The analysis and simulation of a supply chain with Arena

BSc
The analysis and simulation of a supply chain with Arena

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2 Abstract

Today, companies around the globe are competing for a cutting edge advantage by streamlining their supply chain performance. Global supply-and-manufacturing networks need driving strategies to manage the product, information and financial flows on which these businesses run. This is a challenge for supply chain management.

Supply chain management is confronted with more than just the task of fulfilling demand; a supply chain has to be cost effective, since the costs are reflected in the price of the end product.

The Bullwhip Effect is an observed phenomenon in forecast-driven distribution channels, where changes in order amounts are amplified through the system. The consequence of the variation is spiraling stock levels and difficulty to restore stability. The effect is costly – to high stock piles or demand not met. Variation has behavioral and operational causes. Supply chains are inherent to the causes of variation - the underlying demand characteristics and replenishment lead times. Normal logical behavior, without thorough knowledge of a supply chain and its mechanisms, can cause The Bullwhip Effect. Knowing the causes helps specifying remedies.

Different remedies and strategies, together with a thorough knowledge of the supply chain mechanism aids in successful management. Such strategies are Information Transparency, Retailer Managed Inventory and Supplier Managed Availability.

The discovery through computational modeling and simulation has become the third pillar of science, alongside theory and experimentation.[17] As computational power increases, simulation has gained in importance and has become a major research area, where highly parallel computation is utilized.[18] Science turns to simulation, when the valid models become too complicated or exact mathematical solutions are not worked out.

Modeling and simulation has shown to have an own development process in which data is collected, a model is built and the process specified. The significance of a simulation depends on the validity of the data, the model and process. Consequently the development process emphasizes the process analysis, the modeling and the feedback of the result of the implementation, the simulation and optimization, back into process analysis and modeling.

A supply chain seems to be predestined to be simulated – the processes and models can be well defined – date and variability is given in specific ranges – demand needs to be met and cost minimized. This provides the opportunity to see which effects strategies and other choices could have on a system, as well as to test the effectiveness of a supply chain design or changes, before it has been implemented.

This thesis has aimed to provide a thorough understanding of the complexity of supply chains and to provide an introduction into the simulation development process. This knowledge is applied in the simulation development of a supply chain in ARENA[35], the model being The Beer Distribution Game[14]. In the last steps of the simulation development process, OptQuest[25] is used to optimize the model and enhance the performance of the simulated supply chain.

3 Preface

This thesis aims at combining supply chain management and simulation – to give an overview of both areas and show how supply chain management can profit from simulation. In the process, the major causes for a negative phenomenon, The Bullwhip Effect, in supply chains will be examined, followed by the simulation development process for discrete event simulation models. Lastly, a sample of how a supply chain can be optimized, in the simulation development suite ARENA, of Rockwell Software., is given

The research areas covered by this thesis are manly supply chains and simulation modeling. Supply chains, though much of the theory can be backtracked to the work of Hau L. Lee, V. Padmanabhan, Seungjin Whang, is very case specific and learning by example very prominent. For simulation and modeling, Averill M. Law and W. David Kelton have been prominent references. The practical guidelines publicized by the MSCO on simulation development are impressive and has indicated where emphasis should be placed. Though validation showed to be a major part of the simulation development process, examining validation processes exceeds the scope of this thesis.

The developed simulation in ARENA, has been optimized with OptQuest, an AREAN plug-in. The potential which simulation provides for supply chains are shown on the implementation of The Beer Distribution Game, which is a must for every supply chain introductory course for students and managers alike.

After optimizing with simulation and the process is reflected on, the contribution of simulation to the solution is evident and hard to think away. The quality of data for the development of simulation models also becomes evident.

Once one has run his first optimization process, the “science lab fever” is markedly felt. Without limiting the scope, one can suggestively feel the origin of

“The discovery through computational modeling and simulation has become the third pillar of science, alongside theory and experimentation.”

4 Overview

To introduce the structure of this thesis, the goal of this thesis is appropriate.

The goal of this thesis is fourfold.

First - To provide a thorough understanding of the complexity of supply chains: (Chapter 5)

The complexity of supply chains lies not in there components, properties or variables, but in their interaction and the consequences of natural logical choices on a supply chains behavior. Understanding that it is complex is the first step. How normal and logical decisions, when not understanding the functionality of a supply chain, can be contra productive, the second. In a third step we examine the prevention of the Bullwhip effect, caused by variability, caused by not knowing the supply chain.

Secondly - To provide an introduction into the simulation development process: (Chapter 6)

The intention is to convey an understanding of the simulation development process, the sub-processes and their significance – their contribution to the quality of data, for model, process, input and output data – their contribution to the simulation result.

Discrete event simulation is the category of models, to which supply chains belong and which we will examine in the process.

Thirdly - The simulation of a supply chain: (Chapter 7)

As model for this thesis “The Beer Distribution Game” has been chosen. The game has been developed by a group of professors at the MIT Sloan School of Management, to demonstrate the functionally of a supply chain in a readily clearly arranged system, without forfeiting the complexity as is met in reality. It is implemented in Arena, of Rockwell Software, a simulation software suite.

Fourthly – conveying the “science lab feeling” when running the first optimization: (Chapter 8)

Each supply chain has its own challenges. Having understood the challenge and gone through the first iterations of the development process, the result is a simulation model of a supply chain in Arena. Running the simulation produces with self estimated demand,

the stock levels fluctuating through the sites like a sinus curve.

