas for the maximum capacity, follow a similar structure to the Underload formulas. Both define the assigned capacity per supplier, time and resource type [6]. However, in (3.14) and (3.15) the assigned workload must not exceed the maximum capacity $RC_{s,k,t}$ instead of calculating the number of underload hours.

3.3.4 Transport consolidation

To make the model more realistic, consolidation within transport can be included. This will result in two main change in the model. First, instead of paying only for the percentage of the container used, the price for a full container must be paid at all times. Second, the date to start transportation will be modeled as a separate decision. By being able to adapt the start of transportation, items coming from the same supplier and going to the same customer can be transported in the same container. Having to pay the price of a full container, consolidating items should save costs and will therefore be preferred by the model. When looking at the model, this changes multiple constraints. Only the constraints of the model will be discussed that are influenced by adding consolidation.

First of all, a new decision variable is introduced. Decision variable $Y_{i,a,p,s,\tau}$ defines a 'Yes or No' decision and can take the binary values (3.16). The value is 1 if item i in activity a in project p is being shipped from supplier s at time τ. This supplier s is the same supplier as the allocation decision, this is forced by (3.17).

$$Y_{i,a,p,s,\tau} \in \{0,1\} \tag{3.16}$$

$$\sum_{t\in T} t\cdot X_{i,a,p,s,t} \leq \sum_{\tau\in T}\tau\cdot Y_{i,a,p,s,\tau} \qquad \forall s\in S,\ \forall i\in I_a,\ \forall a\in A_p,\ \forall p\in P \tag{3.17}$$

In the objective this only influences the transportation costs since cost must be paid for the number of containers instead of the percentage filled (3.18). (3.18) therefore replaces (3.6) in the original model. An extra variable is introduced, the number of containers required ($C_{p,s,\tau}$). This variable must take integer values of at least zero. The exact number of containers is the total volume of items that are transported from the same supplier to the same customer. The number of containers must take at least this value (3.19).

$$C^t = \sum_{p\in P}\sum_{\tau\in T} C_{p,s,\tau}\cdot tc_{s,p} \tag{3.18}$$

$$C_{p,s,\tau} \geq \sum_{a\in A_p}\sum_{i\in I_a}\sum_{s\in S}\frac{Q_{i,a,p}}{V_i}\cdot Y_{i,a,p,s,\tau} \qquad \forall\tau\in T,\ \forall p\in P \tag{3.19}$$

$$C_{p,s,\tau} \geq 0 \qquad \forall p\in P,\ \forall s\in S,\ \forall\tau\in T \qquad C_{p,s,\tau}\in N \tag{3.20}$$

For the constraints, this has an effect on some of the time constraints. Since starting transportation is separate decision, it is not by definition planned at the end of the lead time. Additionally, the time restriction for starting transportation time is now not dependent on the due date (3.13), this restriction is replaced by a dependency on start of transport. It states that production must be finished before transportation can start (3.21). An additional constraint is required to limit the transportation options. The items should still arrive before the due date (3.22).

$$\sum_{\tau \in T} \sum_{s \in S} \tau \cdot Y_{i,a,p,s,\tau} \geq \sum_{t \in T} \sum_{s \in S} t \cdot X_{i,a,p,s,t} + PT_i \qquad \forall i \in I_a,\ \forall a \in A_p,\ \forall p \in P \qquad (3.21)$$

$$\sum_{\tau \in T} \sum_{s \in S} Y_{i,a,p,s,\tau}(\tau + TT_{s,p}) \leq dd_{i,a,p} \qquad \forall i \in I_a,\ \forall a \in A_p,\ \forall p \in P \qquad (3.22)$$

3.3.5 Feasibility - Infinite supplier

The constraints of the model limit the solution space and for certain input it might be that no feasible solution can be found at all; e.g. if there is not enough capacity in the lead time given. If no feasible solution can be found, no allocation decisions are returned at all. Besides, the model will not include all possible suppliers that Vanderlande has, only the most used suppliers. As a result, there is in reality more capacity than included in the model. To make sure the model can always find a feasible solution, an extra supplier is introduced. An extra supplier is located in every Supply Chain Center (SCC) and has a near-infinite capacity, which will therefore be referred to as the infinite supplier. This supplier will have much higher costs such that this supplier is only chosen if no other capacity is available. When interpreting the allocation decision, extra attention should therefore be paid to the items that are assigned to this infinite supplier. For these items a supplier should be found that is not included in the model or other items should be shifted.

Chapter 4

Solution Design

The previous chapter defines the model that will be used to solve the problem. This chapter describes how the allocation problem can be solved by using the predefined model. First, the characteristics of the problem and model are discussed. Based on these characteristics, multiple solution methods are considered and the best solution method is picked. After that, the chosen solution method is explained in more detail.

4.1 Problem characteristics

The characteristics of both the problem and model are important to consider in determining a good solution method. The problem is a scheduling problem with a limited resource capacity and includes a specific structure of the projects. Furthermore, multiple decisions must be made, namely where to produce and when to start production. These decisions are dependent on each other, since the location defines the transportation time and therefore limits the time range of production.

Another important factor of the problem is its size. The model will schedule multiple projects at the same time. This will probably vary between 1 and 5 projects. Every project contains 10 to 50 activities and every activity contains 1 to 50 items. This provides a wide variation up to 12.500 unique item,activity,project combinations to allocate to a supplier.

The model defines the constraints to which the planning must conform. Both the objective and the constraints are of a linear structure. The decision variables are integer values. The decision variable that decides when and where to start production defines a 'Yes' or 'No' decision, indicated by the values 1 and 0 respectively. As explained in the previous chapter, an extra variable is introduced for the underload hours to keep the model linear, which must take a positive integer value. Since both decision variables must be of type Integer, the model is defined as an Integer Linear Programming. This will be referred to as ILP throughout the rest of this chapter.

4.2 Solution methods

The problem is described by an ILP model. Several methods to solve this problem will be discussed in this section. These methods can be categorised in exact, heuristic policies and algorithms. Each method will be discussed in the following subsections.

