MASTER THESIS

INTERNAL LOGISTICS TIRE PARTS AND MATERIAL HANDLING EQUIPMENT

A DISCRETE EVENT SIMULATION STUDY FOR TRANSPORT CONTROL RULES

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SUMMARY

Components for passenger car radial tires are produced and transported in batches at a tire company using tow trucks, material handling equipment (carts) and material storage equipment (reels and liners). The components are transported between machines that manufacture semi-finished tire parts, assembly machines that consume these parts and external stores that can store the parts until needed.

A discrete event simulation model is created to simulate this transport. The model is used to develop and implement transport control rules that can execute the required transport. The constructed model is able to simulate the operational production scheduling of the plant to acquire a representative demand of production orders for all machines in the system.

The created transport control rules consist of (1) routing of tire parts and empty MHE between the source machines, target machines and external stores, (2) delivery times of tire parts to the target machine, (3) Procedure to pick up empty MHE from machines and distribute it to the machines acquiring empty MHE to load and transport the tire parts, and (4) distribution of the transport tasks between a pool of tow truck drivers.

The developed model is used to verify that the implemented transport rules lead to a similar production output as the real system making them viable for real world implementation. Different system configuration of number of tow trucks and number of MHE are simulated to determine the minimum number of tow trucks and minimum number of MHE needed while simultaneously maintaining the same production output.

Using the developed control rules it is determined that 60% of the currently used tow truck drivers are needed to handle the transport workload and 35% of the MHE is needed to transport and store the tire parts. However, the found numbers of tow trucks and MHE to use cannot be directly transferred to the real system do to simplifications and assumptions implemented into the model.

It is confirmed that discrete event simulation models can be used to create working transport control rules within a complex production plant and that such a model can be used to reduce required resources such as transportation and storage equipment.

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NOMENCLATURE

Names and abbreviation commonly used within the tire company to the report to reduce miscommunication. The names and abbreviations used in the report that are not self-explanatory or have a different meaning in the context of this report are listed here.

Name	Description
PCR	Passenger Car Radial (Tire)
PIBS	Manufacturing information and execution system
MRP	Material resource planning
MHE	Material handling equipment
GT (greentire)	Fully assembled uncured tire
PA (Pre-Assembly)	Tire part consisting of innerliner joined together with a left and right sidewall part
TBM	Tire building machine, a machine that assembles tire parts into a greentire
TBMorder	Tire building machine production order to assembly a batch of Greentires
TBMplan	Production schedule for all TBMs
Processing Machine	Manufacturing or Assembly machine that perform an operation on one or more tire(parts) which creates a new tire part.
Pack	Storage container that holds a tire part (i.e. reel or liner)
MU	Movable Unit – Any object that can move through the plant such as tow trucks, tire parts and MHE.
TTD	Tow truck driver, a person that drives a tow truck throughout the factory to transport tire parts and MHE
Grouping window	Time period between an examined production order and a following production order wherein the following production order with the same material inputis placed behind the examined production order
Order window	Time period between the due date of a production order at the next processing machine and the current (planning) time in which a production order is created
KAL3 (Kalender 3)	Machine that produces all innerliner tire parts
QUADR (Quadriplex)	Machine that produces large part of the tread tire parts
TRIPL (Triplex)	Machine that produces part of the sidewall and tread tire parts
DSE	Machine that produces part of the sidewall tire parts
VPA	Machine that produces Pre-Assembly tire parts consisting of sidewall and innerliner parts.
Mxx	Tire building machine that assembles tire parts into a greentire

1 INTRODUCTION

As part of the Master's degree Mechanical Engineering with as specialization Production Management at University of Twente, I have performed a graduation assignment to improve the internal logistics of part of a production line of a global tire production company.

Have you ever wondered when you track and trace an item that you have ordered, how it is decided when, who and by what your package is transported to the next distribution center or sort center and finally to your home or office. If so, welcome to the interesting world of logistics.

Logistics is defined by the Council of Supply Chain Management Professionals (CSCMP) as "Logistics is … planning, implementing and controlling the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements". [1]

The customer requirements in the case of tire manufacturing are the timely supply of tire parts to manufacturing machines to achieve the highest possible tire production with the least conversion costs. The costs are influenced by the number of tow truck drivers (TTDs) transporting the goods; the amount of Material handling Equipment (MHE) used for transportation and storage of these tire parts and the amount of factory floor space required for storage.

The production process and production planning determine the production demand, which, in turn, determines the transport and storage demand. The storage and transport demand is managed by a transport execution system.

The goal of the research is to investigate in what ways the transport system at the tire company should be modified to better meet the customer requirements.

The first step to improve the transport system is to understand how the transport system works. The transport system is part of the complete manufacturing process. To understand the transport system, one must first understand the production process. It is the production process together with the production planning, that determines the required transport of tire parts. This transport demand determines which transport system is most suitable.

The production process, production planning and current transport system are discussed in the next sections to provide a clear picture of everything influencing the internal logistics at the investigated tire manufacturing plant.

1.1 TIRE MANUFACTURING

The tire manufacturing process is explained in relation to the components that make up a passenger car radial tire (PCR). First the tire structure is discussed. The second part gives an overview of the main manufacturing processes.

1.1.1 TIRE STRUCTURE

A passenger car radial tire consists of at least ten components. The tire structure is shown in ***FIGURE*** 1**.**

Figure 1 – PCR tire structure

- **Innerliner (11) -** The most inner part is the innerliner. Innerliner is a calendered sheet of rubber used to make the tire airtight.
- **Body Ply (8) –** Body plies are the main part of the tire. They consist of one or more layers of rubbered fabric sheet, such as polyester, nylon or wire thread.
- **Steel Belt (5) –** PCR tires consist of two layers of steel belts made out of rubbered steel wires that reinforces the tire treads.
- **Tread (1) –** The outer most layer of the tire is the Tread. This part is in direct contact with the road surface.
- **Sidewall (3) –** Each tire has a right and left sidewall that protects the body plies.
- **Bead (10) –** Beads consist of a bundle of steel wires and an apex that are rubbered. The bead keeps the tire on the rim. [2] [3] [4]

1.1.2 THE MANUFACTURING PROCESS

Tire manufacturing process starts with the raw materials and ends with a quality PCR tire. In between there are five major steps as is presented in ***FIGURE 2***.

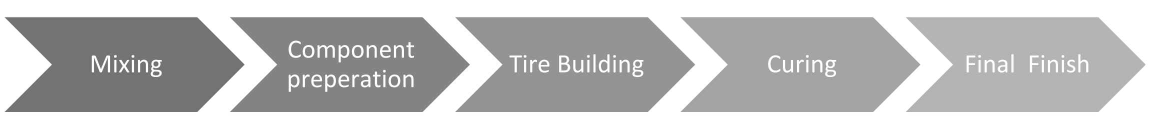


Figure 2 Overview Manufacturing Process

MIXING

In the mixing department natural or synthetic rubbers are mixed with carbon black, adhesives and other chemicals in multiple steps into a master-mix and final mix. The final-mix are rubbers ready for further processing.

COMPONENT PREPARATION

In the Front Factory all tire parts are manufactured that are needed to assemble a PCR tire. In ***FIGURE 3*** an overview is presented of the manufacturing processes of the different tire components.

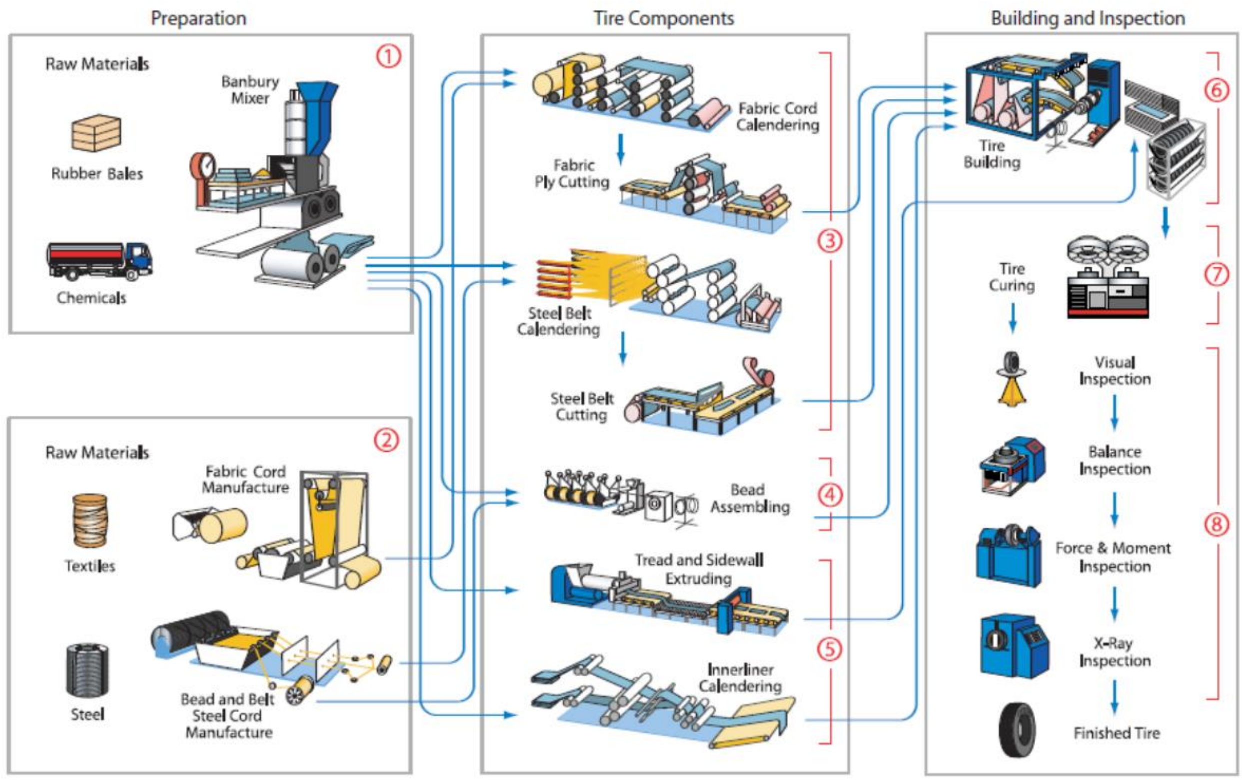


Figure 3 - Overview Production Processes

CALENDERING

Calendering is a process that creates a continuous thin rubber sheet. In between two layers of rubber, a material might be placed, usually steel or fabric to get the desired material properties. There are two calenders at the plant. Kalander 3 (KAL3) manufactures innerliner. Kalander 4 (KAL4) manufactures mother sheets of body plies and steel belts. Callendered material is rolled up in liner. Full liners are placed in carts and wait for further processing. ***FIGURE 4*** shows the MHE used for innerliner tire parts.

Figure 4(a) – Empty liner before production

Figure 4(b) – loaded liner placed on cart after production

Figure 4 - Production on Kalander 3

CUTTING

The body plies and steel belts created on KAL4 need to be cut at the right angle and with the correct width and welded together. BIAS6 is used to cut body plie sheets for the PCR production line. Fisher cutters 1 & 2 (VSC1 and FC2) are used to cut and weld steel belt sheets.

EXTRUSION

In an extruder rubber compound is pushed through a performer and die such that a long sheet of rubber is created in a predefined shape. There are three extruders. The Quadriplex (QUADR) which can extrude up to four different rubber compounds to create treads. The Triplex (TRIPL) can extrude up to three compounds and can be used to manufacture either treads or sidewalls. The Dual Sidewall Extruder (DSE) can extrude up to two different compounds and is mainly used to produce sidewalls for PCR tires. A Steel reel and liner are placed in the machine. The liner together with the rubber compound are rolled up in a reel. Full packs are loaded on a cart. ***FIGURE 5*** shows the different MHE at various extruders.

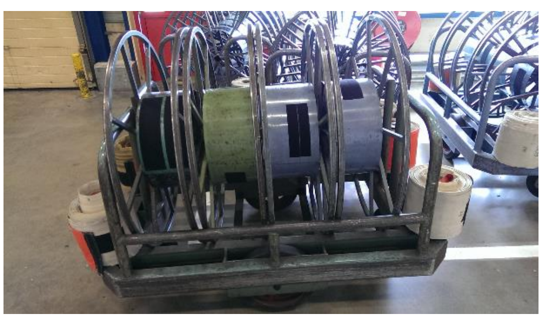


Figure 5a – Empty cart arriving at Quadriplex

Figure 5b – Empty reels waiting to be inserted in Triplex

Figure 5c – Empty liners waiting to be inserted in Quadriplex

Figure 5d – Full Cart with packs tread

Figure 5 - Cart, reels, and liners at Extruder

Bead Making

Beads are manufactured by arranging multiple steel wires in a predefined grid; rubbering the wires and bending the wires in a circle. In addition, small or wide bead filler strips are formed and stuck to the rubbered steel wires. There are four bead making lines where two are used to produce beads with small filler strips and two are used to produce beads with wide bead filler strips.

Pre-Assembly

Pre-Assembly machines (VPA) join innerliner and the left and right sidewall together and roll the pre Assembly (PA) in a liner permanently attached to a Pre-Assembly cart (Cpa). There are two similar Pre-Assembly machines named VPA800 and VPA900. Both machines are identical. Figure 6 shows a fully loaded Pre-Assembly cart. Observe the left and right sidewall on the edges and the innerliner in the middle joined together.

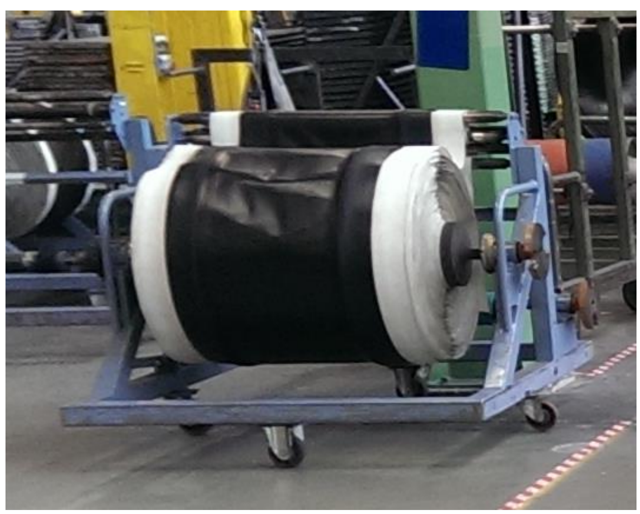


Figure 6 - Fully loaded Pre-Assembly cart

TIRE BUILDING

During Tire Building (TB) the previously described components are assembled together to create a greentire (GT), a fully assembled but uncured tire.

TIRE-ASSEMBLY

When all tire components are created they are assembled in to a greentire. All Components are placed in a Tire Assembly Machine named Tire Building machines (TBM) and pressed together to form a GT. There are 15 PCR Tire Building Machines (TBM) made up of three types. Six Full Automatic Tire Manufacturing Machines (APBM) and two Semi-Automatic Tire Building Machines (MAXX) which both do not need Pre-Assembly. Seven Semi-Automatic Tire Building Machines (HAPBM) do need Pre-Assembly. The APBM are mainly used to assemble high volume smaller inch size greentires. The HAPBM are mainly used to assemble medium sized greentires and the MAXX are used to assemble high-end and large (>18") greentires.

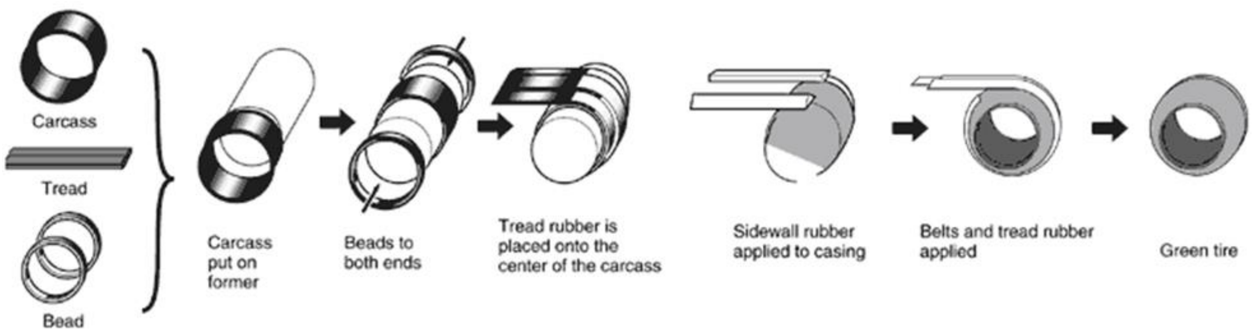


Figure 7 - Tire Assembly process [5]

Greentires are loaded on racks that carry up to 40 greentires. Automated guided vehicles (AGV) transport the racks to store or curing.

CURING

During curing the greentire is pressed in a mould and heated for several minutes until the tire is fully cured and has is given his final shape. There are 90 presses. Each press has two cavities. Each cavity can cure a different specification of PCR tire. 180 different PCR tires can be in production simultaneously.

FINAL FINISH

At the final finish the tires are checked visually and with automated inspection machines to detect defects on the final products.

1.1.3 OVERVIEW TIRE PART TYPES

Four different tire part types are defined to separate the tire parts in different groups throughout the research for which the transport workload will be optimizes. The groups are presented in ***TABLE 1***.

Tire Part Type	Description
Tread	The tread of a tire as described in ***1.1.1***
Sidewall	The left and right sidewall of a tire as described in ***1.1.1***
Innerliner	The innerliner of a tire as described in ***1.1.1***
PA	The joined assembly of innerliner and the left and right sidewall
GT	The fully assembled uncured tire

Table 1 - Tire part types

1.2 PRODUCTION PLANNING

The Manufacturing process is controlled and regulated by a logistic control system called: Production Information and Operating System (PIBS). There is 24/7 production divided in three eight hour shifts each day. Before each shift the entire production plant is rescheduled; production orders are created. A production order (PO) is an electronic card which states the type of part and how many parts are to be created. All created production orders are assigned and pushed to a preference machine which will manufacture the parts. Production orders give order to create tire parts needed for between 200 and 400 GT.

FIGURE 8 gives an overview of the Production planning. The orange parts is the part within the scope of the assignment.

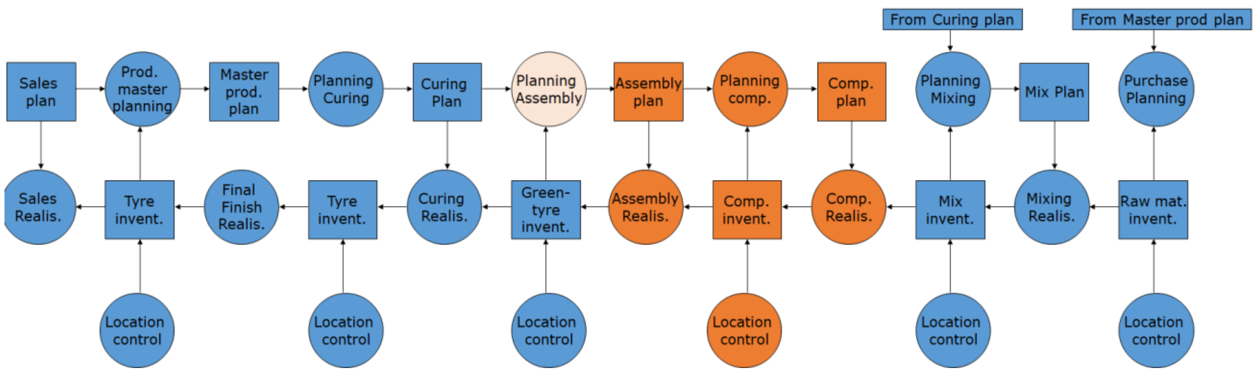


Figure 8 – Overview Production planning

The Master Production plan is determined based on the sales demand and tire inventory. The curing planning, assembly planning and component planning are discussed next in more detail because these determine the production schedule and therefore the material flow demand.

1.2.1 THE CURING PLAN

The production planning starts with the market demand and the current inventory of stock keeping units (SKUs). Using these inputs combined with mould and press availability a curing plan is created which is fixed for two weeks in advance. The curing plan is a production schedule, which states how many tires of a tire specification are produced on each press during each shift. The company has the ability to produce up to 700 different PCR tire specifications in any given year. Given the limited storage space of 17,500 greentires and production capacity of the machines down the production line, not more than 130 different Greentire specifications are cured during a single shift in an attempt to reduce the production mix and therefore the work in progress (WIP). A SKU is planned to produce continuously for 11 days. After that each 11 days there is an inspection moment where it can be decided to change SKUs or clean the mould or continue production.