The next development step is then taken and the variables are optimized to reduce cost. The optimization is done with OptQuest, an Arena plug-in produced by Rockwell Software.

The fascination is intriguing, when running the simulation with optimized values - calculated with repetitive simulation - causing stock levels to have smaller fluctuations.

The variability in the system is visibly reduced by applying a scientific process.

Optimization by simulation - Reducing the running cost.

5 Supply Chains and Supply Chain Management

The goal of this chapter is to describe supply chain components, properties and variables, their interaction and the consequences of natural logical choices on the supply chains behavior. Conveying the underlying complexity and which the pitfalls may be is the goal of this chapter.

After the following overview, The Beer Distribution Game is described to introduce the problem domain, before the Bullwhip Effect and its causes are examined. The Bullwhip Effect is a phenomenon which needs to be understood to manage supply chain successfully.

Definitions

Supply Chain

A supply chain is a system of organizations, people, technology, activities, information and resources involved in moving a product or service from supplier to customer. Supply chain activities transform natural resources, raw materials and components into a finished product that is delivered to the end customer. In sophisticated supply chain systems, used products may re-enter the supply chain at any point where residual value is recyclable. [3]

Supply chain management

Supply chain management is the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole .[2]

History and Challenge [1]

In the 1980s, the term Supply Chain Management (SCM) was developed[9] to express the need to integrate the key business processes, from end user through original suppliers. Original suppliers, being those that provide products, services and information that add value for customers and other stakeholders. The basic idea behind the SCM is that companies and corporations involve themselves in a supply chain by exchanging information regarding market fluctuations and production capabilities.

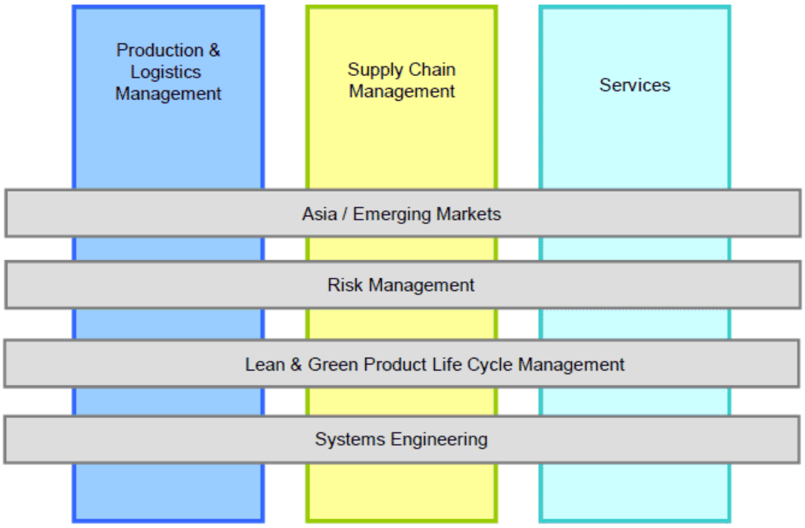
If all relevant information is accessible to any relevant company, every company in the supply chain has the possibility to and can seek to help optimizing the entire supply chain rather than sub optimize based on a local interest. This will lead to better planned overall production and distribution which can cut costs and give a more attractive final product leading to better sales and better overall results for the companies involved.

Incorporating SCM successfully leads to a new kind of competition on the global market where competition is no longer of the company versus company form but rather takes on a supply chain versus supply chain form.

Supply Chain Management general scope

In the organizational arrangement for research strategies at the ETH Zürich [13], Supply Chain Management (SCM), is situated between Production & Logistics Management and Services. SCM intersects with Asia / Emerging Markets, Risk Management, Lean and Green Product Life Cycle Management and Systems Engineering, as to be seen on the on the image below. The area of application is visibly wide.

Organizational Arrangement for Research Strategies - ETH Zürich



[13]

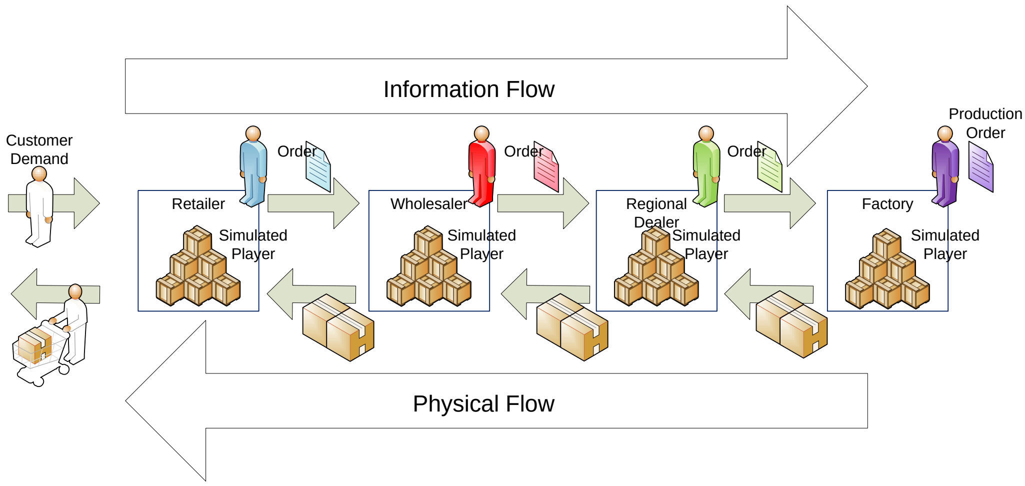
Supply chain thesis scope

As in introduction to supply chain management and to introduce the key concepts and phenomena of supply chains, The Beer Distribution Game has proven to be successful. As a consequence of this, we have chosen to use it as an introduction to supply chains and to the simulation that will follow.