4.2.1 Exact solution

Gurobi, an optimization solver, is used as a solver to find an exact solution to the problem. Gurobi is accessed through a Python module and gives the optimal allocation for the predefined problem. However, the applicability of Gurobi is highly dependent on the size of the problem. Obtaining the optimal solution for a large problem takes a long time or Python might even run out of memory where no solution is obtained at all. Gurobi will be applied to the largest problem size possible. However, due to the size limitations, other solution methods are explored and will be compared to the exact solution provided by Gurboi.

4.2.2 Heuristic policies

Heuristic policies are the next solution method to explore. These policies are generally fast in finding a reasonable solution. However, when increasing the complexity of the problem, the quality of the solution will decrease. This report will evaluate the First-Come First-Served (FCFS) policy and the Current method applied at Vanderlande.

In FCFS the items are sequenced according to their arrival date. In this sequence, each item is allocated to a supplier and given a start production and transportation date. This heuristic will for every item search for the cheapest supplier in terms of production and transportation. The item will be ordered according to a late finish planning; if possible this indicates that no waiting time is required. If the capacity of the supplier does not allow the allocation at that time, earlier times are checked until the arrival date is reached. If there is no option of placing the item at that supplier, the second cheapest supplier will be assigned.

The Current method applied within Vanderlande aims to fill the Vanderlande factories until at least their budget capacity. When for all factories this budget capacity is reached, the items are allocated to the default supplier. If the default supplier does not have the required capacity, a Vanderlande employee makes the allocation decision based on workload distribution.

4.2.3 Algorithms

In this section, several algorithms will be compared on several aspects to determine a suitable method for solving the allocation problem. First of all, the algorithm should search for the global optimum. The algorithm could for example temporarily accept worse solutions or take multiple solutions into account to achieve this global optimum. In addition, the problem defines two decisions to be made; the allocation decision and the start of production must be set. If the transportation decision is added at a later stadium, this increases the complexity. The algorithm must therefore be able to handle multiple decisions and the dependency between those decisions. Lastly, the large size of the problem has an impact on the running time of the solution method. A fast method is therefore preferred.

Three algorithms are compared on the aspects mentioned above, a summary can be found in Table 4.1. Even though Ant Colony Optimization (ACO) is a fast solution method aiming for a global optimum, it can only search for solutions based on one decision variable. In the original ACO, ants are searching for food and can smell where the food has passed; this way they define the shortest route. However, in this situation not only the optimal supplier must be indicated, it must also fit in the time limit and capacity of those suppliers. Particle Swarm can handle multiple variables and approaches the problem as a multidimensional space. However, in this situation the decision variables do not allow for a fully multi-dimensional space to be formed; multiple aspects of the space would be vacant. It is therefore expected that this approach does not allow the variables to be dependent on each other. The only algorithm that satisfies all four criteria is the Genetic Algorithm. The Genetic Algorithm aims to reach a global optimum, usually converges with a reasonable speed and can work with multiple dependent variables. This algorithm will therefore be discussed in more detail in the following section.

Algorithm	**Global Optimum**	**Fast Convergence**	**Multiple Variables**	**Dependent Variables**
Ant Colony	X	X		
Particle Swarm	X	X	X	
Genetic Algorithm	X	X	X	X

Table 4.1: Overview of criteria satisfied by algorithms

4.3 Genetic Algorithm

This section will describe the Genetic Algorithm that is applied to solve the problem. The Genetic Algorithm will throughout this section be referred to as GA. First the structure will be discussed. Followed by the specified application to the problem, including the steps taken in the GA. Lastly, the values for the parameters must be established to start comparing different scenarios.

4.3.1 GA representation

A GA is based on evolution theory and describes the problem solution by using the genetic structure of chromosomes. Every gene has a fixed place in a chromosome and decisions must be made for every gene. In the human chromosome, one of the genes is responsible for eye colour, decision options include, brown, blue and green. In the current scheduling problem, every gene represents an i, a, p (item,activity,project) combination and the decision option is a set of possible suppliers. An example chromosome structure can be found in Figure 4.1 below.

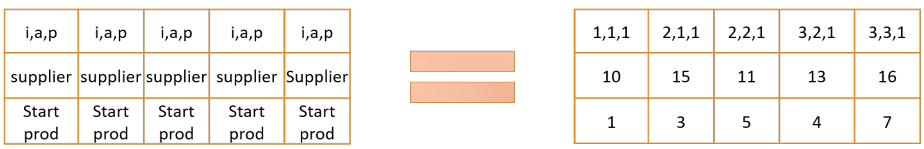


Figure 4.1: Chromosome structure for this problem

In addition to a supplier, a start time for production is assigned. This assignment follows the same structure as the supplier allocation decision. Having decided both the supplier and start time for production, the costs can be calculated. In a GA the objective (cost of an allocation decision) is referred to as the fitness; with the objective to minimise the fitness. An example of a fitness representation is presented in Figure 4.2; a chromosome in which the suppliers are depicted, with its corresponding fitness attached to it.

In this problem, one chromosome denotes one feasible allocation. Multiple chromosomes will be generated during the initialisation of the GA to form a population. A randomly generated population of feasible solutions will be the starting point of the GA.

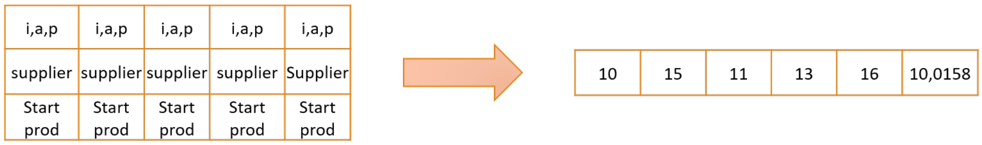


Figure 4.2: Fitness for chromosome

4.3.2 GA formulation

The steps of the genetic algorithm can be found in Algorithm 1. The input parameters required for the algorithm are shown in Table 4.2. The population indicates the number of chromosomes that will be looked at and the Generations indicate how many times the population will be revised to improve the overall fitness. The transition of going from an Old to a New population involves multiple parameters that influence the quality of the GA. Multiple values will therefore be considered in subsection 4.3.3. The output of the GA includes both the allocation of the items to a supplier and the start of production for every i, a, p combination.