FIGURE 9 gives an example of the curing plan as it can be observed in PIBS. The following information is presented:

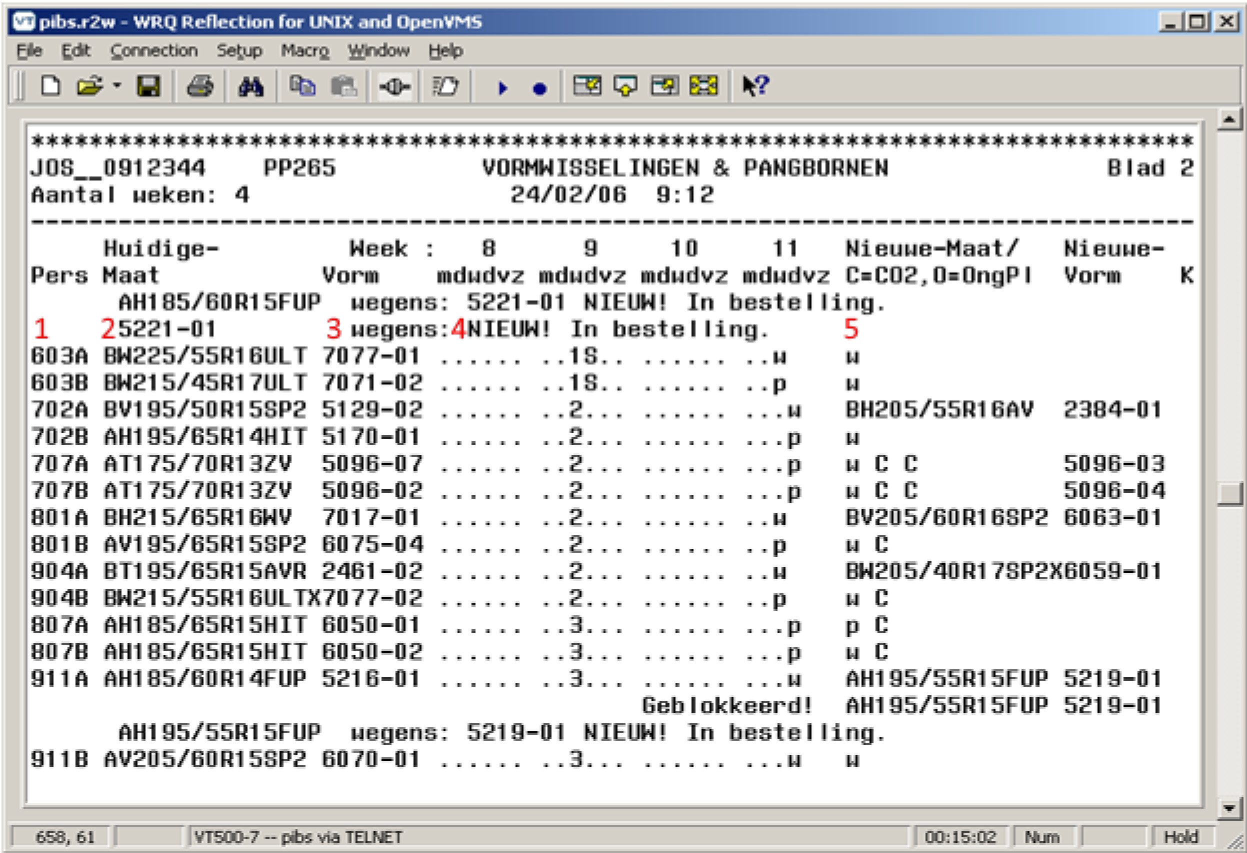


Figure 9 – Example Presentation curing plan in PIBS

1. The press in question
2. The SKU currently cured
3. The mould type required
4. Time window which lists special action if required on a given day, e.g. cleaning (S) or SKU change (W)
5. The next SKU produced on the press if a change occurs in the presented time window

Observe that from the fourteen moulds, five moulds will change products during the two week interval.

1.2.2 THE TIRE BUILDING PLAN

From the curing plan and the current Greentire stock a tire assembly schedule (TBMplan) is created. A TBMplan is a production schedule for each TBM. Before the start of each shift the TBMs are rescheduled based on the current greentire stock and curing demand. First new production orders for the TBMs (TBMorders) are created. A TBMorder consists of an order number, specific tire part, building machine, order size and due date. When a TBMorder is created and how the due date and order size are determined, is shown in ***FIGURE 10***.

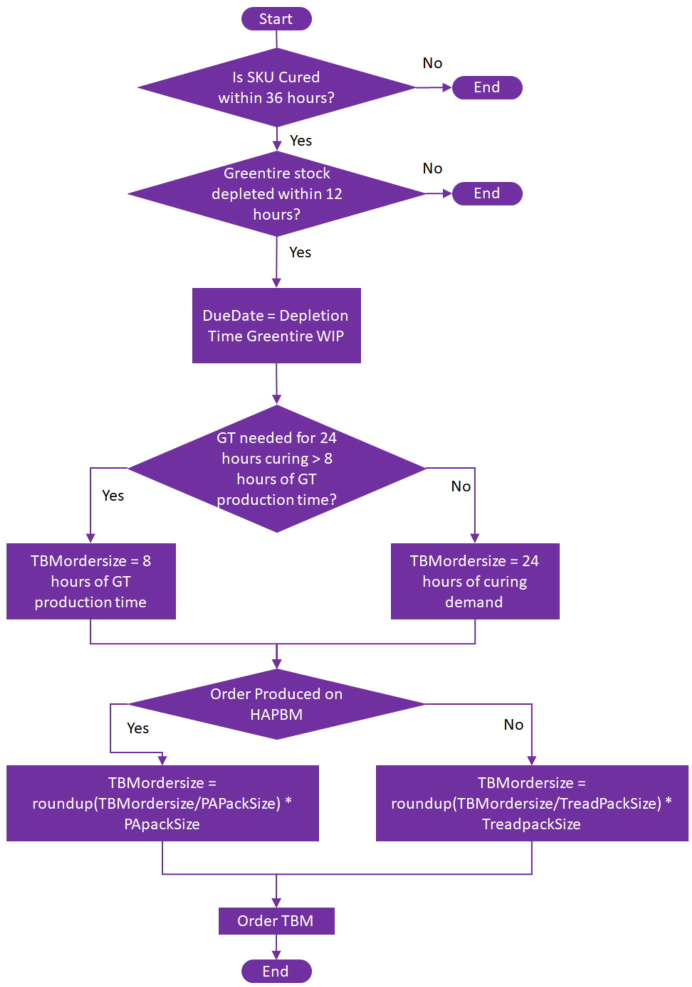


Figure 10 – Generation of TBMorder for all SKUs each shift

TBMORDER DUE DATE

In order to reduce the work in progress (WIP) the TBMorders are planned to start production just in time before the Greentire is scheduled to be needed in the press to be cured. In practice TBMorders are produced whenever a TBM is available unless there are no racks to store and transport the greentires on with AGVs.

TBMORDER SIZE

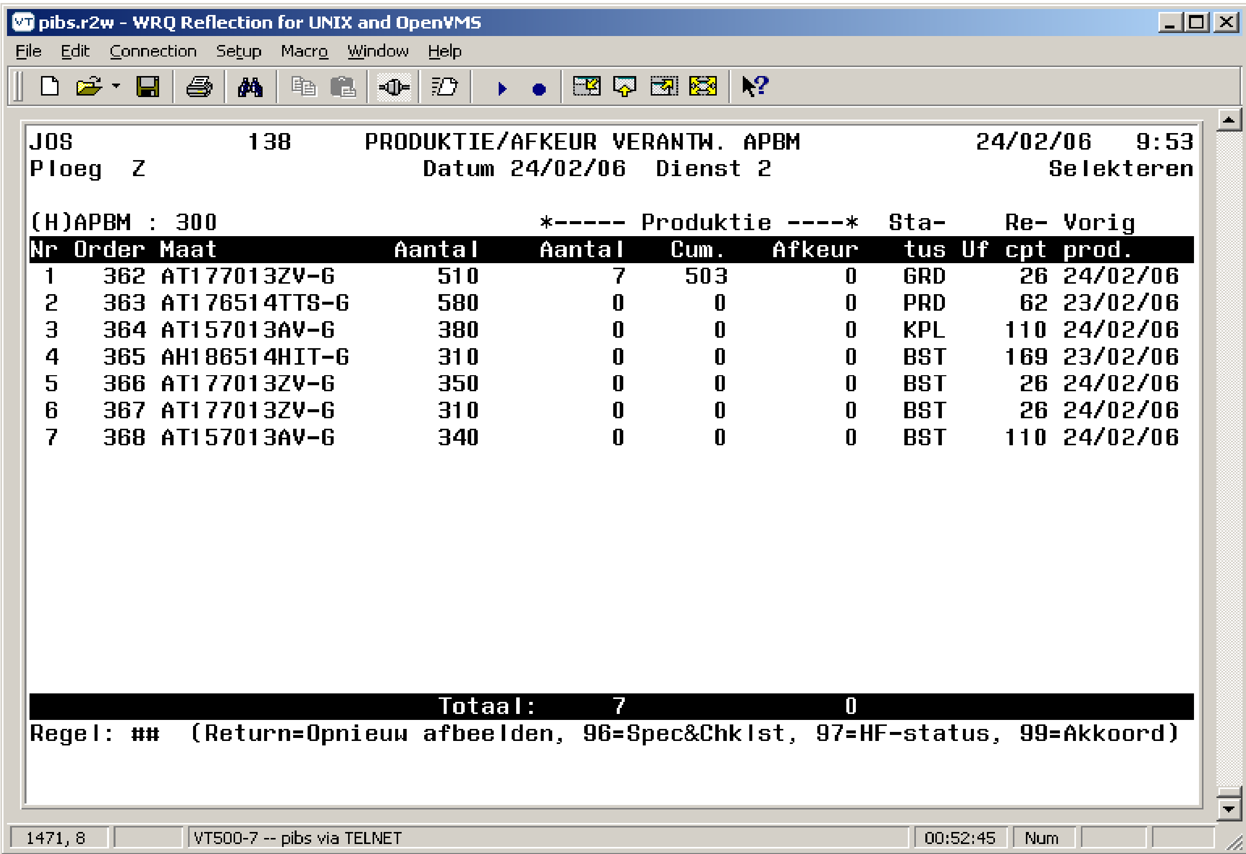
As shown in ***FIGURE 10*** the TBM order size depends on the TBM type it is assigned. If a TBMorder is manufactured on a HAPBM, The order size is increased to the nearest number of complete PA packs. For all other TBMs the order size is increased to the nearest number of complete number of Tread Packs See

1.2.3 for more information on why components are created in complete packs. See ***1.2.4*** for why PA packs and Tread packs determine the TBM order size.

TBMORDER SEQUENCING

The TBM to which to assign a TBMorder is based on the capacity to produce a tire on a specific machine (e.g. inch size, unique tire parts such as inserts); the availability of the relevant machines, the predetermined machine preference of a greentire and the inch size, in order to reduce changeovers. All TBMorders for a TBM are sequenced on ascending due date.

FIGURE 11 Shows the TBMplan for TBM 300 with (1) the order sequence (2) the order number, (3) the order size, (4) the status of the order: GRD = completed, PRD = in production, KPL = all input materials are present at the machine, BST = all input materials are ordered.



Nr	Order	Maat	Aantal	Produktie Aantal	Produktie Cum.	Produktie Afkeur	Status	Uf	Re-cpt	Vorig prod.
1	362	AT177013ZV-G	510	7	503	0	GRD		26	24/02/06
2	363	AT176514TTS-G	580	0	0	0	PRD		62	23/02/06
3	364	AT157013AV-G	380	0	0	0	KPL		110	24/02/06
4	365	AH186514HIT-G	310	0	0	0	BST		169	23/02/06
5	366	AT177013ZV-G	350	0	0	0	BST		26	24/02/06
6	367	AT177013ZV-G	310	0	0	0	BST		26	24/02/06
7	368	AT157013AV-G	340	0	0	0	BST		110	24/02/06
		Totaal:		7		0				

Figure 11 – Example Production Schedule TBM presented in PIBS

In the example the tire building machine M300 has completed order 362 manufacturing seven tires less than scheduled. It is currently starting production on PO 363. Has all input materials for the next PO and has tire parts are ordered for the next four POs after that.

1.2.3 THE COMPONENT BUILDING PLAN

Tire parts of type tread, sidewall, innerliner and PA needed to complete TBMorders are called CBMorders The tire parts and amount of tire part needed to build a single greentire are retrieved from the bill of materials (BOM). If a CBMorder is created and what its properties are, is determined by the planned start time of his parent TBMorder; the time frame, order window in which a specific tire part type is ordered for a specific TBM type and the amount of available unassigned tire parts. How these are related is captured in ***FIGURE 12***.

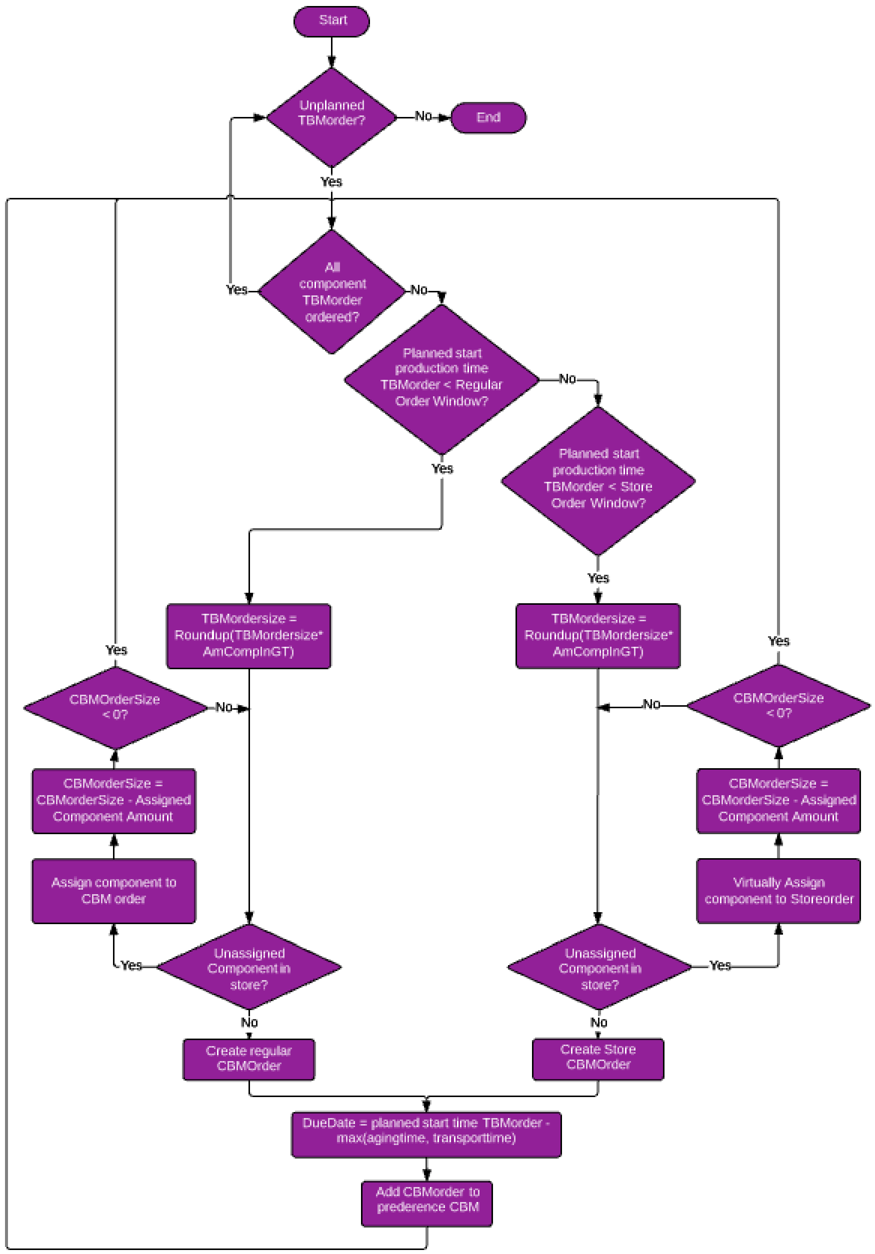


Figure 12 - CBM ordering diagram for all TBM orders

STOCK ORDERS AND ORDER WINDOW

There are two types of CBMOrders regular CBMorders and StockOrders. Regular CBMorders are created for all TBMorders planned to start production up to 22 hours. The cross-over time between regular production orders and to stock production orders is dependent on the machine type. See ***TABLE 2*** for the order windows per TBM type and tire part type. StockOrders are created for treads and sidewalls for all

TBM orders that are planned to start production within 32 hours. StockOrders are used to reduce the number of input material changeovers and therefore increase the production run time of the Extruders.

Tire part packs manufactured as regular CBMorder are permanently assigned to a TBMorder. This means they may not be used in any other TBMorder. Tire parts manufactured as part of a StockOrders are virtually assigned to a TBMorder. This means that they are intended to be used in a specific TBMorder but can be assigned to another TBMorder when a regular CBMorder is created.

Machine Type	TBM	Tire Part Types	Order Type	Order Window (hrs)
APBM	200, 300, 400, 500, 600, 700	Innerliner, PA, Tread, Sidewall	Order	0 - 22
		Tread, Sidewall	StoreOrder	22 - 32
MAXX	98, 102	Innerliner, PA, Tread, Sidewall	Order	0 - 22
		Tread, Sidewall	StoreOrder	22 - 32
HAPBM	82, 84, 86, 88, 92, 94, 96	Innerliner, PA, Tread, Sidewall	Order	0 - 18
		Tread, Sidewall	StoreOrder	18 - 32

Table 2 - Component Order windows

CBMorders are created a limited time in advance so that changes in the TBMplan do not lead to excessive WIP. The time window for HAPBM is smaller because in general TBMorders produced on HAPBM have smaller order sizes and take less time to manufacture. There are already enough production orders created for these machines.

CBMORDER SIZE

The order size of a component is determined in number of packs of tire parts (see ***1.3.1*** for definition and properties of the pack size for all tire parts) by the following relation:

$$Ordersize = roundup\left(\frac{TBMorderSize * \; AmTirePartInParent \; - assigned \; tire \; part \; amount}{PackSize}\right)$$

- Ordersize **-** Number of complete tire part packs for which an order will be created.
- TBMorderSize – Number of greentires planned to be assembled in a TBMorder.
- AmTirePartInParent – The number of meters of tire part that go in the parent part, in this case a greentire, specified in the BOM.
- PackSize – The capacity of a tire part pack.
- Assigned tire part amount – Sum of amount of tire part in all tire part packs assigned to CBMorder.

The order size is always a complete number of packs of tire parts. Producing only full tire part packs is done for several reasons. PIBS can, in large part, only deal with integer amounts. Changeover MHE in a machine takes a certain time, if packs are not fully loaded and there is a continuous manufacturing process, the available time to change the full MHE with the Empty MHE can be too short. Machine operators are often responsible for multiple tasks and not only to change MHE at the output location of the machine. In addition, fully loading each tire part pack increases the fill rate, which can have a positive influence on logistics.

CBMORDER DUE DATE

The due date of a CBMorder is determined by the current time; the planned start time of the parent order; the aging time of the tire part and the planned transportation time. The aging time is the time a tire part needs to wait after it is produced before it may be used in the next production process. Rubber compounds are heated during manufacturing and need to cool down and settle in order to reduce stickiness and deformation. It is determined that after the aging time the tire part can be used in the next production step without problems. The planned transport time is used as a placeholder for the actual transport time and as a safety factor for any production delay at components preparation. In ***TABLE 3*** – Aging and planned transport time per tire part type the aging and planned transport times are presented for all tire part types.

Tire part type	Aging time [h]	Planned transport time [h]
Tread	4	2
PA	4	2
Sidewall	4	2
Innerliner (for PA)	4	2
innerliner (for TBM)	0	2

Table 3 – Aging and planned transport time per tire part type [6]

The due date used for scheduling the CBMorders is determined by the relation:

$$Due\ date = Planned\ Start\ Parent\ Order - \max(\ AgingTime, PlannedTransportTime)$$

A tire part may be transported while it is aging. The longest of the two times therefore determines the due date.

MACHINE PREFERENCE

Some tire parts are manufactured on multiple machines. Each machine on which a tire part is manufactured has a preference number. During the planning process CBMorders are automatically assigned to the preference machine. The shift planner may manually change the manufacturing machine of a specific CBMorder to improve the planning. The planner may also change the preference order for each tire parts so that in the future the tire part is automatically planned on a different CBM.

CBMORDER SEQUENCING

Once all component orders are generated with the correct due date and order size the component building machines (CBM) are scheduled.

The component orders are scheduled based on the due date of the CBMorder. The CBMorder with the earliest due date is scheduled first and so on until all orders are scheduled.