A supply chain consists of chain sites on different levels. Each site places orders with their suppliers to fulfill their customers demand. Each chain site places an order with the site above it, from which it receives the delivery.

A supply chain contains different flows. We consider the information flow and the physical - the product flow.

Considering the sketch below, a four layered supply chain with single sites on each layer as found in The Beer Distribution Game; the sites: retailer, wholesaler, regional dealer and factory. The information flow, orders, flows up in the supply chain, starting with the customer and ending with the factory. The physical flow, products, flows down in the supply chain, starting with the factory and ending with the customer.



Basic Supply Chain – Information and Physical Flow

In the real world, supply chains are more complex, an information exchange difficult, since real demand and delivery times seldom are known. To reproduce this unpredictability to a certain extent, we have order and delivery delays as well as no information sharing between the sites.

The orders in the supply chain are the only elements in the Beer Distribution game, which the players can influence. Consequently, in the simulation, it will be able to change the order strategy. A player as such is not simulated.

The measurement of how successful an order mechanism is of a given strategy is how low the generated cost for a supply chain is. The generated cost of a supply chain consists of two elements, the stock storage cost and the backlog cost. The storage cost is a factor of the storage and the duration it is stored; the backlog cost, a factor of the outstanding deliveries to orders, which has not been received yet and the waited time. This reduces the problem to finding an optimal order strategy for a given situation; a demand and delay configuration.

The reason for concentrating on the order strategy, is that it that it has shown to be difficult to get the stock level under control, even for managers in an executive workshop[14] at the MIT.

The Beer Distribution Game provides the necessary abstraction, with the necessary complexity, to learn to understand supply chains and to examine supply chain phenomena. We will look at probably the most central phenomena in supply chains, the Bullwhip Effect[15], its causes and remedies. The Bullwhip effect refers to an effect, which is claimed to be produced by the distortion of information as it flows upstream and its tendency to misguide upstream members in their inventory and production decisions[16].

First the causes of the Bullwhip Effect causes are viewed and then possible strategies to counteract it.

5.1 The Bullwhip Effect

The bullwhip effect describes the phenomena of the amplification of demand order variabilities as they as they moved up the supply chain. The distortion of information throughout a supply chain can lead to tremendous inefficiencies. The underlying causes for the bullwhip effect are multiple and a thorough understanding can help counteract upon it. This cannot be over emphasized, since the supply chain system is inherent to its cause; the underlying demand characteristics and replenishment lead times.

Strategies to pose the challenge would contain

- information systems,
- defining organizational relationships
- specifying incentive and measurement systems

The bullwhip effect received its name from Procter & Gamble (P&G)[20], to describe an effect, also known as whiplash and whipsaw, which was encountered during the examination of the order patterns of Pampers, one of their best selling products.
The examination showed less variability in the sales in the retail stores, than would be expected, when compared with the degree of variability found in the distributors' orders. The orders to the suppliers of P&G, e.g. 3M, showed even a greater degree of variability, when compared to that of the distributors.
The variabilities did not make sense at first sight, since the demand, the consumption of baby nappies was at a steady rate.

Inefficiencies in the supply chain:

- Excessive inventory in the supply chain
  A factor which could be helpful here, to measure performance –
  Total inventory in supply chain: Days of supply

- Poor demand forecasts
  Avg. Lead time per business – information and goods.
  The longer lead times of information and goods, the stronger the Bullwhip effect[19]

- Insufficient or excessive capacities
  Capacities are designed and planned for avarages.

- Unavailable products and backlogs

- Uncertain production planning (i.e. excessive revisions)
  Expedited shipments to meet orders.
  Overtime

The problem of distorted information can be counteracted upon and the supply chain performance can be improved, when understanding the causes of the bullwhip effect, which can be controlled by coordinating information and planning along the supply chain.

5.1.1 Causes of the bullwhip effect

The Beer Distribution Game illustrates this effect to its players, who experience the phenomena at first hand and are exposed to the inherence of the system. The inherence experienced; the consequence of the rational behavior of players within the supply chain structure, which leads to the Bullwhip Effect has a profound implication. It implies that *to gain control over the bullwhip effect, modifying the chains infrastructure and related processes has to be focused on, rather than the decision makers behavior.*[20]
This does not forfeit the decision makers of understanding demand and inventory information. Studies have shown that humans tend to extreme behavior[19] and that misconception can cause the bullwhip effect [21] .

5.1.1.1 Demand forecast updating

Although forecasts are often history based, the beer game has shown that behavior factors, such as the players' perceptions and mistrust influences the outcome of the game. The layers thought process in projecting the demand pattern based on what he or she observes, is an important factor.

As a consequence the demand signal processing is a major contributor to the bullwhip effect.