Genetic Algorithm Parameters
Generations
Population
% New generation - Elitist
% New generation - Crossover
% Mutation
Prob Local search
% Random VS Mutation

Table 4.2: Parameters

Initialisation
The initial population is created by random allocation of items to suppliers and consists of two steps. Each step will be applied in a random i, a, p order.

Step 1: Allocation of supplier
For every i, a, p, a list of suppliers is indicated that satisfies the time restriction. This implies that both production and transportation fit in the time horizon between arrival date and due date. From this list, a random supplier is chosen for every i, a, p. Due to the infinite supplier that has been included in the model, the set of available suppliers consists of at least one supplier.

Step 2: Determine when to start production
In addition to the supplier allocation, the start date for production must be determined. The combination of both decisions will indicate whether the chromosome solution is fully feasible. During the start date assignment, the supplier capacity is taken into account as well. If no feasible start time can be found, a new supplier will be checked for feasibility. This step will make sure that all chromosomes in the population satisfy all constraints and therefore represent feasible solutions.

Algorithm 1: Genetic Algorithm

```
Output: Allocation s per i,a,p
Initialise population by random allocation
g = 1
while g ≤ Generations do
    Elitist selection
    Crossover
    if g < (RandomVSMutate · Generations) then
        Random generation
    else
        Mutation
    if rnd < probLocalsearch then
        Local search
    g = g + 1
```

When the initial population is designed, evolutionary methods that are part of this GA are applied. The methods applied here include Elitist selection, Crossover, Mutation and Local search. Each will be discussed in the following paragraphs. These methods will refer to the transition from the Old population to the New population.

Elitist Selection

With Elitist selection, the chromosomes of the Old population are ordered according to their fitness in ascending order. Since this problem aims to minimise the costs, the lowest fitness is preferred over a higher fitness. The Elitist selection copies a percentage of the chromosomes with the lowest fitness from the Old population to the New population. This percentage is one of the parameters (%New Generation - Elitist) of which the value must be determined. A visualisation of the Elitist selection can be found in Figure 4.3.

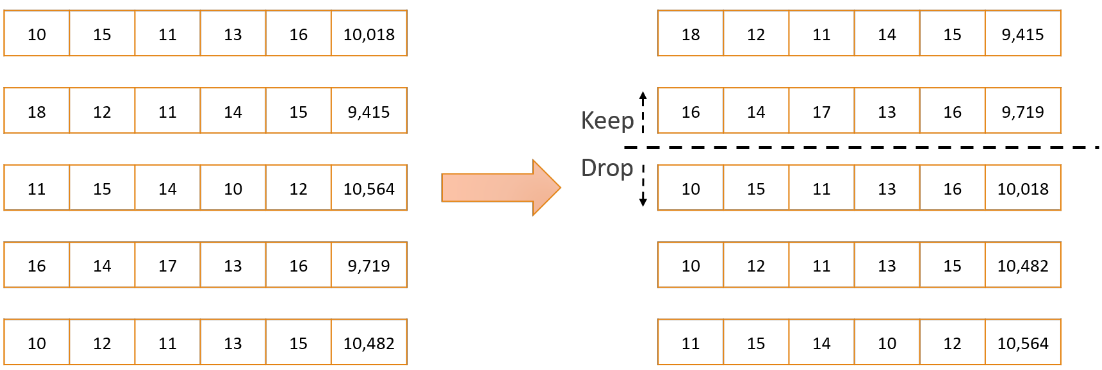


Figure 4.3: Elitist selection

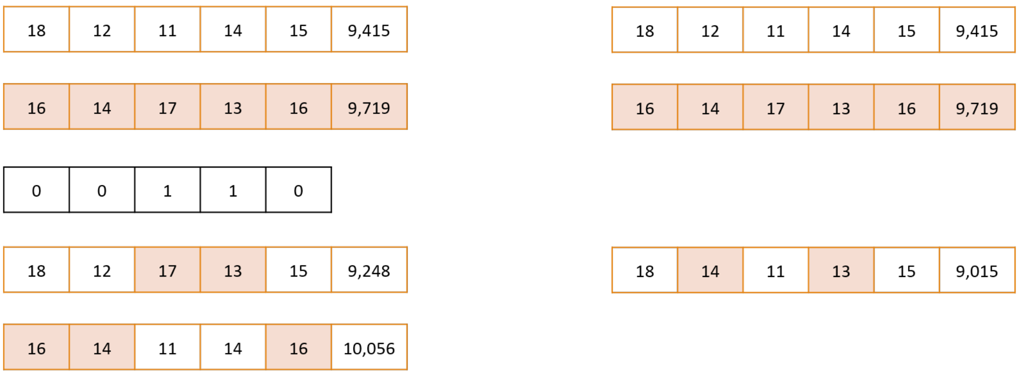
Crossover

During a crossover, two chromosomes are chosen randomly from the Old population and used to create chromosomes for the New population. In this GA, two types of crossover are used, a Random and a Guided crossover.

The Random crossover is visualised in Figure 4.4a where the first two chromosomes represent the randomly chosen chromosomes from the Old population. Below that, an array is depicted with only zeros and ones, named a mask. This mask is randomly generated, for every gene in the mask the chance of obtaining a zero or a one is 50%. Two chromosomes are created for the New population. The first chromosome takes the value of the first Old population chromosome when the mask states 0 and the value of the second Old population chromosome when the mask states 1. The second chromosome takes the opposite values. For these newly created chromosomes the feasibility is checked; if the capacity is exceed somewhere, another supplier is assigned. This obliges every created chromosome to represent a feasible solution.