The CBMorders for KAL3, QUADR, TRIPL and DSE are grouped together based on the material inputs needed for each CBMorder. All these machines have large input changeover times due to the nature of the manufacturing process. The number of changeovers is reduced by grouping orders with the same material input together within a time window. The grouping windows for the different machines are presented in ***TABLE 4***

Machine	Input Group Window (hours)

QUADR	20
TRIPL	20
DSE	20
KAL3	8

Table 4 - Order Input grouping windows per machine

For example, all CBMorders scheduled on the Quadriplex that have a due date within 20 hours of the CBMorder that is observed and have the same input as the CBMorder observed, are placed in sequence directly after the observed CBMorder. Figure 13 shows an example of a sequenced calender. Column 1 shows the inputs (two rubber compounds). Column 2 shows the Duedate of the CBMorder

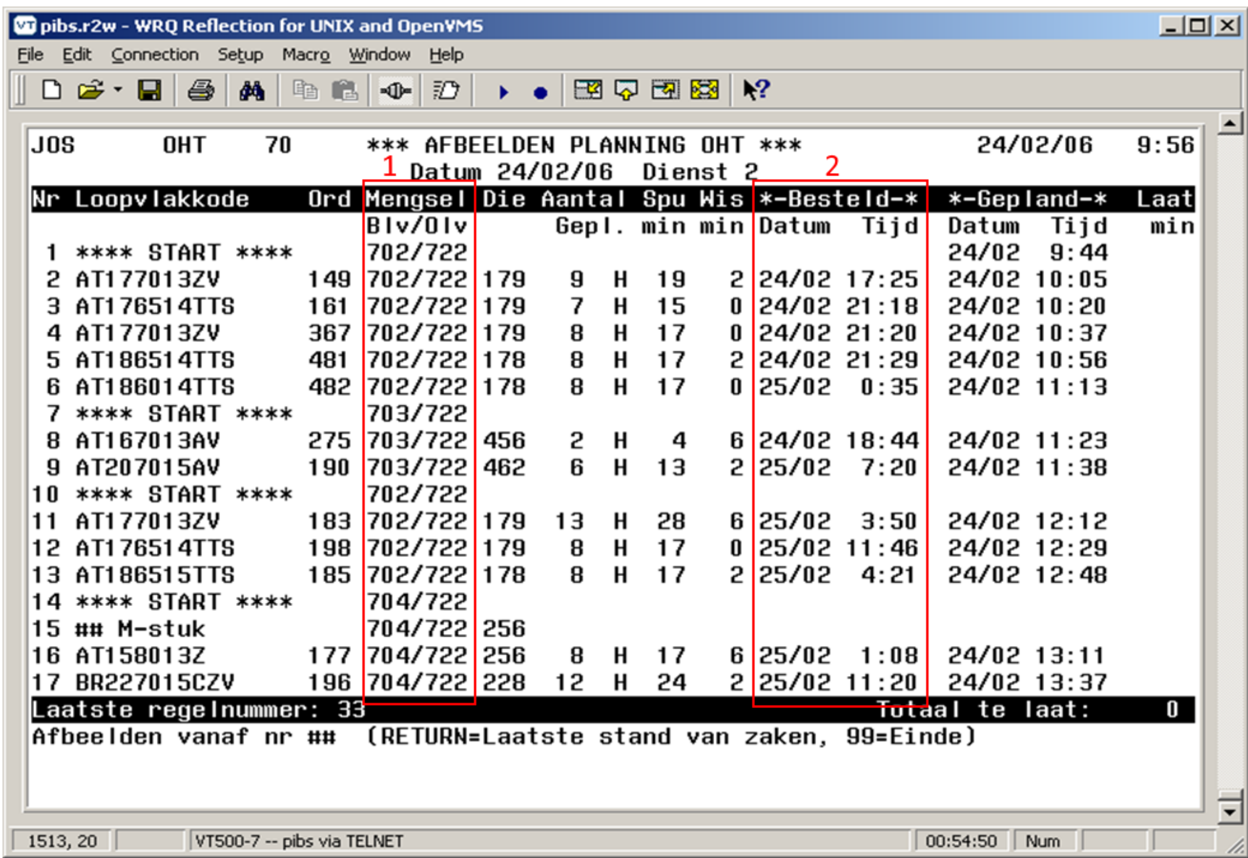


Figure 13 - Example CBMorders grouped together based on Input

It is clear there are some orders that have a later due date that are scheduled to be manufactured before orders that have an earlier due date because they have the same materials inputs as a CBMorder that is produced earlier.

1.2.4 LEFTOVERS

All tire parts are currently ordered and produced in integer amounts of packs. Unfortunately, the capacity of most MHE is different in terms of amount of tire parts per pack. This leads to leftover tire parts at tire building. Unfortunately there are many combinations of tire parts that create a greentire. The amount of tire part that goes into a greentire may vary as well as pack capacities of MHE, which in some cases are dependent on the part type. The TBMordersizes also vary. All these different combinations lead to different amounts of leftover tire parts. This phenomenon is demonstrated by two examples, a TBMorder on the M98 (MAXX) and on a M82 (HAPBM)

EXAMPLE PRODUCTION TBMORDER ON M98

A TBMorder consisting of 256 greentires of type CH216516WXS-G is produced on M98. The tire parts in ***TABLE 5*** – Example tire Parts for TBMorder are ordered, assigned and produced.

TirePart	PartType	ParentPart	AmIn Parent	PackType	Pack Capacity	PackOrder Size	Leftovers
L75Z	Sidewall	CH216516WXS-G	1,212 m	HSZKB	85 m	4 pcs	29,08 m (24 pcs)
LV398	Tread	CH216516WXS-G	2,049 m	HSP75	75 m	7 pcs	-
F435	Innerliner	CH216516WXS-G	1,212 m	LN150	150 m	3 pcs	139,38 m (115 pcs)

Table 5 – Example tire Parts for TBMorder on M98

The TBMOrderSize is ceiled to an integer amount of tread packs, therefore no tread is leftover. Because sidewall and innerliner are also ordered in an integer amount of Packs, there is material leftover. This material needs to be reported, measured, picked up, stored, assigned and discounted in a future order and moved to the TBM where the next order is manufactured (see ***TRANSPORT LEFTOVER TIRE PARTS*** for a detailed description of transport and handling of leftovers).

EXAMPLE PRODUCING TBMORDER ON M82

A TBMorder consisting of 330 greentires of type BR236516CMW-G is produced on M82, The tire parts manufactured for this order are found in ***TABLE 5.*** Note that innerliner and sidewall are first assembled in PA. PA and tread are then assembled into a greentire.

TirePart	PartType	ParentPart	AmIn Parent	Pack Type	Pack Capacity	PackOrder Size	Leftovers
LV123	Tread	BR236516CMW-G	2,121 m	HSPBR	58 m	13	53,02 m (25 pcs)
PA98AM490-840	PA	BR236516CMW-G	1,212 m	LN080	80 m	5	-
M490	Innerliner	PA98AM490-840	1,212 m	LN090	90 m	5	50 m (41 pcs)
L98A	Sidewall	PA98AM490-841	1,212 m	HSZKB	85 m	5	25 m (20 pcs)

Table 6 – Example Tire Parts for TBMorder on M82

The TBMorderSize is based on an integer amount of PA packs, therefore no PA is leftover. Although the amount of innerliner and sidewall that go in to the greentire are equal to the amount of PA that makes up a greentire, the pack size of the innerliner and Sidewall are not equal to the pack size of PA. Innerliner and sidewall material created at the production of PA. In this case there is also leftover tread, since HAPBM orders are rounded up to an integer amount of packs PA.

Dependent on the tire building machine, tread, sidewalls and innerliner components can be leftover. These leftover parts must be transported, stored and processed in new POs.

1.3 THE TRANSPORT SYSTEM

Five tow truck drivers (TTDs) currently manage and execute the transport of tire parts and (empty) MHE. TTDs are responsible for several tasks. An overview of all the tasks make up ***TABLE 7***.

Transport task
Timely delivery of all tire parts assigned to TBMorders at the right machine
Timely removal of all produced tire parts from CBM and placement in store or TBM
Timely removal and inventory update leftover tire parts from TBMs and placement in Store
Timely supply of the correct type of MHE at CBMs
Timely removal of Empty MHE from TBM

Table 7 - Transport tasks tow truck drivers

To accomplish these tasks there is a transport module within PIBS that automatically creates transport orders for some of the transport tasks. PIBS can track and trace the location of all tire part packs. Unfortunately, it does not track and trace (empty) MHE. How the transport system works is better understood if one has a clear picture of the MHE and the (type of) storage locations. Therefore, these are reviewed first.

1.3.1 MATERIAL HANDLING EQUIPMENT

MHE stores and transports materials throughout the factory. If there is no MHE present production cannot take place. MHE is separated in two groups: packs and carts. Carts have the ability to be transported by tow trucks. Packs can only be placed in specific carts and specific storage locations. Packs can thus only be moved on a cart.

Packs are further separated in two types reels and liners. ***FIGURE 14*** shows varies combinations of MHE and storage locations throughout the plant.

Figure 14a – Empty Reels in Pack store at TRIPL

Figure 14b Empty liners in pack store at QUADR

Figure 14c – Treads stored on HSP75 (reel) and LNHSP75 (liner) on CTREAD (cart) in LOLOS

Figure 14d – Empty LN150 (liner) on CINNER (cart) at KAL3

Figure 14e – Empty HSP90 on CSIDE (cart) with HSP90 (reel)

Figure 14f – Empty LNHSP90 on CSIDELNL at external store

Figure 14 - examples MHE throughout factory

Treads and sidewall use reels and liners and Innerliner and PA only use liner as packs. It is important to note that empty sidewall liners may not be transported on an empty sidewall cart (***FIGURE 14E)***. Instead, Liners are placed on sidewall liner carts for transport. (***FIGURE 14F)***.

Each tire part has a specified cart, liner and/or reel it must be transported on. The capacity per pack may vary dependent on the tire part it holds. An complete overview of all MHE; MHE combinations possible, capacity (ranges) is presented in ***0***.

FIGURE 15 presents al possible configurations of tire parts, carts and packs. Tire parts are always placed in liners. These liners are placed in reels if necessary. The reel or liner is placed on the cart. There can be 3-6 packs placed on one cart.

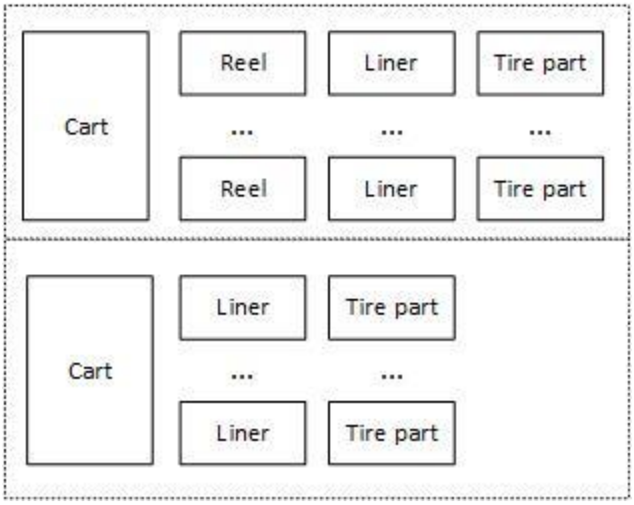


Figure 15 - Possible pack - cart - tire part configurations

1.3.2 LOCATIONS

There are two main location types, machines and external stores. At a machine location tire parts are created or assembled. At external stores tire parts wait until they are required by a machine. At these main locations, sub-locations are defined (see ***FIGURE 16*** for a schematic representation of the locations).

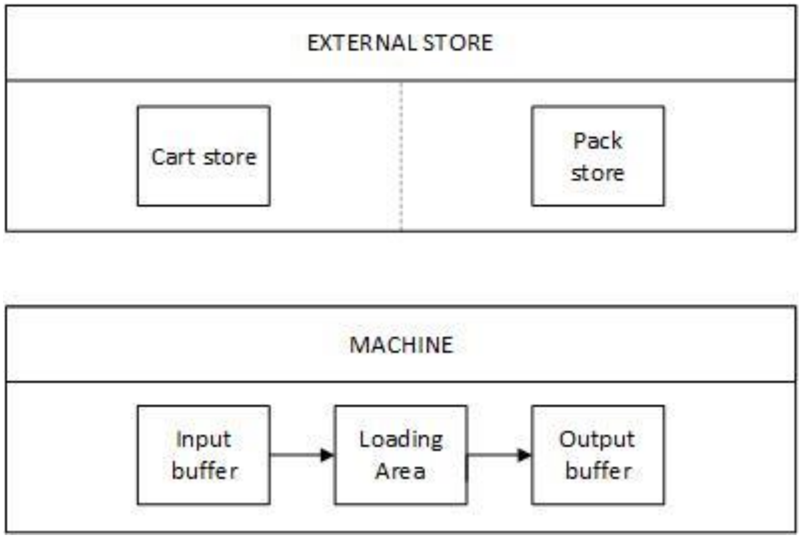


Figure 16 - Schematic view of (sub-)locations

A machine location consists of an Input buffer, loading area and output buffer. In case of a CBM the Input buffer is used to store empty MHE. The Empty MHE is loaded with manufactured tire parts at the loading area. The loaded MHE waits at the output buffer on transport. In case of a TBM. The MHE with tire parts arrive at the input buffer where they wait until the parts are required. At the loading area the parts are consumed by the TBM. The (empty) MHE waits at the output buffer on transport.

External stores consist of either a cart store or a pack store dependent on how the tire parts are stored. Each tire part type has his own storage location where only MHE and tire parts used for that tire part type may be stored. ***TABLE 8*** – External storage locations states the names and possible contents of these and other external storage locations.

External store name	Contents of external store
LOLOS	Tread parts and (empty) MHE used for treads
ZIJLOS	Sidewall parts and (empty) MHE used for sidewalls
PGVLOS	Innerliner parts and (empty) MHE used for Innerliner
PAStore	PA parts and (empty) MHE used for PA

Table 8 – External storage locations

Note that innerliner tire parts are stored in a pack in a fixed rack, whereas all other tire part types are stored on a cart. ***FIGURE 17*** shows LOLOS and PGVLOS.

Figure 17a LOLOS

Figure 17b PGVLOS

Figure 17 - External stores LOLOS and PGVLOS

The part of the factory of this study is presented in ***FIGURE 18***. The CBMs are blue, the TBMs are red and the external stores are green. The truck store is located at the right side next to ZIJLOS. The tow trucks move between the machines in the drawing.

Figure 18 - Layout factory

1.3.3 TRANSPORT

Material flow between CBMs, TBMs and stores is managed by the TTDs with support from PIBS. Transport orders are automatically created by PIBS to transport tire parts to a store or the next processing location. Transport orders are also automatically created to pick up leftover material. However, there are no transport orders created to transport empty MHE from and to a machine. There is a standard operating procedure to handle transport of empty MHE. For each of the transport scenarios that can occur it is described how they are currently handled in the next sections.

TRANSPORTING TIRE PARTS

Tire parts are transported for two reasons. They are manufactured at a CBM and need to move to a store or machine or they are located in a store and need to be moved to the next machine.

TRANSPORT TIRE PARTS FROM CBM

Just manufactured tire parts are moved when either a cart is fully loaded or the production order is finished. A cart can go straight to the next machine, straight to a store or pickup assigned articles and go to a store or machine. Whether the cart goes to the machine or store depends on the delivery window of the next machine and the available space at that machine.

The delivery windows per machine type are presented in ***TABLE 9***. Tire parts may only be transported to the consuming machine up to a set hours before the tire parts are due. These set hours are called the delivery window. Recall that the due date of a tire part is the planned start time of the PO it is assigned to. If a transport order is created to transport tire parts assigned to a PO to the consuming machine outside the delivery window, the parts will be transported to an external store.

A (new) transport order to transport the parts from the external store to the consuming machine is created when the tire parts are within the delivery window.

MachineType	DeliveryWindow
TBM	8 h
VPA	8 h

Table 9 – Delivery window tire parts per machine type [7]

When there is no empty space at the next machine the cart is also transported to an external store. PIBS does not know beforehand if there is available space at the next machine because it does not know how much storage space there is at a machine location. The tow truck driver will manually tell PIBS that the cart with tire parts will be moved to an external store once it arrives at the machine and determines that there is no space.

All the above steps are summarized in ***FIGURE 19***.

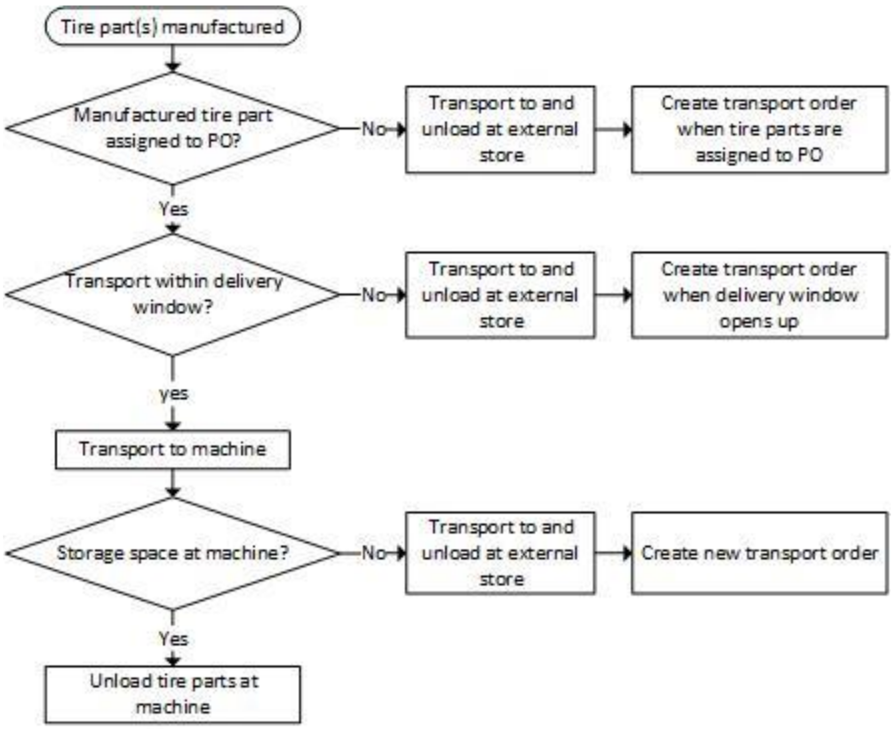


Figure 19 – Flow diagram manufactured tire parts

TRANSPORT STORE ORDERS FROM CBM

When a cart is loaded with unassigned tire parts belonging to a store order the cart will go straight to the store. There it will wait until the parts on the cart are assigned to a PO. After which a transport order will be created when the delivery window of the part opens up.

TRANSPORT ASSIGNED TIRE PART PACKS FROM EXTERNAL STORE

When the last tire part pack of a PO is manufactured a transport order is created for the cart at the CBM. At the same time, PIBS checks if there are assigned tire part packs belonging to the PO. If this is the case, the tow truck driver is instructed to pickup the assigned tire parts form the external store when he executes this transport order. How this is done depends on the tire part type. Innerliner is stored in a rack. If possible, the TTD moves the cart with tire part packs that just finished manufacturing from the CBM to PGVLOS; place the assigned leftover packs from the rack onto the cart and move the cart to the next machine location. If there is not enough space at the cart, the TTD will get an empty cart from KAL3 and transport it to PGVLOS. The assigned tire part packs are loaded on the arriving cart, which is then transported to the next machine location.

Sidewall and treads are always stored on carts. The TTD picks up all the carts where tire part packs belonging to the TBMorder in question are located. At the cart it is checked if there are tire part packs located on the cart that do not belong to the same TBMorder. If this is the case, the cart is moved to a transfer station. A cart suitable for storing the not needed tire part packs is found in the correct store and is transported to the transfer station as well. The not needed tire part packs are transferred to the other cart and that cart is placed back in the store where the location of the tire part packs is changed in PIBS. The cart with the tire part packs belonging to the TBMorder is then transported to the next machine location.

TRANSPORT MANUFACTURED TIRE PARTS FROM STORE

Carts with assigned tire parts that are waiting in the store until there is space available at the next machine are moved when the TTD manually observes that there is space at the next machine or is told that the tire part packs in question are directly needed for production.

Carts with assigned tire part packs that are stored because they contain packs that are produced before the delivery window opens up receive a new transport order when the delivery window opens up.

Carts with tire part packs on them that were assigned to a PO while already waiting in an external store, receive a transport order when the last tire part pack of the same material belonging to the same PO has finished production as explained in section above.

TRANSPORT LEFTOVER TIRE PARTS

After manufacturing a production order on a VPA or TBM there are tire part packs leftover. The machine operator tells PIBS there are leftovers. The TTD receives a transport order to pick up the leftover tire part packs. When the TTD arrives at the machine location, the amount of tire part leftovers is measured by the TTD and manually inserted in PIBS. The leftover tire part packs are transported to the right store and unloaded. When the leftover tire part packs are placed in the store, the tire part packs become available to be assigned to a new PO.

TRANSPORT PA BETWEEN VPA AND TBM

Transport of the cassettes where the PA is stored on is the responsibility of the VPA machine operators. This is a closed loop where PA cassettes are transported between TBMs; the VPA machines and the PAstore.

TRANSPORT EMPTY MHE

Empty MHE needs transport for two reasons. (1) Empty MHE is located at the limited space at the TBM where it must be removed to make room for MHE with tire parts that will be produced on the TBM. (2) The right type of Empty MHE must be available at all CBM before they are able to manufacture any tire parts.

Unfortunately, no transport orders are created in either case. This means that the TTDs have to drive through the factory continuously and communicate with the machine operators at the machines to determine which empty MHE must be removed from the TBMs and which empty MHE is needed when at the CBMs.