Future demands and associated safety stocks are incorporated in a stock order. With long lead times, the amount of safety stock increases. The result is that the fluctuations in the order quantities over time can be much greater than those in the demand data.

Because the amount of safety stock contributes to the bullwhip effect, it is intuitive that, when the lead times between the resupply of the items along the supply chain are longer, the fluctuation is even more significant.

“Because the amount of safety stock contributes to the bullwhip effect, it is intuitive that, when the lead times between the resupply of the items along the supply chain are longer, the fluctuation is even more significant.” [20]

5.1.1.2 Order batching

Orders are not placed with suppliers as inventory depletes. Orders are batched (accumulated) before sending. This has multiple common reasons, which are grouped into two forms, periodic ordering and push ordering.

Periodic Ordering

> Inventory systems are commonly cyclic, since the time and cost of processing an order can be substantial. Certain items move slow, material requirements planning (MRP) systems are often run monthly, economics of transportation; all resulting in monthly or less frequent than possible ordering.
>
> Consequently the supplier faces a highly erratic stream of orders – Spikes. The variability is higher than the demand itself. As a consequence periodic ordering amplifies variability and contributes to the bullwhip effect.

Economics of Transportation
A common obstacle hindering frequent ordering is the substantial differences between full truckload (FTL) and less-than-truckload rates.
There is a strong incentive to fill a truckload when they order materials from a supplier, which lead to moderate to excessively long order cycles.

Push Ordering
Push ordering is when regular surge in demand is experienced.
Sales people are regularly measured; have to fulfill quotas, sometimes quarterly or annually, which causes end-of-quarter or end-of-year order surges. This may lead to signing orders prematurely or “borrowing” quotas ahead. This leads to order patterns, which are more erratic than the consumption patterns that the customers experience. These surges or the "hockey stick" phenomenon is quite prevalent.

Periodic execution of material requirements planning (MRP) or distribution requirement planning (DRP) contributes to the bullwhip effect and is called the "MRP jitters" or "DRP jitters."

“When a company faces periodic ordering by its customers, the bullwhip effect results.”[20]

5.1.1.3 Price fluctuation

Price fluctuation in the marketplace has many causes and results to forward buying. Causes may be attractive price offer or trade deal, special promotions like price discounts, quantity discounts, price- and payment terms, coupons, rebates, and so on.

Such promotions can be costly to the supply chain.[20[11]]

The customer's buying pattern does not reflect its consumption pattern, and the variation of the buying quantities is much bigger than the variation of the consumption rate - the bullwhip effect.

Here the variabilities widens from top, e.g. manufacturer to bottom e.g. distributor - orders from the distributors to the manufacturer, varied more widely.

Wide swings may cause factories to run overtime at other times and be idle – cause premium freight rates to be paid to transport products, because of the excessive amount. Larger than normal volumes and stocking inventories are handle for long periods, which results in damage to systems.

Though substantial research has been done on high-low pricing and how to order optimally to take advantage of the low price opportunities, but most companies suffer because of it.

The irony is that the variations are caused by price fluctuations, which supply chain members, usually manufacturers and the distributors, caused themselves. Such practice has been called the “the dumbest marketing ploy ever.”[20[12]]

5.1.1.4 Rationing and shortage gaming

When rationing occurs or customers anticipating shortages, customers can exaggerate their real needs in order fulfill their actual demand. When demand cools or customers are convinced that their actual demand can be met orders are cancelled. In the process sound, rational economic decisions are made to game the potential rationing. [20[14]]. In the effect of “gaming”, the supplier receives little information concerning the demand of the customer.
“Gaming” is a common practice and is found at all levels of the supply chain.

5.1.2 Countering the Bullwhip Effect

By understanding the Bullwhip Effect, strategies suitable to a supply chain can be developed to mitigate the different causes.

By examining how companies tackle each of the four causes, possible solutions has been found with three underlying mechanisms: information sharing, channel alignment and operational efficiency and has been chosen as topology to discuss the sways to control the bullwhip effect.

With **Information Sharing**, demand information is transmitted from downstream sites upstream in a timely fashion. Electronic data interchange (EDI) is used to share data between the chain members.
Channel Alignment is the coordination of pricing, transportation, inventory planning, and ownership between the upstream and downstream sites in a supply chain.
Operational Efficiency refers to activities that improve performance, such as reduced costs and lead-time.

5.1.2.1 Avoid Multiple Demand Forecast Updates

Usually every supply chain member would somehow calculate its forecast. The Bullwhip Effect is caused when each supply chain member processes the demand from its downstream member to produce an own forecast to send to its upstream member, where the forecast process starts over again, with the new forecast/demand.
It is necessary to receive the original demand, since the differences in forecasting methods and buying practices of different sites, even if in the same organization, scan still lead to unnecessary fluctuations in the order data placed with the upstream site.

By making demand data available to upstream sites - not the forecasts, both sites can update their forecasts with the same information and amplification can be prevented. This would reduce the amount of safety stock - the amount of safety stock contributes to the bullwhip effect.

Apple, IBM and HP requests sell-through data when stock is withdrawn from central warehouses of their resellers. Sell-through data is not as complete as point-of-sales (POS) data.