The Guided crossover is visualised in Figure 4.4b and produces only one chromosome for the New population. The same two chromosomes from the Old population are visualised. In the Guided crossover, for every gene it is checked which value of the two chromosomes provides the best fitness. This value is copied to the new chromosome, if all constraints are satisfied. The genes are checked in a random order to prevent bias throughout all generations.

The percentage of crossovers that is required for the New population is again a parameter of which the value must be determined (%New Generation - Crossover). Since not all crossovers provide an improved fitness, an overload of crossover chromosomes is created. These crossovers are then selected by Elitist selection as described above. In total three times as many chromosomes are created with Crossovers than will eventually be selected; in other words, only the fittest one third of the created crossovers is selected for the New generation.



(a) Random crossover (b) Guided crossover

Figure 4.4: Two types of crossover

Mutation

During mutation, an existing chromosome of the New population is copied and modified. A mask is created similar to the mask created for the crossover method. In this case, a one decides that the gene will be modified and a zero does not change the supplier allocation. However, the zeros and ones are not evenly distributed. For the genes that are modified, the fittest alternative is chosen. The probability of modifying a gene is much smaller. This probability is one of the parameters (% Mutation) for which the value will be optimised.

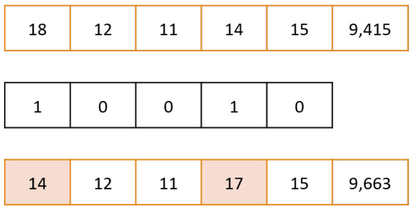


Figure 4.5: Mutation

Local Search
In local search, it is checked whether the fittest chromosome can be improved by adapting one of its genes. It takes the chromosome in the New population that has the lowest fitness (best performing chromosome) and it checks for every gene whether it can find a supplier with corresponding start time that will improve the performance. The best alternative will replace a chromosome currently in the New population. The chromosome with the highest fitness (worst performing chromosome) will be replaced by the chromosome created by local search.

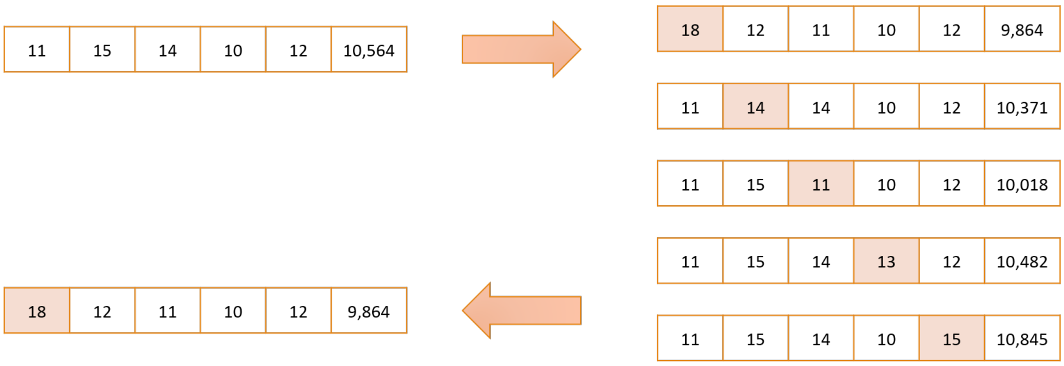


Figure 4.6: Example of local search

4.3.3 Parameter values

The performance of the algorithm is dependent on the parameters that are included. To achieve the highest performance, these parameters will be set according to a Design of Experiments (DOE). During DOE, for every parameters multiple values of a parameter are checked and influences of those parameters on the result can be established. In this design, two values will be checked for every parameter; a upper and lower bound value. These values can be found in Table 4.3 below and are based on an educated guess.

Genetic Algorithm Parameters	**Value range**
Generations	{10,100}
Population	{10,500}
% New generation - Elitist	{5,20}
% New generation - Crossover	{10,70}
% Mutation	{1,10}
Prob Local search	{0.1,0.5}
% Random VS Mutation	{40,60}

Table 4.3: Parameter values

A 2-factor factorial design with star is performed with the values as described above. The 2-factor factorial design (2^{7-1}) results in 64 runs. Additionally, a star of parameter values is created around these 2-factor values including some center points, resulting in in total 80 runs. This experimental design is created using *StatGraphics18*, which is also used for determining the final parameter values.

Figure 4.7 shows the effect of the parameter on the cost objective. The lines display from left to right, the effect of the low value and the high value respectively. The goal is to minimise the objective, which is represented by the lowest value of the line. The longer the line, the stronger the effect on the objective. For example, population has the largest influence according to the effects plot and RandomVSMutate the smallest. In addition, parameters Generations, Population and Elitist all seem to improve the objective with a higher value; whereas the other parameters seem to include a turning point.

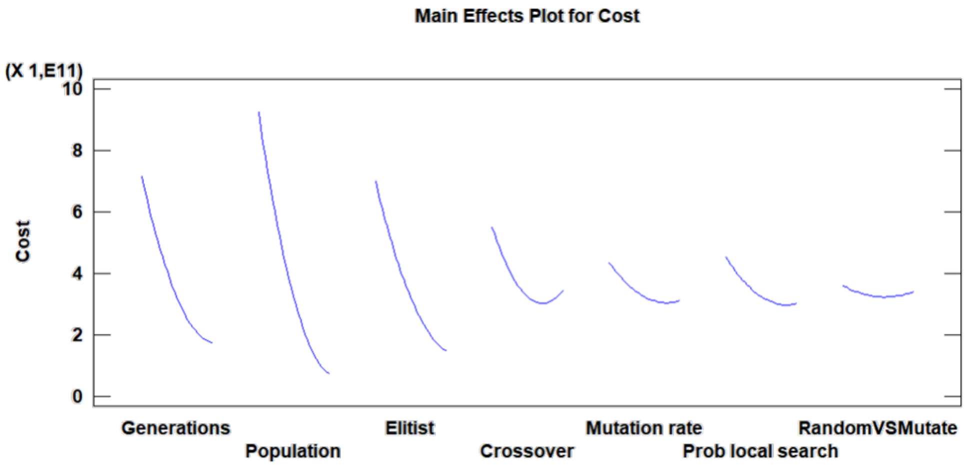


Figure 4.7: Main effects of parameters on objective

In addition to the effect of the parameters, their significance must be taken into account. Figure 4.8 shows the standardised effects of all main parameters and two-factor interactions. Where the significance limit is indicated by the blue vertical line. Only a few effects appear to have a significant effect on the objective. Of the main effects, Population, Elitist, and Generations have a significant effect. Of the 2-factor interactions, all significant values are created by these main effects.