In order to manage this task there are some general rules defined in the standard operating procedure of the TTDs:

- When a TTD picks up a cart with tire parts from a CBM he must return a cart with similar MHE to that machine.
- When a tow truck driver delivers a cart with tire parts, he is obliged to remove a cart with similar MHE
- The TTDs must make sure there is enough stock of empty MHE at all CBMs.

Notice that also using the standard operating procedure this is not very efficient.

1.3.4 TRACK & TRACE

Barcodes are used to track & trace the tire part packs throughout the factory. When a transport order is executed by a TTD, the TTD scans all the barcodes on the cart that it transports. When the TTD tells PIBS that the transport order is finished, PIBS automatically updates the inventory. Meaning, the tire part packs belonging to the barcodes that are scanned are placed in the store of the destination of the transport order.

```
1234      ***      TRANSPORT MODULE      ***      7/02/13  14:28
Personeel Nr : 1234
Zone         :
Opdr/Charge  :
 # | Artikel          | Lokatie         | Order | Aant |   Min
 1 | LV137            | Quadruplex      | 169   |    4 |  -290
 2 | LV143            | Quadruplex      | 156   |    4 |  -116
 3 | LV145            | C39             | 9606  |    2 |   -97
 4 | LV167            | Quadruplex      | 9221  |    4 |   -40
 5 | LV136            | B27             | 8456  |    3 |    -7
 7 | LV117            | A11             | 8875  |    1 |    27
```

Figure 20a Overview transport orders

```
Personeel Nr : 1234
Zone         :
Opdr/Charge  : ______________      (97=Naar Magazijn, 98=Terug, 99=Akkoord)
Artikel    : LV167
Order      : 9221                Charges : 0 van 4
Van lok    : Quadruplex
Naar lok   : 092
```

Figure 20b Execution transport order

Figure 20 - Transport Module [8]

FIGURE 20 shows the screens of the transport module as presented to the TTDs. ***FIGURE 20A*** shows the seven transport orders which are due first. ***FIGURE 20B*** shows the screen which is presented during execution of a transport order. The yellow marked order is being executed. The transport order consists a cart with four tread tire parts that must be transported to M92. When the TTD arrives at the Quadriplex it scans all the barcodes (charges). Then it moves the cart to M92. If there is room the cart is placed there and the TTD presses 99 (confirm). The inventory is now updated. If the cart must be moved to the store the operator presses 97 (To store). In case of treads, sidewalls a storage location for the cart is given. The cart is the transported to this location. When the operator presses 99 (confirm) the inventory is updated.

Within the transport module the location of all tire part packs can be observed. The inventory can be manually changed if needed and tire part packs can be assigned to a different PO as well.

Notice that the external stores are divided in a number of specific locations where as the machines are presented as one buffer.

1.3.5 REMARKS ON THE TRANSPORTATION SYSTEM

As mentioned while explaining the transport system there are shortcomings regarding the current situation. The transportation system is only partially controlled by PIBS and requires the TTDs to manage the distribution of all the empty MHE throughout the factory without them knowing what empty MHE is located where except by observing it themselves. TTDs must continuously drive around to observe where empty MHE is located and communicate with machine operators to determine where empty MHE is needed and if there is space at the receiving location.

The transportation of tire parts does not run smoothly as well. TTDs only observe that there is no space available at a receiving machine when there on site. Then they must find another location to temporary store the cart with tire part packs only to pick it up at a later time to return it to the next machine location. In the case of Innerliner there is no official storage location for carts with innerliner packs. In this case the TTD must remember where it places the cart and return it in due time to not cause machine downtime.

Unfortunately PIBS cannot solve these problems due to fundamental lack of information. ***TABLE 10*** and ***TABLE 11*** show the information deficit within PIBS.

Location	Exists In PIBS	Capacity constrained in PIBS
LOLOS	Yes	Yes
ZIJLOS	Yes	Yes
PGVLOS	Yes	No
PAStore	No	-
SideLNStore	No	-
TempStore	No	-
General machine location	Yes	No
Machine pack / In / out / loading location	No	-
Machine cart / In / out / loading location	No	-

Table 10 - Location information in PIBS

Item	Track&Trace in PIBS
Tire part packs	Yes
MHE	No

Table 11 - Track and trace capability PIBS

2 RESEARCH DESCRIPTION

The goal of this research is to create a simulation model for internal transport between workstations and external stores. This model is used to come up with suggestions for improvement of the current situation. Many aspects of the internal logistics can be improved. This study focus is on the movement of MHE and tire parts between the machines and external stores.

2.1 RESEARCH QUESTIONS

A model is created that can help reduce the conversion costs without negatively impacting tire production. Conversion costs are made up of many parts among which the number of tow truck drivers and MHE used. The aim here is to investigate what the recommended amounts of MHE and tow trucks are given that the production output is maximized. Before these questions can be asked transport control policy must be developed to get a closed loop transport system that is able to function in a simulation study. The research questions become:

1. What additional transport control rules are needed to create a working simulation model of the transport system?

2. What is the recommended number of tow trucks needed to transport tire parts and MHE to maximize production under the simulated conditions?

3. What is the recommended number of material handling equipment used for transport of tire parts to maximize production under the simulated conditions?

4. To what extend can the company use the findings of the simulation study?

2.2 SCOPE

The investigated tire manufacturing plant is large and complex it’s housing production for multiple tire lines. This research will focus on the largest production line: passenger car radial (PCR) tires. Within the PCR production line the most critical part is between tire part production and tire assembly. This part of the manufacturing process has the highest product mix, the most parallel machines, the largest floor space allocated for storage and the most complex transport objectives. Therefore it has much potential to reduce conversion costs and positively influence the system.

TIRE COMPONENTS

The tire components used in the simulation are: (1) treads, (2) sidewalls(L/R), (3) innerliner and (4) Pre-Assembly parts for PCR tires. These tire components are chosen because they determine the order sizes of the TBMorders and therefore all related component production orders. These part types also have large external stores, which occupy valuable factory space.

PRODUCTION MACHINES

The productions machines within this study are those machine that currently manufacture or assemble one or more of the included tire components in the previous section

The component building machines are (1) Kalander 3, (2) Quadriplex, (3) Triplex and (4) DSE. The Pre-Assembly building machine (5) VPA800 and (6) VPA900. The Tire building machines included in the study are the 7 HAPBM, 6 APBM and 2 MAXX. 21 production locations are thus included in the simulation study.

PRODUCTION CONTROL

The production planning methods explained in ***1.2.2 AND 1.2.3*** are, to a certain extent, implemented in the simulation study. These determine the production mix of TBMorder. From these TBMorders the CBMorders are created the same way as in the real system. This is used to get the planned start times for all POs, which are used in the created transport system.

2.3 LIMITATIONS

The simulation study is based on the available data within PIBS and own measurements. Not all data is collected and/or correctly stored for longer periods of time in the right manner to fully utilize in the simulation study. Internal logistics is for a large part managed by the tow truck drivers. It is very difficult to accurately model there behavior and also unwanted. The main data that is missing are: exact movements of each tow truck driver during each shift. Location and position of any material handling equipment. In PIBS only tire parts are seen. Position and capacity of all storage locations are not completely defined and known. Especially model verification is made difficult because the current situation cannot be clearly stated. Assumptions are made to fill these gaps which are discussed in the methodology chapter.

2.4 DELIMITATIONS

The transport of all tire parts and MHE is very complex. A simulation study must focus on certain aspects of the internal logistics. The characteristics of tire manufacturing process that are not taken into account due to time and complexity restrictions are:

- No cancelled production orders. It is assumed that all production orders are produced although in reality production orders are cancelled due to failures in other parts of the plant.
- No NOK parts. Not all tire parts are produced up to specification. These Not OK parts are sometimes stored on the same MHE that is used in production. NOK parts are not present in the research
- No human behavior. It is assumed that all tow truck drivers work exactly according to the rules and can perform every task with the same speed and accuracy every time.
- No MHE damage. In practice especially liners are winded up skew. These liners receive a yellow card are taken out of rotation, repaired at a wind-up station and taken back in rotation.
- No leftovers during production
- No store production orders are scheduled.
- Only a basic routing scheme is implemented to transport tire parts and MHE dependent on each possible scenario that can occur.

More detailed delimitations are discussed in the assumption document where the assumptions and simplifications used to construct the simulation model are described and discussed.

2.5 OUTLINE

The research questions are answered in a systematic method in the remaining chapters of the report. The outline of the remainder of the report is presented here.

In ***CHAPTER 3*** the literature is reviewed focusing on two main topics, logistics and simulation (studies). One section explains what logistics is, gives an overview of transportation models and presents studies and methods to improve logistics. Another section defines what simulation is and how to perform a simulation study.

The knowledge gained in ***CHAPTER 3*** is used in the remaining chapters to perform a simulation study of the transport system described in ***SECTION 1.3***.

CHAPTER *ERROR! REFERENCE SOURCE NOT FOUND.* begins with collecting and mapping all the available data that is used in the simulation study. With the data collected the simulation model is constructed in the discrete event simulation software package Tecnomatic Plant Simulation. A description of the building blocks and workings of the final model is presented. The model is validated and the assumptions and simplifications used to get a working model are discussed. Finally, it is explained which experiments are run and why.

The results of the simulation study are presented in ***CHAPTER 5***. The relation between the number of tow trucks and MHE related to the production output are presented. Following are the detailed analysis of the transport workload, MHE utility and the store occupancy.

A discussion of the applied method and observed results follow in ***CHAPTER 6***.

The research questions are answered in ***CHAPTER 7*** based on the results of the simulation study. Recommendations are made to implement the finding of the simulation study and suggestions are made for expansion of the model, other experiments and further research.

3 Principles of Simulation and Operational Control

A system is a collection of entities that act and interact together toward the accomplishment of some logical end [9] In order to improve any system, experiments are performed on a system. Experiments are performed on the actual system or with a model of a system. Experiments on an actual system are preferred if it is possible and cost effective because the results of the experiments are always valid. If a model is used this is either a physical model or a mathematical model. A mathematical model is a representation of a system in terms of logical and quantitative relationships [10] .

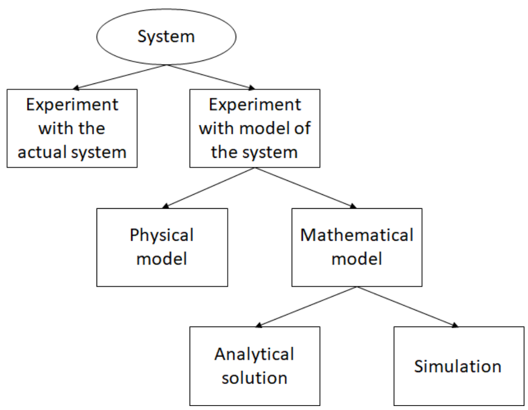


Figure 21 - Methods to analyze a system

Dependent on the experiment and mathematical model there is either an exact solution or a simulation required to get satisfactory results. Exact solutions are only available for simple models. Complex models use simulation. The behavior of logistics system in general and the logistics system in question is complex and therefore uses simulation.

3.1 Simulation

Simulation is a tool to evaluate the performance of a system, existing or proposed, under different configurations of interest and over long periods of real time without the need to change the actual system Simulation is used in situations where no analytical solution is easily obtainable such as manufacturing logistics systems. The purpose of a simulation can be described as obtaining a better understanding of and/or identifying improvements to a system. [11] [12]

Simulation models classify three domains, static or dynamic, deterministic or stochastic and discrete or continuous. This research is concerned with dynamic stochastic discrete simulation. Dynamic because production and transport demand change in time. Stochastic because production performance is unpredictable in nature. Discrete because there is only interest in the state of a system at certain points in time. For example, while a tire part is transported there is no interest in its location at every point in time, the time it leaves the outgoing buffer, and the time it enters the incoming buffer are of interest.

3.2 DISCRETE EVENT SIMULATION

This research uses discrete event simulation. An event is an instantaneous occurrence that can change the state of the system. For example, the arrival of a tire part at a TBM machine can change the state of the TBM if the TBM is waiting for that tire part before it can start producing. The state of the TBM changes from waiting for tire part to manufacturing part.

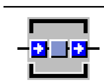
Discrete event simulation models can be modelled using spreadsheets, programming languages or specialist simulation software. Specialist simulation software reduce the modelling time but generally requires a higher investment and have a reduced range of application compared to programing languages. To compensate for the loss of range of application some specialist simulation software have their own pseudo programming language, which increases the range of application. [11]

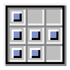
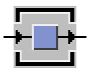
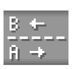
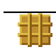
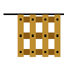
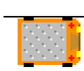
3.3 TECHNOMATIX PLANT SIMULATION

Technomatix plant simulation (PS) is an object oriented discrete event simulation software package that is used in this research. An object is a concept that can contain attributes and procedures called methods. Attributes are data fields that can be manipulated by methods. A method is a piece of code that can alter attributes belonging to the same object of the method or other object. Plant simulation has many build-in object that are used to construct a simulation model. The capabilities of the PS objects influence the structure of the simulation model and therefore the data that needs to be collected. A description of the important objects is presented to give a better understanding of how simulation works.

3.3.1 PLANT SIMULATION OBJECTS

PS separates different groups of objects, namely (1) material flow objects, (2) Information flow objects and (3) Movable units (MUs). Material flow objects are objects that can influence the flow of MUs through the system. Information flow objects are objects that contain different data types and structures. The method object, which contains executable computer code, belongs to this category as well. The MUs contain an entity, transport and container object used to model all movable objects such as tire parts, MHE and tow trucks. Each PS object has specific attributes and methods. The most important objects and attributes are presented in ***TABLE 12***.

Icon	Object Name	Important attributes	Values	Description
	Event Controller			Controls the simulation
		Reset		Deletes all unprocessed events, resets the simulation time to 0, resets the statistics, and removes all failures of all machines in the simulation model
		Start		Calls all initialization methods in the model, starts simulation
		Stop		Stops the simulation.
		EventDebugger		Shows a list with all events. For each event shows the type, time of execution, sender, receiver and parameters send with the event call
	Buffer			The buffer can store up to a chosen number of MUs.
		Capacity	[0,∞]	The maximum number of MUs that can be present in a buffer at any time

		NumMU	[integer]	Number of MUs in the buffer
		Entrance Control	[method]	Calls a method when a MU enters the buffer
		Exit Control	[method]	Call a method before or after a MU leaves the buffer
	Store			Location that stores MUs at a specific location [x,y]. MUs do not leave a store automatically
		X-dimension	[any integer]	Number of MUs it can place next to each other in X-dimension
		Y-dimension	[any integer]	Number of MUs it can place next to each other in Y-dimension
		NumMU	[integer]	Number of MUs in the Store
		Entrance Control	[method]	Calls a method when a MU enters the buffer
	SingleProc			Processes an MU, simulating a manufacturing process.
		Processing time	[const., distribution]	Time that a MU that enters wait before it may leave
		Setup time	[const., distribution]	Time a MU waits before it is processed when setup is executed
		Setup depends on	[MU Name, User defined attr.]	Attribute that is observed to determine if setup is needed or not, if value of attribute different than setup SingleProc
		Entrance Control	[method]	Calls a method when a MU enters the SingleProc
		Exit Control	[method]	Calls a method when a MU exits the SingleProc
	Connector			Establishes material flow connections between two objects on which the MUs move from object to object
	(TwoLane) Track			A path on which a MU can move on
		Length	[any length]	The length of the path
		Capacity	[any integer]	The maximum number of MUs that can simultaneous be on the track
		Sensor		A trigger that can execute a method when a MU is located at its position
		Position (sensor)	[any length < length track]	The position of the sensor relative to the beginning of the track
		Control	[method]	Method that can be executed when MU located at sensor position
		Activate (Sensor)	[Always, depends on location]	Determines when the control method is located
		Destination(sensor)	[object]	The next location to which a MU is transported
	Entity			Represents parts being transported, stored and processed. Can not carry other MUs itself
		Length	[Meters]	Length of the entity
		Width	[Meters]	Width of the entity
		Height	[Meters]	Height of the entity
		Destination	[Object]	Next material flow object Container must go to
	Container			Material flow object that is used to model MHE. It can contain multiple other MUs
		xDim	[integers]	Number of MUs it can place next to each other in X-dimension
		yDim	[integers]	Number of MUs it can place next to each other in Y-dimension
		Destination	[object]	Next material flow object Container must go to
	Transporter			Active mobile material flow object. It is self-propelled allowing it to move on the objects Track and TwoLaneTrack.
		Speed	[M/s]	Speed the transporter moves on a track (if not stopped)

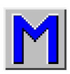
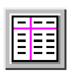
	xDim	[integers]	Number of MUs it can place next to each other in X-dimension
	yDim	[integers]	Number of MUs it can place next to each other in Y-dimension
	Entrance control		Calls a method when a MU enters the laodbay of the transporter
	Exit control		Calls a method when a MU exits the loadbay of the transporter
	Destination	[object]	Next material flow object Transported must go to
	Automatic routing	[true/false]	When on, transporter finds the shortest route to its destination object along the direction of motion. The route must consists of objects of type tracks that are connected via connectors.
	Distance Control	[method]	Method executed when a transporter comes within or exeeds a predefined distance
	Distance (Distance control)	[meters]	The distance used to activate the distance control
	Collision control	[method]	Method called when Transporter collides with MU within the range of motion.
	Method		Contains programming code that is executed when the method is called
	Tablefile		Contains rows and columns that contain all kinds of data such as tables, objects, lists, values. Each Column has a unique datatype

Table 12 - Important PS objects and attributes with description

With these objects a complete transport system is created. Many of the objects have properties that need further explanation for a full understanding.

3.3.2 PROPERTIES OF ALL OBJECTS

All PS objects share a number of common properties. Some important properties that are beneficial to use to model logistics systems are discussed.

USER DEFINED ATTRIBUTES

Each PS object can contain user defined attributes. A user defined attribute has a data type and value. Commonly used datatypes are object, method, integer, boolean, string, datetime and table. User defined attributes make PS very versatile. For example a user defined attribute named “PartTransfer” can be created of type Boolean. The attribute is set to true, if the transporter contains an entity that must transfer to a different transporter and to false, if the entity that needs transfer to a different transported is removed. This attribute can be used in any method.

OBSERVERS

Many attributes of objects can be observed. This means that when the value of the attribute changes a signal is given. When a method is assigned to one of this signals it is called an observer. Observers can be a very powerful tool which is illustrated by an example. Suppose an observer is placed on a user defined attribute state of an entity presenting a tire part. When the state changes a method is called. This method can then determine what should be done given this state change. For example, if the state of the “orderType” of a tire part object changed from “StoreOrder” to “RegularOrder”, a transport order may be generated to transport the tire part to the machine the PO is assigned to. The benefit of observers is that they can make a model robust. In case of the example, it does not matter which method changes the state of the PO. But once it is changed something must be done. In this example, a transport order is created.

3.3.3 MODELING FAILURES

In production systems, machines fail. Failures are unpredictable in nature and must be modeled according to their observed unpredictability. PS models Failures according to the attributes active, start time, stop time, interval time and duration time and mode described in ***TABLE 13***.

Failure Attribute	Value	Descriptions
Active	[true,false]	Failure is used in simulation or not
Start	[constant, distribution, Empirical]	The time the failures can start to occur
End	[constant, distribution, Empirical]	The time after which the failure does not occur
Interval	[constant, distribution, Empirical]	The time between consecutive failures
Duration	[constant, distribution, Empirical]	The time a failure lasts
Mode	[SimulationTime, OperatingTime,ProcessingTime	The state a material flow object must be in for counting the interval and duration time

Table 13 - Plant Simulation failure atrributes

Note that all times can be constant, a randomly sampled distribution or empirical table. PS has a number of commonly used build-in distributions such as, uniform, normal, Negative Exponential, Weibull, Erlang and Poison distribution. Empirical data can also be inserted if no proper distribution is found.

The mode 'SimulationTime' means that all simulation time is counted. The mode 'OperatingTime' means that all time is counted when a material flow object is in operation. A material flow object is in operation when it is not paused (planned stop, unplanned) or failed (e.g. different failure). The mode 'ProcessingTime' means that all time is counted when a machine is actually processing an entity. It is important to insert input data correctly into the model to give correct results.

PS has the useful feature to determine the duration and interval from the attributes mean time to repair (MTTR) and availability. For the duration a negative exponential function is used in which events occur continuously and independently at a constant average rate and for the MTTR an Erlang distribution is used in which very short and very long repair times occur occasionally and average repair times occur frequently. Note that the availability can reflect the available simulation, operating or processing time.

3.4 STATISTICS

The goal of a simulation study is to compare alternative scenarios and determine the influence of the model inputs on the model outputs. It is important to use correct statistical methods so that the right conclusions are drawn from the experiments.

RANDOM NUMBERS

Random numbers are used to sample distributions that are used to model uncertain behavior. In two simulation runs the similar or different random numbers can be used. If two different scenarios are compared the same random numbers should be used. The randomness in both scenarios is the same and does not skewer the results. If the influence of the randomness is the interest of the simulation study, different random numbers should be choses to investigate if that influences the outputs. This shows the sensitivity of the parameter investigated.