A more radical approach
The upstream site becomes the active partner - the downstream site the passive partner
The downstream allows the upstream site to

- Access demand and inventory information
- Control resupply
- Update the necessary forecasts

Vendor-managed inventory (VMI) or a continuous replenishment program (CRP) is a sample implementation in the consumer products industry.
In Echelon inventory - the total inventory at upstream and downstream sites is key to optimal inventory control.
Multi-echelon inventory systems can operate better when inventory and demand information from downstream sites is available upstream.

Direct customer sales
Another approach, which goes further than try to get demand information about the downstream site by bypassing it, is by bypassing resellers, as in Apple's "consumer direct" program, where products are sold directly to customers without going through the reseller and distribution channel.
Dell and Apple use Direct Sales - selling directly to their customers and benefits by seeing the demand patterns of its products.

Highly variable demand due to multiple forecast updates can be helped reduced by improvements in operational efficiency. Long resupply lead times can aggravate the bullwhip effect. Consequently, just-in-time replenishment is an effective way to mitigate the effect.

5.1.2.2 Break Order Batches

Since order batching contributes to the bullwhip effect, strategies that lead to smaller batches or more frequent resupply needs to be devised. Counterstrategies described earlier are useful.
An unusually large batched order could be expected when there is a demand surge and demand is transmitted on in a fixed, periodic schedule.

The relatively high cost of placing an order could be a reason for large batch orders in low frequency. Electronic data interchange (EDI can reduce the cost caused by paperwork by generating an order.
With computer-assisted ordering (CAO) customers order more frequently. In 1997, an order with cost of typically $50 could be reduced to $5.23 [20].

Cost of transportation is another reason for large order batches.
Here the differences in the cost between a full truckload (FTL) and less-than-truckload is so great that companies find it economical to order full truckloads, even though this leads to infrequent replenishments from the supplier.
The full truckload constraint heaves the cost advantage caused by EDI completely. As a consequence some manufacturers induce their distributors to order an assortment of different products, resulting in a truckload of different products from the same producer, rather than a full truckload of the same product.
The effect being a higher delivery frequency from the same distributor with preserved transportation efficiency. **Some distributors offer discounts, e.g. when customers** are willing to order mixed-SKU (stock-keeping unit) loads of any of its products. In the grocery industry, "Composite distribution" is a further specialization of this concept, where fresh produce and chilled products are transported together to be able to make resupply more frequent [20[25]].

Third-party logistics companies also helps make small batch replenishments economical, since they allow economies of scale that were not feasible for a single supplier-customer relationship. **Third-party logistics has multiple advantages for customers and suppliers:**

- They can consolidate loads from multiple suppliers located near each other and achieve full truckload economies, without the batches coming from the same supplier. Additional handling and administrative costs for such consolidations or multiple pickups is often outweighed by the saving.

- Delivering the same product to competitors, such as neighboring supermarkets, can utilize a truckload. This allows more frequent deliveries – moving from daily to weekly, which could be the case if each customer is supplied separately via full truckloads.

- This is especially appealing for small customers whose volumes do not justify frequent, full truckload replenishments.

- Grocery wholesalers that receive FTL shipments from manufacturers can ship mixed loads to wholesalers' independent stores, using third-party logistics companies. customers need to spread their periodic orders or replenishments evenly over time, to reduce the negative effect of batching. Some manufacturers coordinate their resupply with their customers by spreading the replenishments to all the retailers evenly over a week, ensuring their customers regular delivery appointments.

5.1.2.3 Stabilize Prices

The simplest way to control the bullwhip effect caused by forward buying and diversions is to reduce

A) the frequency and
B) the level

of wholesale price discounting.

Manufacturers can establishing a uniform wholesale pricing policy to reduce the incentives for retail forward buying. Everyday low price (EDLP) (or value pricing strategy) is giving the customer the advantage of promotions distributed over the whole year. As a consequence P&G were able to reduce their list prices by 12% to 24%, from 1994 to 1997 [20]. In 1994 P&G were very successful, reporting highest profit margins ever.[20[27]].

It is to note here that the reported statistics does not cover P&G's financial reports of 1995 to 1997.

In this context, retailers and distributors should have a everyday low cost (EDLC) strategy with their suppliers.

Wal-Mart International follows a everyday low price (EDLC-EDLP) strategy.[22]

Diversion

From a stock owner's diversion, the use of stock for other than the intended purposes is a feasible option. This is possible when, e.g. the customer can wait a certain amount of time after the order is placed, while the last production steps are completed and the final finishing touches are made. The stock owner could divert the stock – use e.g. for another product, if idle. (Semiconductor industry: final steps specializes the semiconductor product, the automobile industry: same parts are used in different products, Hamburger shops and shops selling skewers of barbecued chicken)

From an operational perspective, practices such as continuous replenishment program (CRP) can be combined with a rationalized wholesale pricing policy. This will help retailers not having to divert stock.

Manufacturers' use of computer-assisted ordering (CAO) for sending orders also minimizes the possibility of such a practice.

Activity-based costing (ABC)

To be able to recognize the excessive costs of forward buying and diversions, activity-based costing (ABC) explicitly provides accounting for inventory, storage, special handling, premium transportation, and so on, to list costs that previously were hidden and often outweigh the benefits of promotions.