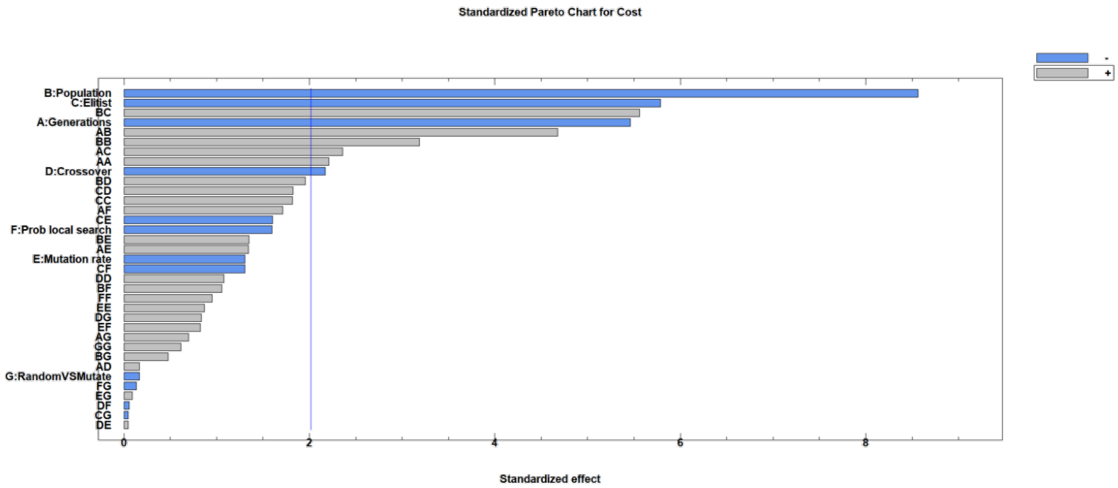


Figure 4.8: Standardized Pareto chart

With these insights the optimal parameter values can be determined. An optimization function is included in *StatGraphics18* and defines the optimized values as seen in Table 4.4. However, by observing the minimum fitness of every generation, it is concluded that it has converged several generations before the 100th generation. Therefore an extrapolation is conducted in *StatGraphics18*. These parameter values are expected to get as close as 99% to objective value o the optimized values, but takes only 25% of the time to reach this value. The values of the extrapolation are therefore taken as the final value for the further result evaluation.

Genetic Algorithm Parameters	**Value range**	**Optimised**	**Final value**
Generations	{10,100}	100	40
Population	{10,500}	500	330
% New generation - Elitist	{5,20}	5	20
% New generation - Crossover	{10,70}	70	35
% Mutation	{1,10}	1	10
Prob Local search	{0.1,0.5}	0.1	0.5
% Random VS Mutation	{40,60}	40	55

Table 4.4: Parameter values

Chapter 5

Analysis

In this chapter the quality of the Genetic Algorithm (GA) will be examined. First, the GA will be compared to the current way of allocating items to suppliers. Next, a comparison to the exact solution by Gurobi will be made. Afterwards, a sensitivity analysis is included which evaluates the GA on size, resources and capacity. In this analysis, also the FCFS policy will be included. Additionally, the details of the model's results will be examined. Lastly, some extra insights are given on the precision of the model. All results are based on one run; for one scenario, multiple runs are executed to determine the precision of the model.

5.1 GA and Current method

There are two main differences between the allocation method of the GA and the Current method. The current method allocates items only to suppliers that are located in the same geographical Supply Chain Center (SCC), whereas the GA can allocate to all suppliers as long as the lead time constraint is met. In addition, Vanderlande factories are filled up to the budget capacity before allocating to other suppliers (subcontractors) in the current method. The GA includes the budget capacity by including extra costs if the budget capacity is not reached. The impact of these main differences are dependent on each other, the total influence will therefore be discussed in this paragraph.

First, three scenarios are evaluated with projects in the three SCCs separately. When following the Current method, all items must be allocated to the same SCC as they are located. In the GA, this is not a restriction. Figure 5.1 shows the geographical regions of the suppliers per project location when using the GA. The category None indicates that no supplier is found and the item is allocated to the infinite supplier. For the GA method, the infinite supplier has fewer allocations than in the Current method. This corresponds to the expectation since the Current method restricts its supplier choice to the SCC, whereas the GA does not limit its allocation to the same SCC.

For projects in the region AsiaPacific (AP), both the Current allocation method and the GA allocate the majority of items to the AP region. When using the Current method, all items are allocated to SCC AP, however; for 20% of the items no supplier is found (None). The GA claims that only 70% of the items should be produced in AP and the remaining 30% should be allocated to Europe (EU). When looking at the region North America (NA), the GA shows a mix of SCCs, with a majority allocated to AP. This situation is expected to be similar to the Current method, since there are not enough suppliers in North America (NA) to produce all items of a medium size project. The programming for the Current method is an approximation and therefore indicates for the remaining items that no suppliers can be found (None). For projects in the region Europe, there are many suppliers available. Using the current method, there is enough capacity to allocate all items within the region. However, the GA shows that it would be more cost efficient to allocate the majority of items to a supplier in the AP region.