CHI-SQUARE TEST

The Chi-square test is a commonly used goodness of fit test between a chosen distribution and the observations. In simulation studies, it is often easy to work with common distributions such as the normal and Poisson distribution to simulate uncertainty rather than use the exact records. In this way, scenarios outside the observed situation are studied. The Chi-square test is used to determine if a common distribution describes the observed phenomenon correctly. For example. A list of failure durations is collected. This behavior is represented by a Poisson distribution. The chi-square test is used to determine if the Poisson distribution describes the real failure duration good enough given the desired confidence interval.

PAIRED T-TEST

A different test is required when the output of two scenarios is to be evaluated. The paired T-test is used to determine if two lists of observations are statistically different given that each observations is independent of the other. For example, there are two lists with production output of two studied scenarios. The test states that either there is or there is no statistical difference between the two scenarios with a certain confidence. This is especially important to test if there is much uncertainty and variation in the investigated model.

3.5 STEPS IN A SIMULATION STUDY

Many authors have defined a number of steps that need to be performed either sequential or iteratively such as the book describing modeling practices by Stewart Robinson [11] and a white paper about simulation by Anu Maria [12]. The steps defined by Averill M. Law [10] are presented in ***FIGURE 22*** and are used in the case study.

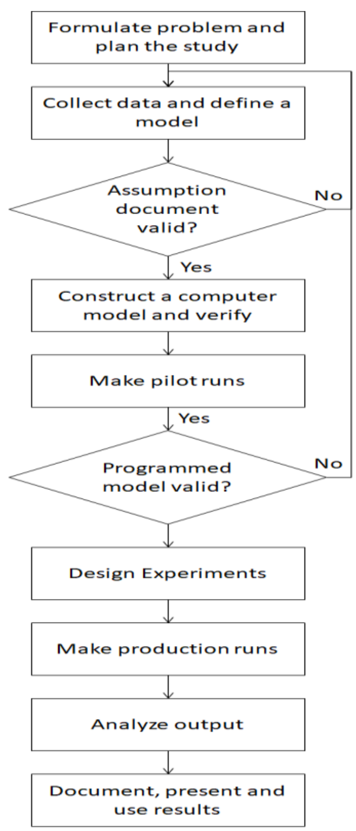


Figure 22- Steps in a Simulation study [10]

A simulation begins with the problem formulation. The problem formulation contains the overall objective of the study; specific questions to be answered; performance measures to be examined; the scope of the model and the system configurations to be modeled. An iterative process is often necessary to formulate the problem well.

When the problem is clear, data is collected and a model of the system is constructed. First the system structure and operating procedures are mapped by talking to subject matter experts (SMEs) and investigating documents such as standard operating procedures (SOPs). Data is collected to specify the model parameters and input probability distributions.

During construction of the model assumption are made and written in an assumption document. When the model is finished the assumption document is validated. When the document is invalid, the model is revised until the assumptions document is valid.

From the model a computer model is constructed in a general purpose language or specialized simulation software. It is verified that the computer model works similar to the general model. Pilot runs are made to verify the proper working of the model. If the model is not valid either the computer model must be changed or the general model must be changed first.

The experiments fixed in system configurations must be designed. This includes determination of the warmup period; number of runs per experiment and using the correct random numbers in the simulation.

When all experiments are performed the data is analyzed. The absolute performance as well as the relative performance between configurations is of interest.

The final step is documentation, presentation and use of the results. Many simulation studies are done without ever using the results they generated.

3.6 OPERATIONAL CONTROL

Operational control is the manipulation of flows of tasks and resources through a system in real-time, or near real-time. Operational control comprises the methods and systems used to prioritize, track, and report against production orders and schedules. [13] Operational control of discrete event logistics system (DELS) consists of three elements. The base system, which is the physical layer with the parts, MHE, buffers, transporters machines etc.; the controller, which makes the decisions and the interface between the two.

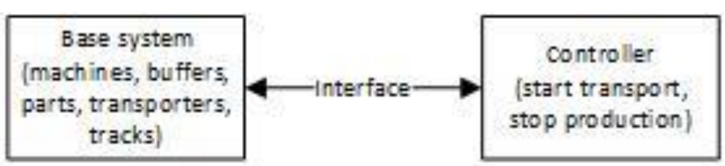


Figure 23 - Elements of operation control system

The control decision consists of five steps. At each step a question is to be answered.

(1) Admission. - “should a task be served?” – A task must be served or not.
(2) Sequencing. - “When should the task be serviced?” - The tasks must be prioritized and coordinated. Tasks are advanced or delayed and batches or split.

(3) Assignment. - "By which resource?" - Each task is allocated to a resource.
(4) Routing. – "Where should the task be sent after it completes the required processing?" – Completion of a task leads to the next task or not.
(5) Change State. – "When, and to which state, does the state of a resource need to be changed?" – The state of the resource changes when the task is served dependent on the task and the outcome. [13]

To implement the transport control rules correctly in a simulation model, these steps are used and the questions answered for all possible tasks in the system. See for example ***SECTION 4.1.6*** where the transport tasks are modeled.

4 SIMULATION STUDY

A simulation study of the transport of tire components and material handling equipment is performed in this chapter using the methodology described in ***SECTION 3.5*** and the theory described in the previous chapter. The problem is formulated in ***SECTION 2.1*** are converted to simulation study objectives.

The data collection process is described together with a more in depth description of the system structure and operating procedures with a focus on how these are implemented in the simulation. The model is constructed in Tecnomatix Plant Simulation and verified. Finally, the running of experiments is described.

4.1 PROBLEM FORMULATION

A simulation study can be performed effectively if clear research objectives are defined. Therefore, the research questions defined in ***SECTION 2.1*** are converted to concrete research objectives as stated in ***TABLE 14***.

Simulation study objectives
Develop operational control able to create and execute transport orders for all transport tasks stated in ***TABLE 7.***
Determine the optimal number of MHE needed
Determine the transport workload and the optimal number of tow trucks needed
Determine the storage space needed in the optimal case

Table 14 – Simulation study objectives

Note that the optimal amount is dependent on what is optimized. In this case a minimum number of resources for which the production output remains, nearly, maximum is considered optimal.

4.1.1 PERFORMANCE MEASURES

Performance measures are needed to evaluate efficacy of the different system configurations that are developed. The performance measures are chosen in a way such that it can be observed if the study objectives are met as well as it provides inside into where the system may be improved. The performance measures are listed in ***TABLE 15***.

Performance measures
Production output (Number of manufactured greentires)
Number of MHE used
Number of Tow trucks (transport workload)

Table 15 - Performance measures used to evaluate efficacy of different system configurations

As stated in the research questions and simulation study objectives the optimal amount of tow trucks and MHE are determined. These parameters together determine the system performance.

4.1.2 SCOPE OF THE MODEL

The scope of the simulation study is defined in ***2.2*** and will not be further discussed here. Limitations of the model studied are discussed in the validity assumption document in ***SECTION 4.2***.

4.1.3 EXPERIMENTAL DESIGN

Experiments are run on the simulation model with the goal to answer the research questions stated in ***2.1***. To determine the recommended number of tow trucks this parameter will be set in a range around the critical point. This critical point is the point where the transport responsiveness starts to negatively impact the production output. This point is found after running preliminary experiments. In these experiments an unlimited number of MHE is used to make sure the number of tow trucks is the limiting factor. It is expected that a reduction in the number of towtrucks will lead to slower execution of transport orders which is turn leads to machine downtime due to late deliveries. This should lead to a clear decrease in production output when the parameter becomes critical.

The same analysis applies to the number of MHE in the simulation. Too few MHE lead to machines tardiness which leads to reduced production output.

The goal of all the experiments combined is to find the optimal point between the number of MHE and number of tow trucks used that leads to a high production output. Obviously not every possible combination can be simulated due to the required computation time. Therefore an experiment grid is used to give a result close to the optimum around the aforementioned critical point. This experimental grid used is shown in ***TABLE 16***

	# tow trucks in experiments				
% of currently used MHE in experiments	2	3	4	5	∞
25%	X	X	X	X	
30%	X	X	X	X	
40%	X	X	X	X	
50%	X	X	X	X	
∞					X

Table 16 - Experimental parameter settings

Note that an experiment is included with unlimited number of MHE and tow trucks. This experiment is included to determine the maximum production output with the investigated parameters. This experiment is used as benchmark for the production output values observed during the other experiments.

4.1.4 SYSTEM STRUCTURE & DATA COLLECTION

The system structure as used in the simulation is discussed in this section together with the data collection needed in the simulation. Where the structure of the model deviates from the real system as described in chapter 1 the assumptions made are stated. The system structure is discussed in the way the production originates. Starting with the production planning and scheduling followed by production execution; transport order generation and finally transport order execution.

4.1.5 PRODUCTION STRUCTURE

First, the system input is chosen. The scope of the simulation study ends with tire assembly. The demand for greentires is defined in the TBMplan, which is derived from the curing plan and greentire inventory as explained in ***SECTION 1.2.1.*** A Historical TBMplan is used as input for the simulation model. There are several reasons for this. Ideally a TBMorder generator is constructed that randomly assigns a greentire specification and order size based on statistical data regarding the frequencies of occurrences of these parameters. In this case all possible situations can occur and not just one particular actual case. Unfortunately construction of an production order generator is very complex in this case. A greentire specification is not randomly chosen but always produced regularly for a fixed amount of days while it is in curing after which it is taken out of production for a longer period. Modelling this behavior in an order generator is too complex to incorporate in the study. This particular behavior has significant influence on the availability of TBMorders were leftover tire parts can be assigned to and the quantity of different tire parts in the system at any given time.

Historical production data is collected from PIBS and converted into usable input. The greentire specification and actual build size of all manufactured TBM production orders is collected in the period between 01-01-2016 and 01-03-2016. All production orders consisting of sample materials is discarded. The order size of the remaining production orders is rounded to the nearest complete pack of tread or PA tire part packs that are used as input in the production order. This will serve as the simulation input for all experiments. ***TABLE 17*** shows a sample of the simulation input: a list with TBM production orders in sequence for one of the TBMs.

Machine	Greentire	Order size
M102	CY205516ULCX-G	216
M102	CY224517ULVX-G	253
M102	CY224517ULC-G	251
M102	CY205516ULCX-G	288
M102	CH216516QT5-G	256
M102	CY224517QT5X-G	278

Table 17 - Simulation input

CREATING AND SCHEDULING PRODUCTION ORDERS TBMS

The first step in the simulation is creating and scheduling the production orders for the TBMs. The TBM plan horizon is 72 hours or a nine shift period. TBMorders from the simulation input are created and scheduled until the planned start time of the next TBMorder lies behind the TBM plan horizon. This process takes place at the start of every shift. The planned start time is determined based on the standard cycle time of each part and the standard changeover time between each part. This results in a TBM order list as shown in ***TABLE 18*** for one of the TBMs

Machine	Planned start time	Greentire	Inch size	Order size	Produced	Cycle time	Changeover Time
M400	03.01.2016 16:09:04.3200	AV205516QT5-G	20	321	243	38.88	30:00.0
M400	03.01.2016 20:07:04.8000	AH196515QT5-G	19	600		38.88	30:00.0
M400	04.01.2016 03:05:52.8000	AV205016QT5-G	20	330		38.88	30:00.0
M400	04.01.2016 07:09:43.2000	AV195515SP5-G	19	300		38.88	30:00.0
M400	04.01.2016 10:54:07.2000	AH196015QT5-G	19	287		38.88	
M400	04.01.2016 14:00:05.7600	AH196515QT5-G	19	640		38.88	
M400	04.01.2016 20:54:48.9600	AV205516QT5-G	20	281		38.88	30:00.0
M400	05.01.2016 00:26:54.2400	AW207015CLS-G	20	76		38.88	
M400	05.01.2016 01:16:09.1200	AH196015QT5-G	19	287		38.88	30:00.0
M400	05.01.2016 04:52:07.6800	AH206515QT5-G	20	313		38.88	30:00.0
M400	05.01.2016 08:44:57.1200	AH196515QT5-G	19	600		38.88	30:00.0
M400	05.01.2016 15:43:45.1200	AH205015QT5-G	20	302		38.88	30:00.0
M400	05.01.2016 19:29:26.8800	AV205516QT5-G	20	321		38.88	

M400	05.01.2016 22:57:27.3600	AV195515SP5-G	19	300	38.88	30:00.0
M400	06.01.2016 02:41:51.3600	AH196515QT5-G	19	600	38.88	
M400	06.01.2016 09:10:39.3600	AH196015QT5-G	19	287	38.88	
M400	06.01.2016 12:16:37.9200	AV205016QT5-G	20	289	38.88	30:00.0
M400	06.01.2016 15:53:54.2400	AV205516QT5-G	20	201	38.88	

Table 18 - Example TBM order list

Note that there is a 30 minute changeover time between two POs when the second PO has a different inch size. It takes 30 minutes to setup the machine for a different inch size. TBMs only have inch size changeovers. The planned start time is calculated as the planned start time of the previous TBMorder or the current simulation time in case of the first PO. The planned start time is calculated according to equations ***(1)*** and ***(2)***.

$$Planned\ start\ time_2 = current\ simulation\ time + (order\ size_1 - produced_1) * Cycle\ time_1 + changeover\ time_1 \quad (1)$$

$$Planned\ start\ time_i = Plannedstart\ time_{i-1} + order\ size_{i-1} * Cycle\ time_{i-1} + changeover\ time_{i-1} \quad (2)$$

$$with\ i = TBMorder\ sequence\ number$$

Creating and scheduling CBMs

After all the TBMs are (re)scheduled, all tire parts that are needed to manufacture the TBMorders planned to start manufacturing within the order window of the TBM are ordered. The simulation uses the same ordering, assigning and scheduling procedures as the real system which are explained in ***1.2.3***. ***Figure 24*** shows how the tire parts are related to each other and the greentire and stock-keeping units (SKU). The highlighted parts are within the scope of the study.

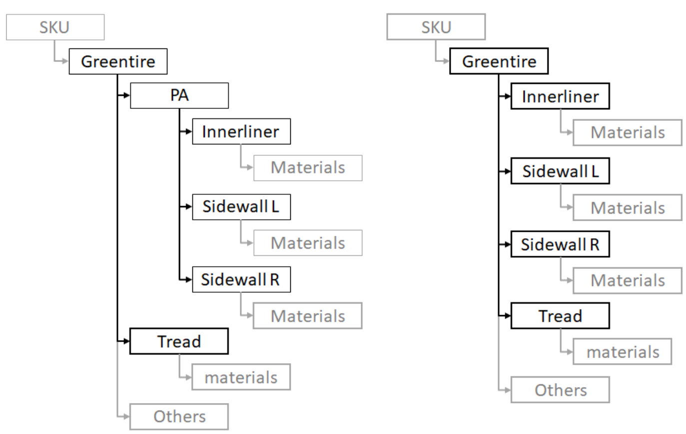


Figure 24 – Possible SKU part structures

Table 19 shows part of the BOM used in the simulation. The BOM lists the tire part name and amount needed for each tire part to manufacture a single greentire.

Greentire	Pre-Assembly	Amount Pre-Assembly per greentire [m]	Innerliner	Amount Innerliner per greentire [m]	Sidewall	Amount Sidewall per greentire [m]	Tread	Amount Tread per greentire [m]
AV206013CLS-G			F435	0.97	22Z	1.167	LV217	1.722
AV206016QTLX-G			H450	1.208	24Z	1.407	LV309	1.957
AW207015CLS-G			F450	1.129	29Z	1.327	LV184	1.957
BH178014CLS-G	PA49ZF405-736	1.054	F405	1.054	49ZH	1.054	LV182	1.896
BH188014CLS-G	PA32ZF410-760	1.054	F410	1.054	32ZH	1.054	LV180	1.94
BH188015CLS-G	PA33AF410-746	1.133	F410	1.133	33A	1.133	LV170	1.975
BH188016CLS-G	PA33AF410-748	1.212	F410	1.212	33A	1.212	LV180	2.09
BH195516QT3-G	PA57SH360-628	1.212	H360	1.212	57S	1.212	LV387	1.842
BH196016QT5C-G	PA21SF390-676	1.212	F390	1.212	21S	1.212	LV432	1.925

Table 19 - Part BOM used in simulation

To give an impression of the complexity ***TABLE 20*** lists the number of different specifications per part type; number of different amounts that go into the parent part and the range for the different amount of tire part needed to produce a single greentire.

Tire Part	Unique specifications	Unique amounts	Amount range in one tire [unit of measurement]
Greentire	859	1	1 [qnt]
PA	375	11	1.054 - 1.856 [m]
Sidewall	115	15	1.054 - 1.856 [m]
Innerliner	97	16	0.970 - 1.856 [m]
Tread	267	375	1.545 - 2.472 [m]

Table 20 - BOM properties

Note that there are many different combinations of tire parts possible to construct many different greentires. The simulation uses the exact data from the BOM to construct the CBMorders. An example of the result, a CBM order list, is presented in ***TABLE 21***.

Order Number	Machine	Target Machine	Due time	Planned Start time	Tire Part	Order size	Produced parts	Setup Type
564	QUADR	M400	03.01.2016 17:43:26	03.01.2016 18:54:57	LV431	7	2	
240	QUADR	M94	03.01.2016 18:16:12	03.01.2016 19:57:09	LV409	7		INPUT
752	QUADR	M88	03.01.2016 21:47:39	03.01.2016 20:16:24	LV409	7		
396	QUADR	M102	04.01.2016 01:52:33	03.01.2016 20:53:50	LV119	7		INPUT
416	QUADR	M102	04.01.2016 03:44:45	03.01.2016 21:09:43	LV119	6		
60	QUADR	M84	04.01.2016 05:10:23	03.01.2016 21:41:32	LV167	12		INPUT
30	QUADR	M82	04.01.2016 05:52:22	03.01.2016 22:15:26	LV168	13		Die
65	QUADR	M84	04.01.2016 07:49:27	03.01.2016 22:49:27	LV167	12		Die
160	QUADR	M88	04.01.2016 08:32:49	03.01.2016 23:38:16	LV301	8		INPUT
408	QUADR	M102	04.01.2016 08:40:00	04.01.2016 00:00:26	LV323	9		Die
612	QUADR	M500	04.01.2016 10:00:05	04.01.2016 00:28:29	LV302	10		Die
732	QUADR	M700	04.01.2016 13:17:32	04.01.2016 00:58:22	LV301	8		Die

Table 21 - Example CBMorder list Quadriplex

Note that in case of the Quadriplex there are different setups possible between two POs. This is further discussed in the next section. In contrast to the real system production orders are not grouped together based on input in order to reduce the number of input setups due to the complexity it adds to the model

MANUFACTURING

After a machine is scheduled manufacturing can take place. The manufacturing process consists of multiple steps listed in ***TABLE 22***. How these steps are modeled is discussed in the next sections.

Manufacturing step
Determine manufacturing requirement
Setup machine
Procurement input materials
Placement empty MHE
Manufacturing tire part
Transfer MHE

Table 22 - List of all production steps

MODELING MANUFACTURING REQUIREMENT

The first step in manufacturing is determining if manufacturing is required. In general, the machines in the system produce continuously. If there are no production orders the machine waits until a production order is added. There are no clear protocols currently in place for machines to be planned stop. The head planner has the ability to stop a machine if he thinks it is necessary. It is assumed in the simulation that this does not happen. Each machine continuous to manufacture as long as there are POs available.

MODELLING MACHINE SETUPS

When a production order is manufactured the second step is determining if a setup is required. Machines must often be setup when different tire parts are manufactured on the same machine. Different setups are needed for different machines. ***TABLE 23*** presents an overview of all setup types and setup times that can occur on the machines in the simulation.

Setup Type	Setup Times [min]					
	KAL3	QUADR	TRIPL	DSE	VPA	TBM
Input	10.0	18.2	20.2	8.5	2.0	
Die		3.4	3.4	1.8		
Preformer		0.6	0.6			
Inch Size						30.0

Table 23 – Overview all setup types and setup times machines in simulation

Input setup occurs when the input material between two consecutive production orders differs. Usually, different rubber compounds are required. Die and preformer setups are tooling changes needed for manufacturing different tire parts. During an inch size setup the drum of a TBM is changed for one with a different diameter. To model the correct setups the input material is collected for all tire parts occurring in the model from the BOM. In addition, for all treads and sidewalls the die and preformer used are collected and for all greentires the inch size is collected.

When the next production order is manufactured the model checks which setups are executed based on the current and previous values of the input, die, performer and/or inch size. The setup time used in the simulation is the longest setup that occurs. If for example both an input and die change occur at the QUADR than the setup time equals 18.2 minutes. It is thus assumed that setups are executed simultaneously. Note that the run-in period is part of the setup time.

MODELING INPUT MATERIALS

Consumption of input material is simulated for the VPAs and TBMs. For all CBMs requiring input materials falls outside the scope. It is assumed that the input material is always present and is not simulated.