This, to show the actual costs involved when companies run regional promotions, which enables some retailers buy in bulk in the area where the promotions are held and then divert the products to other regions for consumption.
The costs of diversion and similar practices are huge but may not show up in conventional accounting systems. ABC therefore helps companies implement the everyday low price (EDLP) strategy.[20[28]]

5.1.2.4 Eliminate Gaming in Shortage

Suppliers can allocate products based on past sales records, rather than on orders, when shortage is at hand. Consequently customers would have no incentive to exaggerate their orders. Information sharing – the sharing of capacity and inventory information is insufficient when there is a genuine shortage.
Strategies against gaming may include the cooperation of customers to place orders well in advance of the sales season. Consequently production capacity or scheduling can be adjusted with better knowledge of product demand.
Generous return policies that manufacturers offer retailers aggravate gaming. By enforce more stringent cancellation policies, customers are discouraged to exaggerate their needs and cancel orders.

5.1.1 Supply Chain Coordination Initiatives

Below the causes and counteraction initiatives has been presented schematically.

Causes of the Bullwhip Effect	Information Sharing	Channel Alignment	Operational Efficiency
Demand Forecast Update	• Understand system dynamics • Use Point-of-sale (POS) data • Electronic Data interchange (EDI) • Computer-assisted ordering	• Vendor-managed inventory (VMI) • Discount for information sharing • Consumer direct	• Lead-time reduction • Echelon based inventory control
Order Batching	• EDI • Online Ordering	• Discount for truckload assortment • Delivery appointments • Consolidation • Logistics outsourcing	• Reduction of in fixed price in ordering by EDI or electronic commerce • CAO
Price Fluctuation		• Continuous replenishment program (CRP) • Every day low cost (EDLC)	• Everyday low price (EDLP) • Activity based costing
Shortage Gaming	• Sharing sales capacity and inventory data	• Allocation based on past sales	

By thoroughly understanding the inherence of the system and the underlying causes of the bullwhip effect, which results from rational decision making by members in the supply chain, effective counteractions are possible.

Victory by comprehension…

5.2 Supply Chain Performance

Measuring the performance of a supply chain and consequently creating a value system for the supply chain is probably one of the more complex tasks, when optimizing a supply chain.
Though the generalization and quantification of supply chain performance exceeds the scope of this thesis, following were found to be potentially interesting to examine when evaluating the performance. This, though it is clear that the profit of the supply chain as a whole is the ultimate evaluative figure.

Abbreviations:

u	unit
:	place in relation to

• Minimum Throughput of SC:	MinT	[u/t]
• Maximum Collective Stock in SC:	MaxCS	[u)]
• MinT: MaxCS		[(u/t) / (u)] = [1/t]

• Average Throughput of SC:	AvgT	[u/t]
• Average Collective Stock in SC:	AvgCS	[u)]
• AvgT : AvgCS		[(u/t) / (u)] = [1/t]

- Throughput: Sum (Excess stock in system) incl. / excl stock in transit

Losses - Little lost can be more effective than no lost

5.1 Supply Chain Agility

How much can the throughput of a supply chain be accelerated, with the supply chain maintaining stable – cost staying proportionate to throughput?

- What is the cost of acceleration, if not proportionate to the throughput?

- The upper limit of the acceleration range is the production limit. Production can be static or flexible.

- What is the influence of the order frequency on the stability?

Though the agility of a supply chain exceeds the scope of this thesis and in the papers read did not theme it, it is clearly a factor which needs consideration when designing a supply chain.

6 Modeling and Simulation

In this chapter simulation models are classified - it will determined that supply chains belong to the category dynamic, discrete, stochastic. Dynamic, discrete, stochastic models will be examined as well as the simulation development process necessary for development.

6.1 Modeling Approaches

Simulation models are the base of simulations. They could be physical or logical and are done in different ways, to suit the circumstances.
It could be possible to *physical simulation and test a system*, e.g. building a Starbucks in-house, have an online voting system, or traffic lights to control the traffic driving onto a highway. In comparison though, *some systems are too big or critical to play with*; a flight control system or emergency room protocols. The physical system could not be there yet: an underground parking lot, which needs to fulfill service and profitability criteria and still needs to be built.

The logical, also called mathematical model, addresses problems where mathematical solutions have been worked out. We are able to computer analyze the behavior of a valid logical model with assumptions and approximations. Simulations can be used, when the valid models become too complicated or exact mathematical solutions are not worked out.

There are different ways to classify simulations. The following classification of Averill Law and David Kelton has three dimensions [23[9]]:

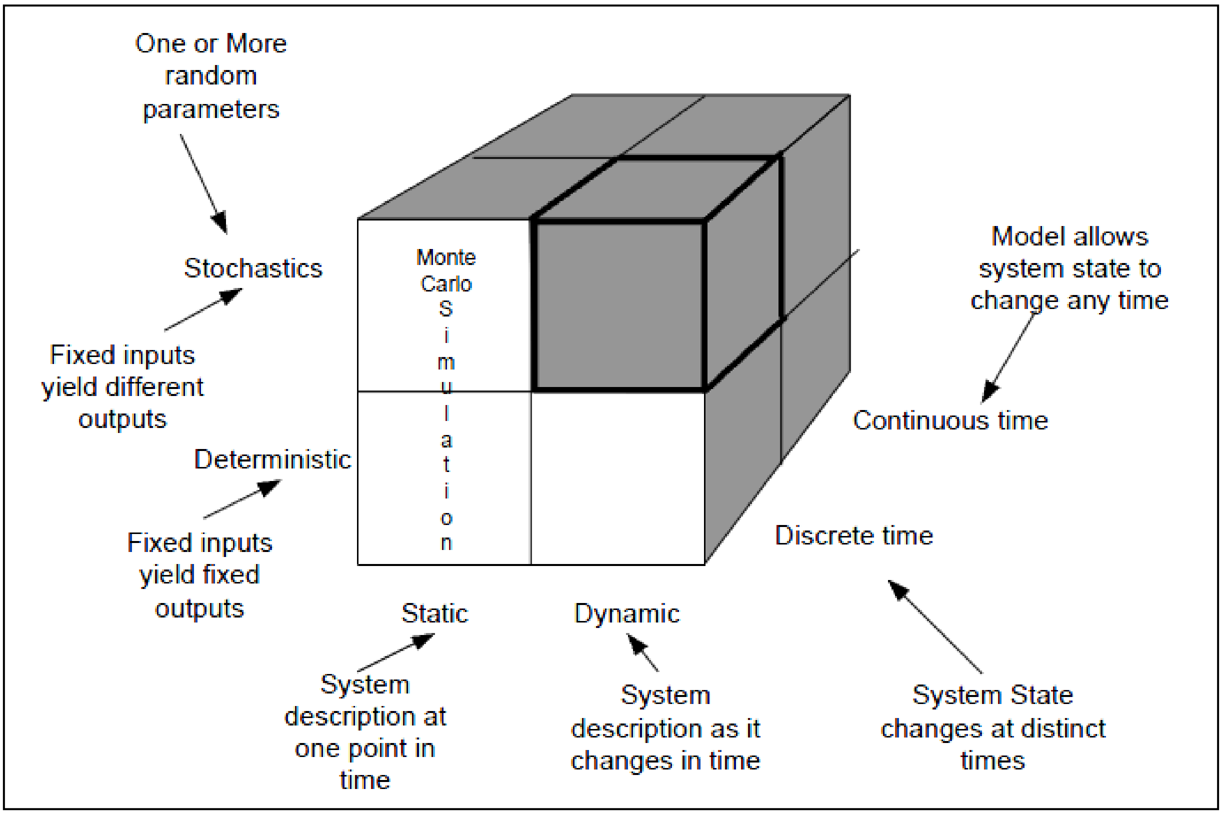
I. *Static vs. dynamic simulation models*
II. *Discrete vs. continuous / dynamic* simulation models
III. *Stochastic vs. deterministic* simulation models

In dynamic simulation models, time plays a role; the system evolves over time. In static models, time does not play a role. Flipping a coin to determine the outcome “head or tail”, is time independent.

In a discrete simulation model change occur at separate points in time – the systems change is connected to time. It is possible to simulate a naturally continuous system with a discrete simulation with a so called mixed continuous-discrete model [34], e.g. a container continuously being filled with water.

The input is random - some randomness in the model
Stochastic models contain randomness – random numbers are generated to change the state of the model; deterministic simulation models don’t.

Below, depicted the classification of different kinds of models:



Classification of different types of Models [29]

6.1.1 Continuous Simulation

In a continuous model, state variables change continuously as a function of time. In general analytical methods, like inductive mathematical reasoning is used to define and solve a system. [29]

6.1.2 Static, stochastic simulation models - Monte-carlo Simulation

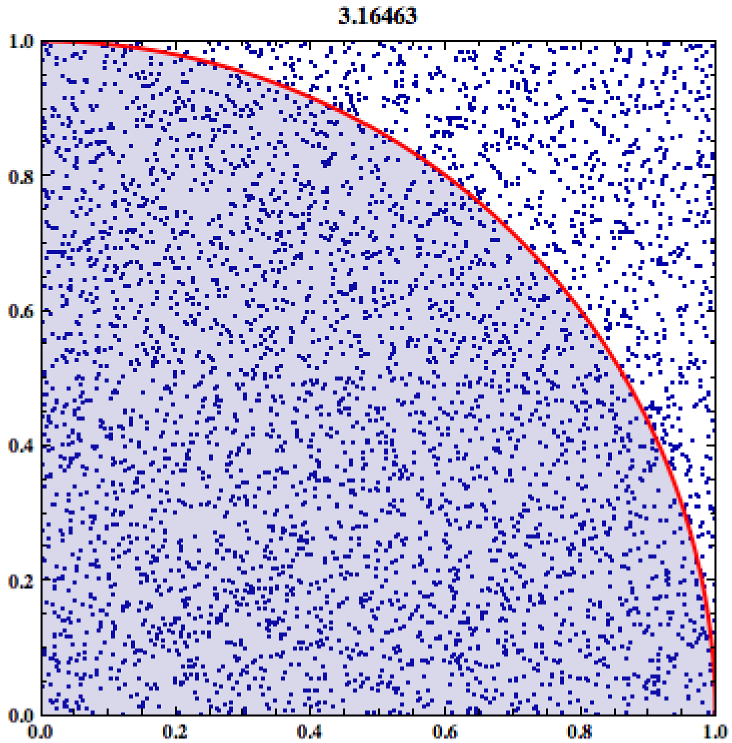
According to wikipedia.org the Monte Carlo methods varies, but tend to follow a particular pattern:

1. Define a domain of possible inputs.
2. Generate inputs randomly from a probability distribution over the domain.
3. Perform a deterministic computation on the inputs.
4. Aggregate the results.