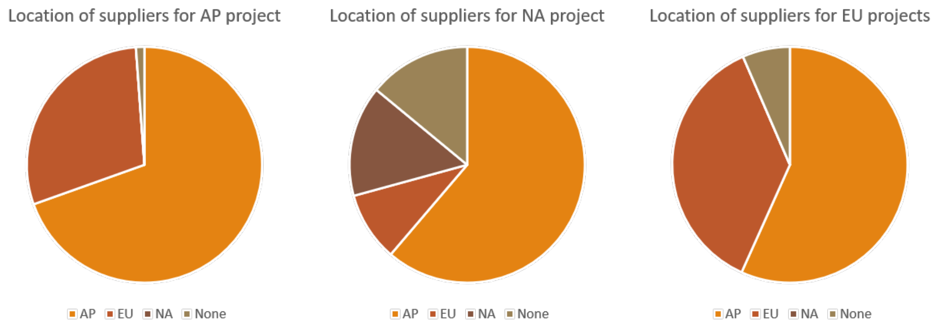


Figure 5.1: Allocation for projects per SCC with Genetic Algorithm

5.2 GA and Gurobi

Small problems can be solved by Gurobi. However, if the size of the problem increases beyond a certain point, the computer will run out of memory and Gurobi will not find a feasible solution. The smallest problem of all scenarios tested was taken and ran with Gurobi. Unfortunately, this resulted in a memory error and no solution was found. Therefore an even smaller problem was used to compare the GA to the optimal solution. This resulted in a project with 109 items. For this problem, both Gurobi and the GA were able to find the optimal solution. It is therefore expected that the GA will obtain good quality solutions for larger size problems too. For this small problem, Gurobi was much faster than the Genetic algorithm. This is due to the GA's population size and number of generations. Besides, the GA is not restricted by the problem size in obtaining a solution.

	Gurobi		Genetic Algorithm		
Scenario	**Objective**	**Runtime (sec)**	**Objective**	**Runtime (sec)**	**Gap (%)**
109 items	29.768	±36	29.768	±300	0

Table 5.1: Scenario comparison Gurobi and GA

5.3 Sensitivity Analysis

This section includes a small recap of the comparison of the methods described and used throughout the report so far. These include the Genetic Algorithm (GA), Gurobi, the Current method, and the FCFS policy. In addition, a sensitivity analysis is conducted on multiple variables used in the Genetic Algorithm. These variables include the number items to be allocated, resource hours per item and the capacity of suppliers. Lastly, the differences between the Current method and the GA will be examined in more detail.

Due to the deterministic input of the problem, also the outcome will be deterministic for three of the four solution methods described. For the Current method and the FCFS policy a fixed sequence of allocating is defined, resulting in the same allocation decision when repeated. Gurobi aims to find the optimal solution. Therefore, if Gurobi can handle the problem size, the same optimal solution will be found when repeated. The GA also aims at the global optimum; however, for larger size problems it is expected that the GA will find a near-optimal solution. Due to the random assignment and evolution to the next generation, the GA will generate different solutions with corresponding objective values with every run. The precision will be discussed later in this section.

Problem size
It is expected that the size will influence the GA, just like it influences Gurobi. Therefore, three scenarios are examined with different number of items, 517, 1.165, and 3.235. These correspond to 1, 2 and 4 projects respectively.

Scenario	**Runtime (sec)**
517 items	±6.000
1165 items	±12.000
3235 items	±39.000

Table 5.2: Runtime per scenario

Table 5.2 describes the runtime for the three scenarios with increasing size. What can be seen is that the runtime increases with the number of items. Based on the three runs, the runtime is expected to increase linearly with the number of items to be allocated. However, the local search that is included in the GA does influence the runtime of the algorithm. Local search is executed with a probability of 55% during every generation. A deviation from this probability over all generations has an impact on the runtime of a single run. Both the Current method and the FCFS policy provide a solution much faster, since the allocation decision is made only once and no iterations are made. These runtimes are therefore not included in the Table above.

Besides the runtime of the solution method, the value of the objective is compared. For all three the scenarios, the GA outperforms the Current method and the FCFS policy. Additionally, FCFS outperforms the current method too; this implies that the Current allocation method is not cost efficient, which corresponds to the expectation since the current method does not base its allocation decisions on costs, but solely on workload.

Scenario	**Genetic Algorithm**	**Current method**	**Gap (%)**	**FCFS**	**Gap (%)**
517 items	499.691.776.793	993.727.803.181	99	672.491.766.137	35
1165 items	546.022.034.961	1.544.488.077.020	183	730.372.048.891	34
3235 items	1.758.629.778.661	3.385.296.343.852	92	2.073.179.751.538	18

Table 5.3: Objective values of Allocation methods and Gap to GA for different problem sizes

Resource hours per item
Items that must be allocated each require resource hours. The number of hours required is expected to have an impact on the allocation quality. Of all the projects considered, they require on average 20 resource hours; with a standard deviation of 50 hours. The three scenarios examined are therefore categorised in low, medium and high resource hours required, indicating:

- Low resource: Hours Parts required and Hours Assembly required are less than 20.

- Medium resource: Hours Parts required and Hours Assembly required are less than 70. Additionally, either Hours Parts required or Hours Assembly required must be higher than 20.
- High resource: Hours Parts required and Hours Assembly required must be higher than 70.

When looking at the objective values in Table 5.4 below, it can be concluded that both the GA and the FCFS policy significantly outperform the Current method. For the Medium and High resource hours, the GA also performs significantly better than the FCFS policy. For the Low resource scenario, the Gap for both the Current method and the FCFS policy are significantly lower than for the other two scenarios. It is therefore expected that Low resource items can be allocated to the most cost efficient supplier more easily than high resource items.