Required material

Before a tire part pack is manufactured the required materials are found, placed at the correct machine input location and consumed. The required material is the tire part pack belonging to the production order with the oldest production date. The standard operating procedure is that the oldest, partially consumed, tire part packs are used first (FIFO).

Locating required material

Required material can only be found and transported to the machine from the input buffer of the machine. If the required material is not found, the machine waits until a cart arrives at the machine input buffer and searches the cart for the required material. While the required material is not present the machine remains idle.

Placement input material

The input materials are consumed straight from the MHE located at the input buffer. There are no unloading locations created and further detailed movement of input materials is not simulated.

Consumption of input material

All the input material must be consumed before a new tire part is created. The amount needed to manufacture one tire part (pack) is subtracted from the amount of tire part currently used as input. If there is not enough input material, the empty MHE is transported to the output buffer and the next input material is located.

PLACEMENT MHE

Before a tire part is manufactured the MHE storing the part must also be present at the machine output location(s). This process is similar to the procurement of input materials. First, the required empty MHE is searched for at the machine location. If none is present, the machine remains idle and waits until MHE arrives at the machine input buffer that is needed. When the right MHE is located, it is placed at the right machine out location. Note that the left and right sidewall are always manufactured simultaneously and thus require two liners and two reels before manufacturing takes place.

MODELING MANUFACTURING TIRE PART

When both the input material is consumed and the required MHE is present, a tire part is manufactured when the machine is available. A machine may not be available due to machine breakdowns or because the machine is in use by a different production line

Machine unavailability

Machine downtime is modeled according to ***3.3.3***. The availability and MTTR for each machine are calculated and grouped by type and presented in ***TABLE 24***.

Machine group	Availability	MTTR [min]
CBM	0.85	24
TBM	0.83	17

Table 24 - Availability and MTTR machines

The distributions of unavailability due to manufacturing of non-PCR tire parts are given in ***TABLE 25***.

Machine	Type	Distribution
KAL03	Interval	*N*(441,174)
	Duration	*N*(101,44)
DSE	Interval	*N*(309,152)
	Duration	*N*(79,47)

Table 25 - Derived distributions unavailability due to manufacturing non-PCR tire parts

The derivation of the data is elaborated on in ***4.2***.

Processing

Manufacturing start with the creation of a tire part. When a tire part is created the attributes belonging to it are added. The tire part is processed during the ideal cycle time simulating the manufacturing process. It is assumed that all tire part (pack)s created have the right quality; The time it takes to manufacture a tire part (pack) equals the ideal cycle time and that always exactly the scheduled amount of material is manufactured.

TRANSFER MHE

When the tire part finishes manufacturing it is placed on the pack(s) present in the machine. The packs must be transferred to a cart. If there is no cart present at the cart loading location a cart is searched for at the cart in location at the machine. If no cart is found the machine is idle until a cart arrives that may be used. When a cart is found the cart is placed at the cart loading location. When there is a cart located at the cart loading location the pack(s) are loaded on the cart. If the cart is full or the order is finished the cart is moved to the machine output buffer where it will wait for transport to the next location. Note that in case of the VPA the pack is permanently attached to the cart. The cart loading location is the machine out location in this case and the finished part is placed directly in the pack on the PA cart. The PA cart is then transferred to the machine output buffer when possible.

4.1.6 TRANSPORT STRUCTURE

The focus of the research is to create a transport control system that manages the operational control of all the transport tasks instead of the transport tasks being partially managed by the tow truck drivers. An operational control system is developed in two parts. The first part is the generation of transport orders; the second part is the execution of transport orders.

TRANSPORT ORDER GENERATION

In the simulation, transport orders for all required transport are generated. The transport tasks are listed in ***TABLE 7*** in section ***1.3***. In a Discrete event simulation (DES) model, all relevant events that can occur must be listed and handled in accordance with the system structure. Therefore, the first step is to map all events that trigger the creation of transport orders. ***TABLE 26*** lists all the events that can lead to transport order creation.

Transport Task	Event triggering creation of transport order
Timely removal manufactured tire parts	Tire part Manufactured
Timely delivery input tire parts	Cart with tire parts arrives at external store
Timely delivery of empty MHE	Cart with empty MHE arrives at external store
	Input material consumed at TBM
Timely removal of empty MHE	MHE consumed at CBM

Table 26 - Events triggering creation transport order

Under which circumstances these events lead to creation of transport orders is explained. Each transport order has three attributes, (1) pickup location (2) destination and (3) priority, which are set when a transport order is created. The transport priority is a due time at which the transport order ideally is removed. The values of these parameters differ per transport task. How these values are set is explained per transport task. An overview is given in ***TABLE 27***

Transport task	Transport order parameters		
	Pickup location	Destination	Priority [Due time]
Timely removal manufactured tire parts	Machine output buffer	External Store	Creation time transport order
Timely delivery input tire parts	External Store	Machine input buffer	Due time tire parts
Timely delivery of empty MHE	External Store	Machine input buffer	Creation time transport order
Timely removal of empty MHE	Machine output buffer	External Store	Creation time transport order

Table 27 - Transport order parameter values per transport task

TIMELY REMOVAL OF MANUFACTURED TIRE PARTS

Transport orders to remove manufactured tire parts are created when a manufactured tire part is placed on a cart which is then fully loaded or when the manufactured tire part is the last part of the PO.

The pickup location is the machine output buffer where the loaded cart is waiting for transport.

The destination is the external store for the specific tire part type. Recall that every tire part type has its own external store. The simple transport rule that is adopted is that manufactured tire parts that are removed from the machine are always transported to an external store. There a new transport order is created to complete the task to timely deliver input parts to a machine. This means that in the simulation tire parts are never transported directly from machine to machine. This is done to reduce the complexity of the transport system and therefore the simulation model.

The priority of the transport order is the creation time of the transport order. Machine output buffers are small and it is important that items located there are removed soon after they are placed there.

TIMELY DELIVERY OF MANUFACTURED TIRE PARTS

Transport orders needed to get the required tire parts to the corresponding machine are created when a cart with assigned tire parts is placed in the external store.

The pickup location is the external store, the destination is the consuming machine also called the target machine.

The priority of the transport orders is the due time of the tire part packs. Recall that this is the planned start time of the PO the tire parts are assigned to.

Timely removal of MHE

When the last tire part pack on a cart is consumed, and the MHE becomes empty a transport order is created.

The pickup-location is the output buffer of the machine.

The destination is the external store assigned to the MHE. A simple transport rule is chosen again. All empty MHE are always transported to an external store. When the empty MHE arrives at the store a transport order might be created to serve the task to Timely delivery of required MHE.

The priority is the creation time of the transport order because the item(s) to transport are located in a small machine output buffer.

Timely delivery of required MHE

Before it is discussed when transport orders are created, it must be formalized when empty MHE are required. Again a simple control rule is chosen. If there are less the five items of a type of MHE that is required by a machine are present at the input buffer of that machine, empty MHE of that type is required. Said differently, the reorder point of empty MHE is five for each type of MHE.

Transport orders are created due to two events. (1) Empty MHE is consumed by the machine and falls below the reorder point and that MHE is present and available at an external store (2) Empty MHE arrives at an external store, which is required, by one of the machines. Note that if multiple machines require the same empty MHE, the destination of the MHE is the machine with the lowest stock. If the stock is the same the machine that comes first alphabetically is chosen.

The pickup location is the external store where the empty MHE is located and the destination is the input buffer of the machine the empty MHE is assigned to.

The transport priority is set at the transport order creation time. It might be the case that the empty MHE is completely depleted in which case transport must be commenced as soon as possible.

Transport Order execution

Transport orders are executed as soon as possible. There are two events that can trigger the execution of a transport order. Either a transport order is added to the transport order list or a tow truck driver becomes available. When a transport order is added to the transport order list the transport control system (TCS) checks is a TTD is available. If a TTD is available, the transport orders with the highest priority is executed.. Similarly, when a TTD becomes available, the TCS checks if there are transport orders. If there are transport orders, the transport order with the highest priority is executed. If a TTD becomes available after it has finished a transport order and no transport orders are available it drives to the tow truck store. A buffer where all tow trucks are located when idle and waiting on transport order. Note that while TTD is driving toward the two truck store the driver is not available. A TTD is only available directly after it has finished a transport order and when it is located in the tow truck store.

Transport order execution times

The execution of a transport order consist of a selection of actions listed in ***Table 28***. For each action, a standard time is determined.

Action	Value	UoM
Scan tire parts packs in cart	5	[s]

Load cart behind tow truck	5	[s]
Transport	2.1	[m/s]
Unload cart to destination	5	[s]

Table 28 - Transport order execution action overview

Execution of a transport order starts with a tow truck driving to the location of the cart. When the tow truck arrives at the cart, the cart is loaded behind the tow truck and the tire part packs are scanned if required. The TTD transports the cart to the destination. When a TTD arrives at the destination, the cart is unloaded. At this point the TTD becomes available again and tries to execute the next transport order

4.2 VALIDITY ASSUMPTION DOCUMENT

The validity of the assumptions made in the previous section is further elaborated on where necessary

In the previous section, assumptions are presented in order to create a simulation model. The validity of these the assumptions is discussed before the model is implemented in plant simulation. ***TABLE 29*** states the assumptions.

Assumption	**Validity (impact)**
All production orders of the CBMs are sequenced of due time of the parent order only (No grouping of POs on Input type in order to reduce setup.	If production orders are grouped together than many tire parts are manufactured before other tire parts which have an earlier due time. The tire parts that are manufactured earlier occupy MHE that cannot be used for tire parts that are manufactured later. This means that more MHE is required to keep production running. This is not a valid assumptions to determine the performance of the real system. However it does provide a valuable insight in to how many MHE is needed if no grouping occurs. Because the grouping and sequencing procedure is complex to model and more data must be collected for it, grouping POs is disregarded.
No production of unassigned tire parts (No store orders)	Store orders are introduced to get large enough production series with the same input. Since sequencing of POs on input is disregarded store orders serve no purpose anymore.
All liners and reels are permanently attached to the carts	If liners and reels are fixed to the carts this means that if a cart containing four sets of liners and reels is loaded with two tire part packs, two liners and reels are used, when otherwise they would be removed from the cart and used for the next part. Since the main interest of the study is in transport workload and the number of carts to use, the inaccurate use of liners an reels does not outweight the added complexity needed to model liners and reels separately from the cart objects.
Manufactured parts are always transported to an external store first and from the external store to the target machine	In the real system it is estimated that around 30% of the manufactured tire parts is transported directly to the machine. Since the direct route form source machine to target machine is shorter than from source machine to external store to target machine the assumption will lead to an increase in transport workload. This overestimation of the transport workload is taking for granted because the implemented transport rules are much easier to model.
Exactly the right amount of tire part is manufactured for each PO (No Leftovers occur)	IF there are no leftovers, No leftovers are transported from the target machine (back) to an external store. This leads to a reduction of transport workload. Since in practice there

	are not many leftovers that are transported back to an external store this assumption does not impact the results much. However, if there are no leftovers, there are also no unassigned tire parts. Which means that no tire parts have to be assigned to POs. and the production size of these POs does not have to be changed. This greatly reduces the complexity of the model which outweighs the loss of accuracy in calculating the machine workload.

Table 29 - Validity assumption document

4.3 THE PLANT SIMULATION MODEL

The model described in ***SECTION 0*** is translated to a plant simulation model. During contstruction of the model in PS changes have been made to the logical model to accommodate the modeling process this has been an iterative process as described in ***SECTION 3.5***. Figures are shown and the implementation of the empty MHE Manager is described to give an impression of the working of the PS model in general.

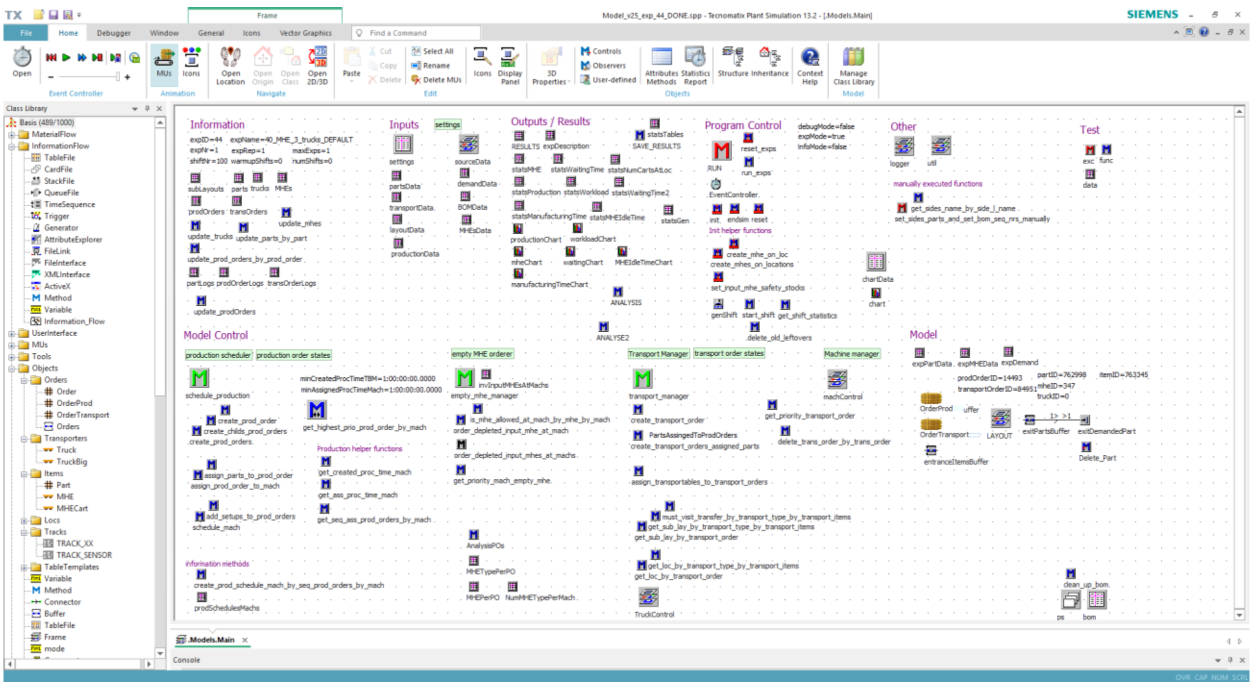


Figure 25 - PS model main method

FIGURE 25 gives an impression of the overall view of the main model. All the icons represent PS objects. This can be methods, tables, movable objects and variables.

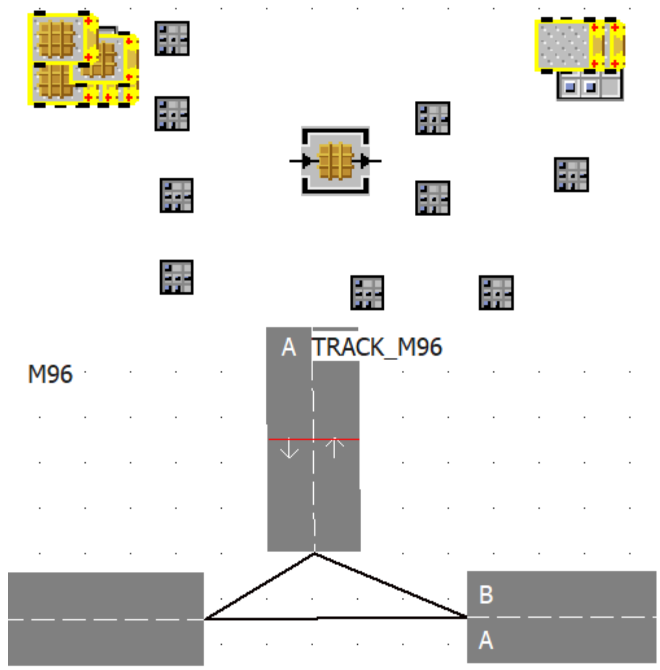


Figure 26 - Part of the layout during simulation in PS model

FIGURE 26 shows part of the layout during a simulation run. Observe on the left upper corner the input buffer of M96 tire building machine full with tire parts on MHE. In the upper center the processing station of M96 with a tire part being manufactured. In the right upper corner the empty MHE. There are three two lane tracks connected with connectors to move the items. The red line in the middle track is the sensor where the truck drives towards to (un)load items at M96.

4.3.1 IMPLEMENTING EMPTY MHE MANAGER IN PLANT SIMULATION

The empty MHE manager keeps track of the inventory of empty MHE at all machines and calls the transport manager when a transport order must be created. The empty MHE manager is a method object (see ***3.3.1***) which has two input parameters, the eventID of datatype integer and eventMHE of datatype object. See ***FIGURE 27*** for part of the code of the Empty MHE manager method. The entire code of the empty MHE manager is found in XX.

```
...empty_mhe_manager

param eventID: integer, eventMHE: object -- eventSubLay: object

-- is mhe simulated?
if not root.settings["simMHE",#expID]
  return
end

-- set local variables
var eventSubLay: object:= eventMHE.get_sub_Lay()
-- get all mhes
var mhes: object[] := eventMHE.get_all_mhes()  -- includes self
var inv:object:= invInputMHEsAtMachs
if eventID = 0 or eventID = 1 then
  var mach: object:= eventSubLay
elseif eventID = 2
  var store: object:= eventSubLay
end

-- ============= UPDATE INVENTORY EMPTY MHE AT MACH =============
-- update "stock" and "ordered" inventory available input mhe(s) at machine(s)
var idx: integer
if eventID = 0
  -- mhe (with contents) arrive at mach -> does empty mhe arrive?
  if not eventMHE.has_parts then
    for var i := 1 to mhes.dim
      idx := inv.getRowNo(mhes[i].name + mach.name)
      inv["stock", idx] += 1
      inv["ordered",idx] -= 1
    next
  end
elseif eventID = 1
  -- input mhe consumed by mach -> subtract consumed MHE from stock
  idx := inv.getRowNo(eventMHE.name + mach.name)
  inv["stock", idx] -= 1
end

-- ============= ORDER EMPTY MHES =============
-- order depleted input mhes at mach
var mainMHE: object
```

Figure 27 - Part of empty MHE manager method code

The eventID is an enumerator with all possible events:

0 item(s) received by machine
1 input MHE consumed by machine
2 item(s) received by external store

The eventMHE parameter contains a cart object. If an item is received by a mach the received item is the eventMHE, if input MHE is consumed by mach, the eventMHE is the MHE consumed and if a cart enters an external store the arriving cart is the eventMHE.

A table called invInputMHEsAtMachs is used to keep track of the inventory (see ***FIGURE 28***). The table is initialized at the start of each simulation. For each Machine-Empty MHE combination possible under the simulation settings a row is created. ‘stock’ and ‘ordered’ are set to 0 and the safetyStock at the chosen empty MHE reorder point of five. The table helps the empty MHE manager.

.Models.Main.invInputMHEsAtMachs

	string 0	string 1	string 2	integer 3	integer 4	integer 5
string	idx	MHEName	MachName	stock	ordered	safetyStock
1	CINNER_LN150_6KAL3	CINNER_LN150_6	KAL3	0	1	5
2	CINNER_LN090_6KAL3	CINNER_LN090_6	KAL3	5	0	5
3	CSIDE_HSP90_6_LNHSP90_6DSE	CSIDE_HSP90_6_LNHSP90_6	DSE	0	0	5
4	CSIDE_HSP90_6_LNHSP90_6TRIPL	CSIDE_HSP90_6_LNHSP90_6	TRIPL	0	0	5
5	CSIDE_HSZKB_4_LNHSZKB_4TRIPL	CSIDE_HSZKB_4_LNHSZKB_4	TRIPL	5	0	5
6	CTREAD_HSPBR_4_LNHSPBR_4QUADR	CTREAD_HSPBR_4_LNHSPBR_4	QUADR	3	0	5
7	CTREAD_HSP75_4_LNHSP75_4QUADR	CTREAD_HSP75_4_LNHSP75_4	QUADR	0	0	5
8	CTREAD_HSPBR_4_LNHSPBR_4TRIPL	CTREAD_HSPBR_4_LNHSPBR_4	TRIPL	3	0	5
9	CTREAD_HSPBX_3_LNHSPBX_3TRIPL	CTREAD_HSPBX_3_LNHSPBX_3	TRIPL	5	0	5
10	CTREAD_HSP75_4_LNHSP75_4TRIPL	CTREAD_HSP75_4_LNHSP75_4	TRIPL	1	0	5
11	CPA_LN080VPA	CPA_LN080	VPA	0	0	5
12						
13						

Figure 28 - Empty MHE Inventory table

How each possible event is called and handled is discussed individually.

ITEM(S) RECEIVED BY MACHINE

Every time a cart enters a machine input buffer object a method is called. This method in turn calls the empty mhe manager with the correct parameters. See ***FIGURE 29*** for part of the code that calls the empty mhe manager when an item is received by a store object. Note that the method receive_item manages the arrival of items both at machine input buffers and external stores.

.Models.Main.LAYOUT.DSE.receive_item

```
-- ============== MANAGE EMPTY MHE ==============
switch subLay.superType
case "MACH"
  root.empty_mhe_manager(0, receivedItem)  -- 0 = mhe (and contents) received by MACH
case "STORE"
  root.empty_mhe_manager(2, receivedItem)  -- 2 = mhe (and contents) received by EXTERNAL STORE
else
  debug
end
```

Figure 29 - Code from receive_item method that calls the empty MHE manager .