Scenario	**Genetic Algorithm**	**Current method**	**Gap (%)**	**FCFS**	**Gap (%)**
$R \leq 20$	2.266.729.158.210	16.752.144.881.327	639	2.371.729.146.068	5
$20 \leq R \leq 70$	627.357.485.408	8.174.673.580.731	1203	829.857.497.878	32
$R \geq 70$	410.002.493.390	4.768.082.417.985	1063	513.082.371.596	25

Table 5.4: Objective values of Allocation methods and Gap to GA

Capacity size

For the capacity, the scenario of 517 items is taken and checked whether increasing or decreasing the capacity has any influence on the objective value. Compared to the original 517 items scenario, the capacity is increased to 130% and decreased to 70%. As can be seen in Table 5.5, the Current method and the FCFS policy each result in the same objective value for all scenarios. This indicates that the capacity restriction does not limit the allocation of the items. When looking at the GA, the objective value decreases 4% and increases 1% when taking a higher or lower capacity respectively. However, since the GA is based on random processes, this difference is not significant. For these scenarios it is therefore expected that there is an overcapacity and lowering the capacity to 70% therefore has no significant influence on either of the solution methods.

Scenario	**Genetic Algorithm**	**Current method**	**Gap (%)**	**FCFS**	**Gap (%)**
Capacity 130%	478.923.767.989	993.709.720.466	107	672.473.756.365	40
Capacity 100%	498.223.757.227	993.709.720.466	99	673.473.743.061	35
Capacity 70%	503.673.753.874	993.709.720.466	97	673.473.744.809	34

Table 5.5: Objective values of Allocation methods and Gap to GA

Even though an overcapacity is expected for the 517 items scenario, the gap in objective value is still significant between the solution methods. Compared to the Current method, the GA finds a value for the objective that divides the value of the Current method into two. Also, the FCFS policy results in an objective value of ±35% on top of the objective value of the GA.

Detailed comparison
There are two main differences between the Current method and the Genetic Algorithm (GA). In the Current method, the allocation decision is restricted to the SCC in which the project is located and if a Vanderlande factory is situated in that SCC, it is the preferred allocation over subcontractors. Both these restrictions are relaxed in the GA. To examine where the largest savings are achieved, an allocation method will be run. This method will be the GA with a SCC restriction. This indicates that the GA has less suppliers to choose from. Table 5.6 shows that 17 % of the savings are achieved from relaxing the Vanderlande factory preference and the remaining 78% are achieved by additionally relaxing the SCC restriction. It can therefore be concluded that this second relaxation has a larger influence on the objective.
Additionally, the infinite supplier has an influence on the objective. The cost of production at this supplier has been given a very large number. If a lot of items are allocated to this supplier, the objective will not be representative for the actual costs and savings. Therefore, an extra value is checked which includes only the production costs that are not assigned to the infinite supplier, the transportation and waiting costs. The relative values for this comparison can also be found in Table 5.6. This shows that the relative savings have indeed decreased, but that there is still a large opportunity to achieve cost savings.

Comparison	**Current method (%)**	**SCC restriction (%)**	**Genetic Algorithm (%)**
Objective	100	83	5
Actual Cost	100	85	34

Table 5.6: Relative value compared to Current method

As stated in the model, the cost objective includes four types of costs: production, transportation, waiting and underload. The underload costs account for the majority of the costs are the same for all three methods. It will therefore be left out of the following comparison. The waiting costs are negligible and for all allocation methods account for less than 1% of the costs. The interesting shift can be found between production and transportation. Table 5.7 shows that in the Current allocation method, 98% of the costs are incurred by production; whereas in the GA this is only 87%. Additionally it must be said, that the total costs represent the percentage and that the absolute costs are not the same. The absolute costs of the GA are only 34% of the absolute costs of the Current method (5.6). The increase in transportation costs can therefore be seen as insignificant compared to the savings in total cost.

Cost type	**Current method (%)**	**SCC restriction (%)**	**Genetic Algorithm (%)**
Total	100	100	100
Production	98	96	87
Transport	2	4	13
Waiting	0	0	0

Table 5.7: Cost split-up

Characteristics

To check the variability of the output of the GA, the scenario of 517 items is run 15 times. The results are summarized in the boxplot in Figure 5.2. The y-axis of the Figure shows only a 4% deviation from the median. The interquartile range box shows less than 1% deviation from the median and the whole boxplot has a maximum deviation of 1.5% from the median.

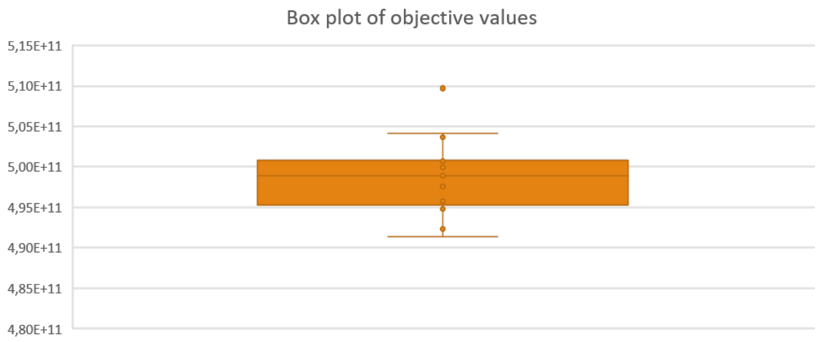


Figure 5.2: Boxplot of Objective Values

Lastly, the progress of the GA is evaluated. The objective of the algorithm improves fast in the beginning and eventually makes small improvements during every generation. Figure 5.3 visualises this progress made during the runtime (sec) of the GA.

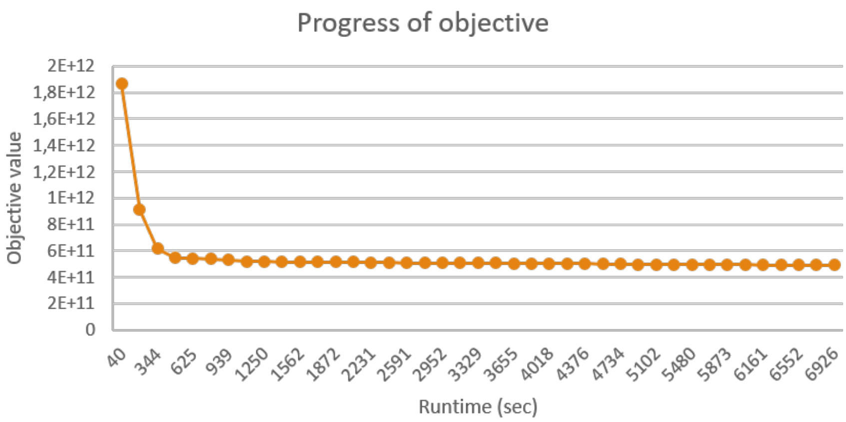


Figure 5.3: Progress of Objective over runtime

Chapter 6

Conclusions and Recommendations

The main goal of this project is to both gain insights in the current allocation costs and provide an alternative allocation method. In this chapter, section 6.1 will answer the research question. Additionally, some practical recommendations will be given for Vanderlande (6.2) and the limitations and opportunities for further research will be discussed (6.3).