When the empty mhe manager is called the empty mhe manager increases the stock for the machine-MHE combination in the table by one and descrease the 'ordered' value in the same row by one

INPUT MHE CONSUMED BY MACHINE

When a machine consumes MHE the empty MHE manager is called with eventID = 1. In this case there are a couple of actions taken. (1) The stock in the table in the row with the correct machine-MHE combination is decreased by one (2) if the 'stock' plus the 'ordered' column in the row is less than the 'safetyStock' number the now required MHE is ordered if the nescesary empty MHE is found. If the MHE is found the transport manager is called to generate the actual transport order for the found MHE to be transported to the requiring machine. If this is the case the 'ordered' column is inscreased by one.

ITEM(S) RECEIVED BY EXTERNAL STORE

When an item is received by an external store the empty manager checks in each row of the table if the received MHE is needed at one of the machines. If a machine is found, the transport manager is called again with the request to create a transport order for the reveived item to be transported to the requiring machine.

4.4 MODEL VERIFICATION

The model is verified using different methods during and after model contruction. During the contruction of the model each method is walked trough step by step to verify that the method works as expected and all attributes are set appropriately.

During and after model contruction the model is inspected visually. Animation shows the state of the machine and where the movable items are located during a simulation run. This way the movement of items is verified.

Additional statistics are gathered during test runs. This data is analyzed to check if the data is in the range of values that is expected.

In many methods there are error handlers created that alert the user if a situation occurs that is at odds with the intended model. For example if an empty MHE located at an external store has the state "waiting to be consumed by mach" the user is notified that this state is invalid at the location.

4.5 DESIGN EXPERIMENTS

When designing experiments there are two parameters that must be determined. (1) The length of a simulation run and (2) the length of the warmup period.

The length of a simulation run depends on the variability of the output data. In this case, for example the variability of the production output per shift. If the variability of the production is large, a longer simulation run is needed. This way there are more data points to use in a Pairwise T-test (see ***3.4)*** to find statistical differences between experimental setups. If the variability within one experiment is large and there are not many data points the impact of the investigated parameter may not surface within the randomness of the system. After preliminary experiments it is determined that the variablilty of the output parameters is not large and 100 data points will suffice.

The warmup period of the simulation is the time it takes a simulation run to reach steady state. Production output is a good parameter to determine the warmup period. The warmup period is defined as the number of shifts it takes before the production output within a shift is larger than the average production output of all shifts without the shifts within the investigated warmup period. For different scenarios the warmup period is determined and the largest value found to reach a steady state is after three shifts. Three shifts is taken as the warm-up period for all experiments. This means that the first three shifts are disregarded as data points in the results.

4.6 RUNNING EXPERIMENTS

During simulation in Technomatix Plant Simulation all data is collected and written in tables. At the end of each shift summary data is collected and written in tables. At the end of a simulation run all output data is calculated and collected. The result are stored in text files for further processing in Plant Simulation and MS Excel.

4.7 OUTPUT DATA PROCESSING AND ANALYSIS

During each simulation data is collected to compare the different scenarios described in ***SECTION 4.1.3***. The data to be collected is already described in ***TABLE 16***. The analysis of the collected data follows in the next chapter.

5 RESULTS & ANALYSIS

The production output is determined for many configurations of tow trucks and MHE. The relation between these parameters is discussed first. More detailed analysis of the transport workload, including a sensitivity analysis; the number of used MHE and the resulting storage space follow.

5.1 PRODUCTION OUTPUT

The main finding of the simulation study is the realized production output under constrained transport and storage in the form of limiting the number of tow trucks and MHE available. This relation is presented in ***FIGURE 30***.

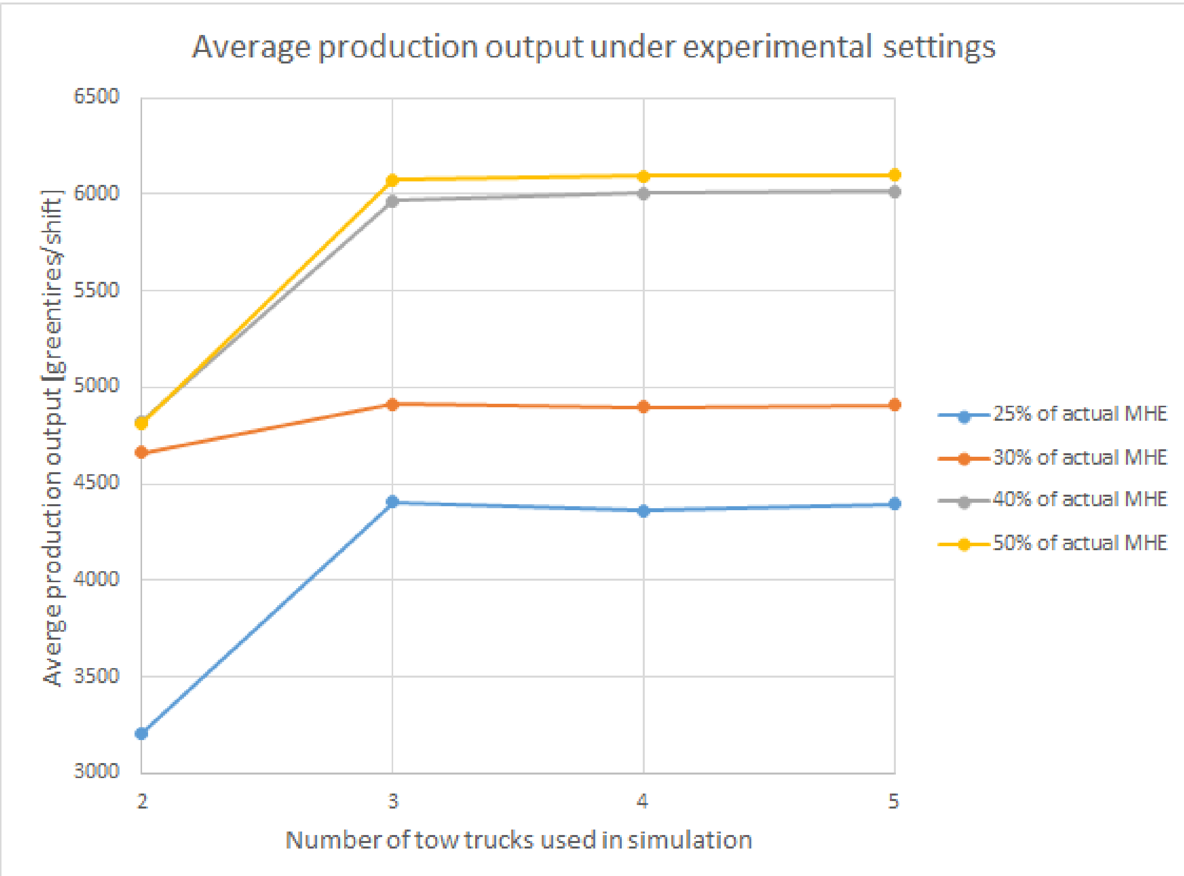


Figure 30: Relation Production output vs # tow trucks and MHE

The foremost observation is that the production output is constrained by the number of tow trucks and number of MHE. In case of an unlimited number of tow trucks and MHE an production output of around 6200 greentires per shift are manufactured whereas in the most restricted case (two tow trucks and 25 percent of the currently used MHE the production output is reduced to 3200 greentires. A reduction of around 50 percent.

Optimal number of towtrucks

Observing the relation between number of tow trucks and the produciton output it is clearly seen that, given unlimited MHE, when three or more tow trucks are used the production is (near) maximum. The production output starts to decrease when fewer than three tow trucks are used. It seems that three tow trucks are suffient to transport the MHE and tire parts between the machines and external stores. Further analysis of the transport workload is presented in ***SECTION 5.2***.

Optimal number of MHE

Similar to the number of tow trucks there is also a sharp decrease in production output when the number of available MHE is 30 percent or less of the currently used MHE instead of 40 percent or more. This suggest that somewhere between 30 and 40 percent of the currently used number of MHE is sufficient to keep maximum production output under the simulated conditions. Utilization of the MHE during the simulation is discussed in detail in ***SECTION 5.3***.

Cross influence MHE and tow trucks

It is observed that an decrease in MHE cannot be compensated for by more tow trucks or vice versa. It could be possible that when few MHE are available a more responsive transport system, by means of more tow trucks, can move MHE quicker to the required machines. This in turn allows the CBM to manufacture a tire part earlier which can than be transported to the required TBM earlier and faster. Apparently this is not the case. It could be possible that in case the MHE become critical the bottleneck are the machines that must consume the tire parts for the MHE to become empty. The time MHE waits to become empty and thus available is small relative to the time it takes after that to transport the empty MHE to a machine it requires. That te transport system is faster does not matter in this case.

Benchmark case

Based on the above situation it is observed that under the simulated conditions a near optimum production output can be sustained by using **three tow trucks** and **40% of the actually used MHE**. This case will be used in the remaining analysis and is named the benchmark simulation.

5.2 TRANSPORT WORKLOAD

The transport workload is divided among the tow trucks and is made up by the (un)loading and driving time. Transport is always carried out by two truck one unless it is occupied, then transport is carried out by tow truck two and so on. With an unlimited number of tow trucks a maximum of 28 tow trucks are in use simultaneously. Of course this is far from optimal since the last tow trucks will be inactive more than 95% percent of the time. It is far more interesting to look at the individual workload of the trucks around the critical number of tow trucks during production. ***FIGURE 31*** shows the individual working time during the simulation for three and four tow trucks.

In case of the simulation runs with two tow trucks they are both occupied nearly 100% of the time.

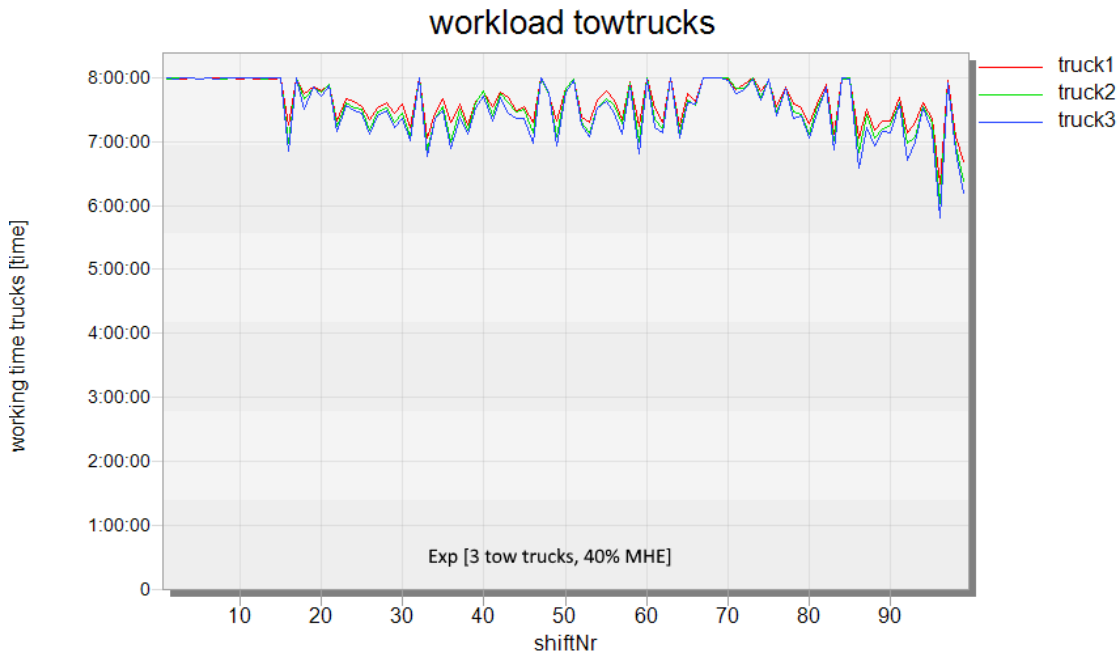


Figure 33.1: Three tow trucks

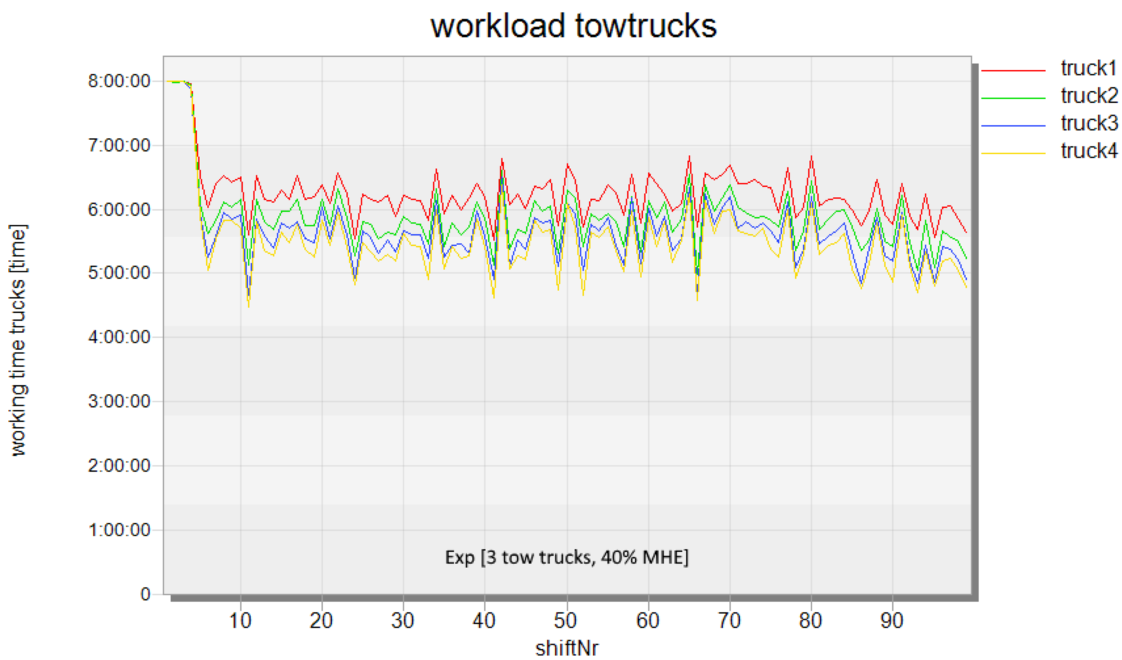


Figure 33.2: Four towtrucks

Figure 31: working time per tow truck per shift

Three tow trucks

In this case all three tow trucks are continuously active during many of the simulated shifts indicating that the workload during some shifts is too high to handle where in others there is some overhead. A clear sign that three tow trucks are about adequate to handle the transport workload. It also shows that apperantly the transport workload is not equal during each shift and it can well be possible that at a peak transport moment production output may be reduced. A phenomenon that cannot be observed in ***FIGURE 30***.

The workload between the tow trucks barely fluctuates as is expected. When workload is critical there are usually more than enough open transport orders for every tow truck.

Four tow trucks
The most important observation in the case of four trucks is that there is an over capacity during the complete simulation disregarding the warmup period in which the empty MHE buffers for the CBM are stocked. Interessetingly, the average utiliy of the four tow trucks is 75% exactly an equavalent of three trucks. The fact that when three trucks are used they are not continously working during each shift is because when more tow trucks are used simultanenously there is more transport of empty trucks between the truck store and the (un)loading locations. The transport time of the empty trucks is part of the transport workload.

5.2.1 SENSITIVITY ANALYSIS

When three tow trucks are used these are almost continuously utilized. It is therefore interesting to observe what will happen if some of the assumed transport system parameters deviate. The transport speed and transfer time are taken because these are the two choses parameters which make up the total transport workload (together only with the time a tow truck is blocked by another tow truck)

Transport speed
The main portion of the transport workload is made up by driving time between the locations. It is assumed that the tow trucks drive with a constant speed of 2.1 m/s. This results in a total driving time in the benchmark simulation of 17 hours or 2.5 tow trucks continously working. If the driving speed deviates by only 1 m/s the resulting transport time due to driving would be between 9 and 25 hours or between 1.7 and 3.2 tow truck equavalents. This shows that when the average tow truck driving speed divers by only 1 m/s the workload can fluctuate by 1.5 tow truck. A simulation run with three tow trucks, 40% MHE and a driving speed of 1.1 m/s results in a driving time of 9.6 hours similar to the calculated 9 hours what is expected.

Transfer time
The average number of executed transport orders during a shift in the benchmark simulation is 865. This leads to an average transfer time of 4.8 hours per shift. (loading and unloading during 10 seconds) If (un)loading takes 20 seconds, which is often the case in the non ideal situation where MHE is not neatly stored and placed at the correct location the the workload is increased by 4.8 hours or 0.6 tow truck equavalent. This shows the potential gain of being able to quickly (un)load carts. No simulation run is performed to confirm this reduction.

5.2.2 TRAFFIC TIME

Given that more than one tow truck is in transit during production, tow trucks can block each other when (un)loading at the same location at the same time is required. This is named the traffic time. During the benchmark simulation the average traffic time per shift is ten minutes with a standard deviation of two minutes. On an average transport workload of more than 22 hours the traffic time makes up less than one percent and can be regarded as a minor issue in the simulated system.

5.3 MHE UTILITY

The utilized MHE, defined as all MHE loaded with tire parts or Empty MHE used a safety stock at the input buffer of a machine, during the benchmark simulation is presented in ***FIGURE 32***.

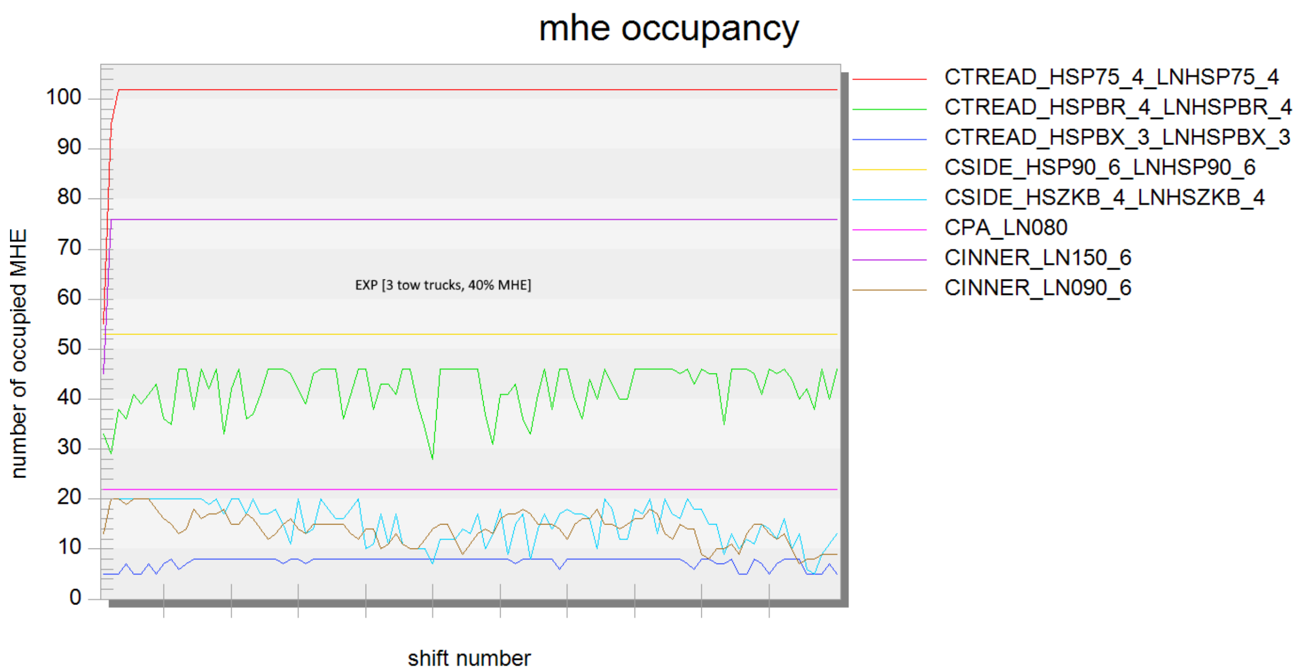


Figure 32: MHE utilization during benchmark simulation

From the utilization of all the different MHE it is immediately, clear that not all MHE types are utilized completely and thus form a bottleneck Clearly, CTREAD_HSPBR, CSIDE_HSZKB and CINNER_LN090 carts are less critical than the other MHE types. Interestingly the non-critical MHE types are all the less common variant storage variant per tire type. The demand for the less common variant may fluctuate more intensely than the more common variant and therefore more MHE may currently be in use at the company.

All other MHE types are utilized 100 percent of the time. This is to be expected because the supplying CBMs do not have a production stop and 24 hours of WIP can be created whereas in the benchmark situation only for around 5 hours of WIP can be stored on the MHE. If MHE occupancy is to be used as an indication of the criticality of the number of MHE required production must be restrained. Otherwise, the CBMs that have overcapacity will keep manufacturing tire parts until there is no more MHE (or no more production orders).

5.4 STORAGE SPACE

The maximum storage space of interest that WIP occupies during production simulation for the benchmark settings results in ***TABLE 30***.

Store location	Store type	Maximum occupancy	Estimated current size
TBM	Input buffer	26	9 - 36
	Output buffer	3	Unspecified

CBM	Input buffer	20	13 – 45
	Output buffer	3	2
PA	Input buffer	78	15
	Output buffer	3	Unspecified
ZIJLOS	External Store	22	24
LOLOS	External Store	28	150
PASTORE	External Store	2	10
PGVLOS	External Store	24	25

Table 30 - Occupancy during simulation run (num. tow trucks = 3, MHE % = 30#)

The storage locations groups consist of all TBMs, CBMs (excluding PA) and the separate external stores. The machine locations separate an input and output buffer. The maximum occupancy is the maximum number of carts present during any part of the simulation at the specified location. The estimated current size is the range of the approximated total number of storage locations for the carts used in the simulation study at each location. Where there are different storage sizes for machines belonging to the same category the minimum and maximum range is given. For example at M92 there is space available for 9 carts and at M600 there is space available for no less than 36 carts.

Output buffer

Observe that the maximum output buffer occupancy is three carts. This is an indication of the responsiveness of the transport system. Before a fourth cart can be placed in the output buffer of a machine location one of the transporters already removed the third cart. Therefore, no more than three cart locations are needed at each machine output buffer under the benchmark settings to make sure a machine has to stop due to buffer overflow.

Input buffer

The occupancy of the input buffer is in general larger than the current available buffer space. For the TBM and PA input buffer this is caused due to the fact that each cart loaded with tire parts is allowed to be transported to the machine requiring those parts. In the actual system, parts are only allowed to go to their required machine within eight hours of the planned start time of the production order they are assigned to. If this control rule would be implemented, all input buffers with tire parts in them would have a reduction in the maximum occupancy. Recall that in the simulated situation up to 24 hours of tire parts can be created. All these tire parts are allowed to be transport to the machine input buffer. In the worst case three times as many carts with tire parts can occupy space at the machine input buffers than in the actual system.

The CBM input buffer is neatly within the currently used range. The maximum occupancy of 20 carts at a CBM is not surprising. Recall that for each type of MHE there is a safety stock of five. Some CBMs such as the TRIPL use four different types of empty MHE. If all these MHE are available there are 20 Empty carts at the TRIPL. This is exactly what we see in the results.

External stores

The foremost observation is that the maximum occupancy of LOLOS during the simulation is only 20 percent of the estimated storage space. This has several reasons. (1) Production orders are not grouped together by input compound therefore all parts are manufactured in the same sequence they are used, leading to faster throughput and therefore shorter MHE occupancy. (2) there are no bulk production orders in the simulation study which would otherwise occupy MHE in LOLOS. (3) There are no leftover parts that would be placed on MHE and wait in LOLOS until assigned to a new production order and transported to the acquired TBM.

Interestingly, ZIJLOS and PGVLOS external stores for sidewall and Innerliner parts are close to the estimated capacity. Given reason (2) and (3) it is expected that a similar difference would occur at these external stores. It seems the ZIJLOS and PGVLOS buffer are smaller relative to LOLOS which is to be expected looking at the estimated size of the buffer and the observations that the average number of carts per production order for sidewall and innerliner are not very dissimilar to those of treads. It comes as no surprise if there are currently buffer overflow issues regarding the ZIJLOS and PGVLOS external stores as is reported.

6 DISCUSSION

Any model is but a representation of a real system and therefore assumptions must be made to be able to create a model of a system. The transport system of a tire manufacturing company is no different. For any system simplification and assumptions can be made about that do not influence the phenomena of interest. Unfortunately, in this study simplification and assumptions are made about the transport system of the investigated company due to the highly complex way of managing transport and the complex way the production is scheduled in the actual system. The assumptions made have an impact on the acquired optima's found and presented in the previous chapter. The complete assumption document is given in ***SECTION 4.2*** where the expected results of the assumptions are given. Here the impact of the assumptions and simplifications on the results are discussed.

UNDEFINED TRANSPORT
To be able to model a transport system in reasonable time it must be based on clearly defined rules. In the real transport system the tow truck drivers often have to find transport jobs and available storage locations themselves. This will take up time that is not represented in the model. The found transport workload is expected to be lower than what is actually needed if one would work as in the actual system because of this assumption. However there are two arguments to use clearly defined transport rules. The complex human behavior is impossible to model in the first place. Even if this could be modeled, it is not the way transport should be managed. Searching for empty space and storing carts at unspecified locations is inefficient and leads to loss of valuable production time when tire parts simply cannot be found in a large factory.

PRODUCTION SCHEDULING DUE TO SETUP REDUCTION
As explained in ***SECTION 4.1.5*** the extruders used to manufacture tire parts take up around 20 minutes to setup when the rubber input components differ. In order to reduce these setups production orders with the same input component are grouped together in order to reduce this setup time. This results in production orders not being manufactured in the sequence in which they will be consumed by the TBMs. Tire parts manufactured long before they are due occupy MHE for a longer period of time. These occupied MHE cannot be used during this time, thus more MHE are needed to store tire parts. Disregarding grouping of production orders on their input components thus leads to an underestimation of the required number of MHE. This impact can be great.

If it is assumed that there are 24 hours of production orders sequenced, the grouping window is also 24 hours, there are six different inputs and the same amount of production orders for each input type. Than each production batch is around 4 hours. In the worst case scenario the first six production orders sequenced on due date all have a different input type, This means that the sixed highest priority production order is only manufactured after 20 hours' worth of production time is manufactured before it. All these tire parts are stored on MHE. On average one production order takes up around 2 hours of production time and around 2 carts. This results in 24 more occupied MHE when the sixth highest priority production order is manufactured. 24 additional MHE are much compared to on average around 50 MHE of a single MHE type found as optimal.

LEFTOVERS
In the actual system production orders are rounded up to fully fill the MHE. When different tire part types are used to make a greentire some the tire part types are depleted before the others. When one of the tire

parts is depleted production stops and the leftover tire parts are transported to the external stores where they will be assigned to a new production order that uses that tire part. Assuming that there are no leftovers as the model does results in an underestimation of the number of tow trucks and MHE required. More transport is required because all leftover parts are transported to an external store and to the TBM of the production order they are assigned to next. The time from when a tire part becomes leftover until the time it would be manufactured would it not exists is the additional time the leftover tire part occupies the MHE. During this time this MHE is not available and additional MHE is needed to replace it.

The extent to which these assumptions change the found results is the unknown inaccuracy of the results. This must be kept in mind while using the results to make changes to the actual system. It is estimated that additional transport workload to handle leftovers is between five to ten percent of the total transport workload. Only a small fraction of all tire parts becomes leftover.

PRODUCTION OUTPUT

Looking at the results the general finding is that they are inline with what is expected. Due to unconstrained number of tow trucks and MHE it is expected that production output is 6300 greentires per shift. This is the number of greentires that is produced when all TBMs manufacture greentires without delay at standard manufacturing speed during one shift with a downtime of 15%. In the real system around 5600 tires are manufactured. If output loss due to machine tardiness, which in the actual system is around seven percent, is subtracted from the simulation results, the production outputs of the simulation mode and the actual system are within the same range.

6.2 NUMBER OF TOW TRUCKS

In the actual system five tow trucks are used for transporting tire parts. However these tow trucks are responsible for the transport of all tire parts. Recall that in the simulation the transport of beads, ply, and steelbelt tire parts are disregarded. It is estimated that the disregarded tire parts account for around 30 percent of the transport workload. This means that for the parts that are simulated it is expected that 3.5 tow trucks are needed. The study shows that with the implemented transport control rules 3 tow trucks are needed.

6.3 NUMBER OF MHE

Similar to the number of tow trucks the number of MHE in the system can cause a reduction in production output. CBMs will not manufacture a tire part until an empty MHE arrives on which the tire parts can be loaded. If all MHE are occupied the machine has to wait until the contents on an MHE are consumed by a TBM and the empty MHE is transported to the requesting CBM. Only then, the CBM resumes production. If a TBM is waiting until a tire part arrives, and that tire part is waiting to be manufactured because there is no empty MHE, the production output reduces. If there are fewer MHE in the system, the likelihood a CBM has to wait until empty MHE arrives increases.

The simulation results show that loss of production output occurs first when the number of MHE used is 30% of the currently used number of MHE. If All the actually used MHE are occupied by tire parts it will take all TBMs approximately 24 hours to completely consume all the manufactured tire parts. Equally, 100% MHE is approximately equal to 24 hours of WIP. If 40% of the MHE is used about 10 hours of production time is present as WIP.

Little's law can be applied to determine the lead time of a cart through the system. The law states that the lead time is equal to the WIP divided by the throughput. Take for example CINNER_LN150 carts used to transport innerliner parts. The WIP when all CINNER_LN150 are loaded is 75. On average, each TBM completes 2.3 POs per shift and each PO uses 1.7 CINNER_LN150. Since there are 15 TBMs manufacturing simultaneously the lead time according to little's law is 75 CINNER_LN150 divided by 59 carts /shift is 1.3 shifts or 10 hours. This is to be expected. If there is on average 10 hours of worth of production time available. It takes 10 hours to deplete all WIP and the MHE can be used again. This is the definition of lead time. The time it takes on average for an item to move trough a system.

$$\boldsymbol{Lead\ time} = \frac{\boldsymbol{WIP}}{\boldsymbol{Throughput}}$$

In summary the results of the simulation study are in line with what is expected which indicates that discrete event simulation can be used to obtain accurate number of tow trucks and MHE required in a transport system. The assumptions which made to come to a working simulation model are of such an influence on the obtained results that these cannot be applied on the current system without accounting for the differences between model and system.

7 Conclusions & Recommendations

In general the research shows that with discrete event simulation optima for resources needed for internal transport in manufacturing plants can be found. In this case it is determined that clearly defined transport control rules are needed to be able to create a working simulation model. These rules must be simple enough to be able to be implemented in computer code. If the actual system uses many exceptions to the standard operating procedures and above all uses human intervention this behavior is impossible to model and also undesirable since this is not how a system functions properly. More conclusions are drawn by answering the research questions.

What additional transport control rules are needed to create a working simulation model of the transport system?
The transport rule created to create a working simulation model is the Empty MHE order rule which states that whenever the safety stock of a type of MHE falls below five units a new empty MHE is sent to the machine when available. This rule makes sure that transport orders are created for all transport tasks that the tow truck drivers must execute. In addition, existing transport rules are simplified in comparison to the real system such as the routing that all parts go via an external store.

What is the recommended number of tow trucks needed to transport tire parts and MHE to maximize production under the simulated conditions?
By simulation of tow trucks driving around tracks representing the layout of a large tire manufacturing company and un-loading tire parts and MHE it is determined that three continuously present tow trucks is optimal. This is the number of tow trucks for which case the production output can be maintained at a near maximum possible production output and transport costs are lowest.

What is the recommended number of material handling equipment used for transport of tire parts to maximize production under the simulated conditions
The optimal number of MHE to be used in the tire manufacturing plant is 40% of the currently used number of MHE. This is the lowest number of MHE in which the simulation study maintains near maximum production output and the MHE take up the least space.

To what extend can the company use the findings of the simulation study?
The research shows that under the stated assumptions less resources are needed while maintaining production output. In case of the assumptions the company can determine if the assumptions can be made a reality. Leftovers can be eliminated by manufacturing exactly the right amount.

The transport control rules can be incorporated in the existing transport system to create a more efficient transport system where tow truck drivers do not drive around looking for transport jobs.

7.1 Recommendations

The foremost recommendation is that the company implements the transport control rules created in this study. In order to incorporate these rules the actual transport system must be improved. The information used by the control rules must be gathered and stored in the transport control system. These are defining all individual storage locations and track and trace all MHE. This is needed to implement the empty MHE ordering system created.

In general it is suggested that the transport control system managed all transport and the tow truck drivers do what the system demands instead of partly using a transport control system while managing part of the transport tasks manually leading to inefficiencies and a complex and unmanageable system.

7.1.1 FUTURE WORK

The simulation model can be extended to be able to determine the optimum number of tow trucks and MHE more accurately by implementing phenomena such as tow truck working schedules, machine downtime due to failure, creation and processing of leftovers and production order grouping on input components.

When any of these phenomena is modeled, the optima can be determined again and serve as guide for the actually used numbers. Also the effect of the newly added parameters such as the window by which to group production orders based on input type become interesting to vary to see the effect it has on the optimum number of tow trucks and MHE to use.

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Appendix A OVERVIEW OF MHE

In this appendix an overview of all MHE used in this study is presented.

Tire Part	Cart	Capacity (# Packs)	Pack	PackType	Pack Capacity	Pack2	Pack2Type
Tread	Ctread	4	HSP75	Reel	47 - 75 m	LNHSP75	Liner
		4	HSPBR	Reel	48 - 75 m	LNHSPBR	Liner
		3	HSPBX	Reel	49 - 75 m	LNHSPBX	Liner
Side	Cside	6	HSP90	Reel	60 - 85 m	LNHSP90[1]	Liner
		4	HSZKB	Reel	61 - 85 m	LNHSZKB[1]	Liner
	CsideLNS	16	LNHSP90	Liner			
		12	LNHSZKB	Liner			
	CsideLNL	40	LNHSP90	Liner			
		26	LNHSZKB	Liner			
Innerliner	Cinner	6	LN150	Liner	90 m		
		6	LN090	Liner	150 m		
PA	Cpa	1	LN075	Liner	75 m		
		1	LN080	Liner	80 m		
GT	AGV / Rolling Frame	1	PLR3	Rack	24 pcs		
		1	PLR4	Rack	32 pcs		
		1	PLR5	Rack	40 pcs		
		1	PLR5N	Rack	40 pcs		

Table 31 - Overview MHE names, types and capacities

[1] LNHSP90 and LNHSZKB can only be transported on Cside when loaded on a Reel, not when empty and separated from a reel.

Appendix B EMPTY MHE MANAGER PROGRAMMING CODE

Below the complete programming code of the plant simulation method "Empty_MHE_manager" code is displayed. The code is written in SimTalk 2.0, a plant simulation specific language. The greyed out sections are comments.

```
-- name          input_mhe_orderer
-- purpose       make sure that the used input MHE stock at each machine is kept above the safety stock
--               by ordering available mhe from stores to be transported to machines
-- inputs        simulation event by ID: integer {0: mhe received by mach, 1: input mhe consumed by
                 mach, 2:mhe received by store} mhe (and contents) associated with the event: object {cart with
                 packs, reel, liner}
--               location associated with event: object {machine, external store}
-- returns       -
-- called by     machControl.consume_input_items_by_mach, <subLay>.receive_items()
-- author        Frank Reekers
-- date          01-01-2018
-- version       -

/* summary of method
(1) add received / subtract consumed mhe(s) from invInputMHEsAtMachs["stock"]
(2) subtract consumed mhe from invInputMHEsAtMachs["ordered"]
(3) order depleted MHE(s) at mach(s)
      (1) create transport order to acquired available input MHE
      (2) add ordered mhe(s) to invInputMHEsAtMachs["ordered"] */

/* input mhe orderer eventIDs:
0 = item(s) received by mach
1 = input mhe consumed by mach
2 = item(s) received by store */

param eventID: integer, eventMHE: object -- eventSubLay: object

-- is mhe simulated?
if not root.settings["simMHE",#expID]
   return
end

-- set local variables
var eventSubLay: object:= eventMHE.get_sub_Lay()
-- get all mhes
var mhes: object[] := eventMHE.get_all_mhes()  -- includes self
var inv:object:= invInputMHEsAtMachs
if eventID = 0 or eventID = 1 then
   var mach: object:= eventSubLay
elseif eventID = 2
   var store: object:= eventSubLay
end

-- ============ UPDATE INVENTORY EMPTY MHE AT MACH ============
-- update "stock" and "ordered" inventory available input mhe(s) at machine(s)
var idx: integer
if eventID = 0
   -- mhe (with contents) arrive at mach -> does empty mhe arrive?
   if not eventMHE.has_parts then
      for var i := 1 to mhes.dim
         idx := inv.getRowNo(mhes[i].name + mach.name)
         inv["stock", idx] += 1
```

```
            inv["ordered",idx] -= 1
        next
    end
elseif eventID = 1
    -- input mhe consumed by mach -> subtract consumed MHE from stock
    idx := inv.getRowNo(eventMHE.name + mach.name)
    inv["stock", idx] -= 1
end

-- ============= ORDER EMPTY MHES =============
-- order depleted input mhes at mach
var mainMHE: object
if eventID = 1
    -- mhe consumed by mach -> is mhe at mach depleted?
    idx := inv.getRowNo(eventMHE.name + mach.name)
    if inv["stock", idx] + inv["ordered", idx] < inv["safetyStock", idx]
        -- mhe is depleted at mach -> order mhe from store
        store := root.util.get_store_loc_by_mhe_name(eventMHE.name)
        for var i := 1 to store.numMU loop
            mainMHE := store.mu(i)
            if order_depleted_input_mhe_at_mach(mainMHE, inv["MHEName",idx], mach)  -- inputs: available MHEs,
                                                                                     needed MHE, needing MACH
                return
            end
        next
        if inv["stock", idx] = 0
            --root.logger.log_warning(inv["MHEName", idx] + " is depleted and not ordered for " + inv["machName", idx])
            --debug  -- can depleted needed empty mhe not be ordered?
        end
    end
elseif eventID = 2
    var deplMHEName: string
    -- mhe arrived at store -> is mhe available?
    if not eventMHE.is_available
        -- mhe not available -> stop search for depleted mhe on arrived cart at store
        return
    end

    -- Sent empty mhe to priority mach
    var machs: object[]; var invs: integer[]; var po: object
    for var i := 1 to inv.yDim
        if inv["stock", i] + inv["ordered", i] < inv["safetyStock", i] and inv["MHEName", i] = eventMHE.name
            machs.append(root.util.get_mach_by_mach_name(inv["machName", i]))
            invs.append(inv["stock", i] + inv["ordered", i])
        end
    next
    if machs.dim = 0
        return
    elseif machs.dim = 1
        mach := machs[1]
    else
        if invs[1] /= invs[2]
            -- sent cart to mach with least MHE in stock
            if invs[2] > invs[1] then mach := machs[1] else mach := machs[2] end
        else
                -- sent cart to mach which needs MHE first (= mach with po that uses MHE and has earliest   duetime)
            var pOrders: object[]
            for var r := 1 to root.prodOrders.YDim
                pOrders.append(prodOrders[0,r])
```

```
            next
            pOrders := root.util.sort_prod_orders_on_due_time(pOrders)
            var stop: boolean:= false
            for var i := 1 to pOrders.dim
                if pOrders[i].state < 4 and root.expPartData["transportable", pOrders[i].partName] = eventMHE.name
                    for var j := 1 to machs.dim
                        if pOrders[i].mach = machs[j]
                            mach := machs[j]
                            --print(to_str(eventController.simTime) + ": move empty " + to_str(eventMHE) + "("+ eventMHE.name
                                +") to " + mach.name + " for p.o " + to_str(pOrders[i].Id))
                            stop := true
                            exitloop
                        end
                    next
                end
                if stop then exitloop end
            next
            if mach = void
                if z_uniform(1,0,1) > 0.5 then mach := machs[1] else mach := machs[2] end
            end
        end
    end

    if not order_depleted_input_mhe_at_mach(eventMHE, eventMHE.name, mach)
        debug
    end
end
```

Appendix C MEASUREMENTS TRANSPORT SPEED

The table shows the measured transport time and calculated transport speed for transport between various locations throughout the plant.

From	To	Time [m:s]	Distance [m]	Speed [m/s]
400	KAL3	2:22	319	2.2
CWW	STRAM	0:37	59	1.8
98	82	1:07	143	2.1
PGVLOS	KAL3	1:58	205	1.7
TRIPL	LOLOS	0:59	114	1.9
92	700	1:19	140	1.8
82	PGVLOS	1:44	83	2.0
HL1	98	1:16	262	2.8
QUADR	LOLOS	0:45	65	1.7
VSC1	OSSEBOER	1:17	128	2.0
HL1	98	1:15	262	2.7
BIAS6	102	2:40	197	1.8
HL2	98	2:00	169	2.0
BIAS6	OSSEBOER	1:33	168	1.8
LOLOS	TRIPL	0:53	55	1.9
BIAS6	98	2:45	225	2.0
HL2	102	2:06	185	1.9
LOLOS C34	TRIPL	0:45	55	2.3
Computer	CWW	0:45	144	2.5
800 (VPA)	600	0:41	129	2.5
600	500	0:40	83	2.1
500	VSC1	1:21	186	2.3
96	PGVLOS	0:30	67	2.2
Computer	CWW	1:09	144	2.1
HL2	88	0:54	112	2.1
Computer	500	1:00	130	2.2
Computer	QUADR	0:22	57	2.6
Computer	86	0:54	134	2.5
102	102	0:56	60	1.9
			Average	**2.12**

The average transport speed is determined to be 2.12 m/s.