6.1 Conclusion

This project models the current and desired allocation process and designs a new allocation method to answer the defined research question:

How can items be allocated to global production facilities to create a cost efficient Supply Chain Planning (SCP) in a multi-project environment?

Multiple allocation methods were explored that allocate items to suppliers; an approximation of the Current allocation method, an exact solution method, the First-Come First-Served (FCFS) policy, and a Genetic Algorithm (GA). The Current allocation method forces the allocation to occur in the same region as the customer project and allocates to Vanderlande factories if possible; both restrictions are relaxed for the other allocation methods. Only for a very small problem, Gurobi was able to obtain an exact solution. For this problem the GA also obtained the optimal solution. For larger size problems, the FCFS policy was taken as a second benchmark for the GA next to the Current method. The GA randomly allocates items to suppliers and iteratively improves the allocation quality. A design of experiments was conducted to establish the parameters used in the algorithm. The final parameter values were sub-optimal but provide a shorter runtime of the algorithm.

The results show that relaxing the restriction of allocation within the SCC of the project is a more cost-efficient method. The GA indicates that the extra transportation costs are compensated by the lower production costs. Several project sizes were examined, with a maximum of four projects (3225 items) allocated at the same time. The results show that at least a third can be saved on the objective value when using the GA compared to the Current method.

By conducting the research as described above, an answer to the research question can be formulated. It was found that the Current allocation method is not cost-efficient due to limiting the supplier options. The FCFS is an improvement to the Current allocation method, but does not outperform the GA. The GA is able to handle multiple projects and include global production facilities. For a very small problem, it was proven that the GA can find the optimal solution. Additionally, it outperforms both the Current allocation method and the FCFS policy. It is therefore expected that the GA is also able to find relatively cost efficient solutions for larger problems.

6.2 Practical recommendations

The goal of Vanderlande in this project is to both gain insight in the cost efficiency of their Current allocation method and obtain a new allocation method that is more cost efficient than the Current method. The three allocation methods described throughout the report provide for both goals. The approximation of the Current method provides the insights in the current allocation costs. The designed Genetic Algorithm (GA) provides a more cost efficient allocation method for Vanderlande compared to the Current allocation method. Besides, the cost efficiency of the First-Come First-Served (FCFS) policy is better than the Current allocation method but worse than the GA. However, it does provide quicker insights into the cheapest production regions.

The input is a crucial aspect of the model. If the input variables are not correct or up to date, the model will not give a reasonable allocation decision as output. Even though the current allocation tool already includes a lot of the input information, some extra information is required to include the cost and transportation aspects of the model. Two categories exist in the extra information required, steady and time dependent. Steady information includes the transportation times in weeks and costs and should be reviewed every few months. Time dependent input includes the capacity per supplier and the item cost per supplier. The capacity is entered per week and should therefore regularly be updated or forecast to ensure the quality of the model output. The item costs are taken from a database, which should therefore be regularly updated to allow the model to allocate items to suppliers at all.

6.3 Limitations and future research

In this report, four allocation methods are discussed (Exact solution by Gurobi, Current method, FCFS policy, and Genetic Algorithm(GA)). Gurobi was only able to solve a very small problem. For small problems it is concluded that the GA provides an optimal solution to the problem. However, for larger size problems, the remaining three methods could only be compared to each other. For future research it might be interesting to identify extra allocation methods to increase the comparison and therefore the quality of the GA.

In the model description, consolidation during transportation is proposed as an extra option to improve the model. This could be achieved by adding a separate decision to start transportation. This is currently not included due to the complexity increase of both the model and the solution design. It might be interesting for future research to design a solution method that does include this transportation decision. To achieve this, the GA could for example be rewritten to include the start transportation decision or the transportation decision could be added after obtaining the allocation and start production decision.

The model is designed to match the process at Vanderlande specifically, however; the structure at Vanderlande is quite comparable to general production processes in the Make-to-Order industry. An extra step to further generalise the model is therefore not included in this research. Only two aspects could be considered for generalisation; the i, a, p structure and the resource hour division over the production lead time. However, in the solution design the combination of an item, activity, and project is always considered as one allocation decision. The depth structure of items in an activity in a project is therefore eliminated from the problem complexity. Only when including the consolidation in transport this depth will reoccur, with only a depth of two (item in project) instead of three. For the resource hour division, generalisation was not further explored since a uniform division of the hours over the production lead time seems like a reasonable assumption. Whether these hours are split into Parts and Assembly production has no influence on the generilisability of the model.

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Appendix A

Indirect assumptions

1. Production costs include material, set-up and employee cost
2. Production time is a deterministic average
3. The planning in this model is based on z-items, not exact items
4. The planning includes first level items that are in the z-item BOM. The further component structure is not considered
5. Once a production process is started, it cannot be interrupted
6. There is no shortage of materials in production, for purchasing some extra time is already considered
7. All demand of an activity must be ordered at the same supplier
8. There are no breakdowns of machines
9. Depreciation of machines / buildings is out of scope
10. Quantity / Bulk discounts are not taken into account
11. Transportation cost include import costs
12. Transportation costs and time are estimations and considered as deterministic values
13. Only a one-way transportation is required in the transportation costs of the model. The containers can usually be re-used at the place of destination