For example, the simulation of the surface of π and consequently that of a circle: Consider a circle inscribed in a square. Given that the circle and the square have a ratio of areas that is π/4, the value of π can be approximated using a Monte Carlo method:[30]

1. Draw a square on the ground, then inscribe a circle within it.

2. Uniformly scatter some objects of uniform size (grains of rice or sand) over the square.
3. Count the number of objects inside the circle and the total number of objects.
4. The ratio of the two counts is an estimate of the ratio of the two areas, which is π/4. Multiply the result by 4 to estimate π.



The simulation of π [30]

Monte Carlo simulation is also used to integrate analytically not integrable integrals, is a static, stochastic simulation model. [23[12]] In short it reaches a solution by forming a system of related definite integrals – formed by choosing a large number of points uniformly distributed on the integration interval. The numerical approaches) in which the integrand is evaluated a large number of times at random points that are uniformly distributed along the interval over which the integral is being evaluated.

6.1.3 Discrete Event Simulation

Discrete, dynamic, stochastic models falls into this category. A category covered by more in literature than others [23[9]]. Note, that there are some differentiation in this group, distinguishing discrete-time models as a sub category of discrete-event models [23[18]], if needed.

Discrete event models represents only those time steps at which change occurs – is consequently so called *event based or event driven,* where the system jumps from one event to another, leaving out the irrelevant behavior, for the model, between the events.

The following components are in most discrete event based simulation models, according to Law and Kelton's theory [23[9]]. They are also to be found in ARENA, the simulation software used in this thesis:

- **System state:** The collection of state variables necessary to describe the system at a particular time.
  ARENA, variables and entities

- **Simulation clock:** A variable giving the current value of simulated time.
  ARENA: The system variable TNOW is also visible in the info bar, bottom right.

- **Event list:** A list containing the next time when each type of event will occur.
  ARENA: Events are “created” by a Create element – are stored in the simulation tools event calendar for release and is part of the simulation framework. [34]

- **Statistical counters:** Variables used for storing statistical information about system performance.
  ARENA: A Record element can be used and each variable can be flagged to have its statistics recorded in the variable list.

- **Initialization routine:** A subprogram to initialize the simulation model at time zero.
  ARENA: Warm up period can be set in the run setup

- **Timing routine:** A subprogram that determines the next event from the event list and then advances the simulation clock to the time when that event is to occur.
  ARENA: Invisible to user, but is active in the background. [34]

- **Event routine:** A subprogram that updates the system state when a particular type of event occurs (there is one event routine for each event type).
  ARENA: These events are “created” by Create elements.

- **Library routines:** A set of subprograms used to generate random observations from probability distributions that were determined as part of the simulation model.
  ARENA: Library routines are available and can be used in most places, by right clicking on the text field and choosing “Build Expression…”

- **Report generator:** A subprogram that computes estimates (from the statistical counters) of the desired measures of performance and produces a report when the simulation ends.
  ARENA: Presented as simulation result after a simulation run (1 or more simulations).

- **Main program:** A subprogram that invokes the timing routine to determine the next event and then transfers control to the corresponding event routine to update the system state appropriately. The main program may also check for termination and invoke the report generator when the simulation is over.
  ARENA: Part of the applications framework.

There are different opinions on how to view events, their generation and calendaring.

Interesting to note that, Peter Steadman do not agree with Law and Kelton[23[9]] and Zeigler's[23[18]] way of describing discrete event scheduling as "maintaining a list of events sorted by their scheduled event times, and executing events sequentially on that list."[23]
This for two reasons

I. In Steadman's schema events are triggered by an internal state or state change of the component models.
II. To Steadman "An Event List" does not seem the most natural way to model dynamic systems. Though this may quite often be an appropriate simplification, we expect that quite often it is not. It seems to introduce a notion of pre-determination that is at odds with the notion of a system's evolution through time. Life does not have an event schedule. (At least, not so far as we know.)"[27]

Referencing I.) The question arises how is the internal state changed? More important though, the question if the two schemas can be compared. The comparison of the two schemas exceeds the scope of this thesis, but as a thought,

- could input, as described by Steadman not be considered as events?[23]
- could Steadman's schema not be simulated by an single event?

Referencing II.) Agreeing that simplification only makes sense as long as the model stays valid, one could not speak of "pre-determination" as Steadman formulates it, if the two events were randomly generated independently of each other and consequently there is no dependence between the two events. The difference in the probability of the 2 events when generated sequentially, or before and after an internal state change has no consequence, since the events are independent. Concluding that, though life does not seem to have an event schedule, it would make no difference as long as the event list stays unknown.
Since the system evolves through time as Steadman says, one could argue that the same event's effect is on a system depends on the systems state. If the system indeed has the same state at two different points in time, and delta t does not change the system state, then the same effect would be expected by the event at t or at t + delta t. The evolution of the system would hence not differently be influenced by "when" an event is generated, nor by when it is executed. Conclusively, Law, Kelton and Zeigler's simplification of events in time as an ordered event list is still to be falsified by contradiction.

ARENA, the simulation tool with which we will be working, has such an event calendar. [34]

Supply chains belong to the category dynamic, discrete, stochastic models and are the focus of this thesis. The applicability, his group of models find their applicability in a diversity of fields, e.g. agriculture [10], complex biological systems[11] and supply chains[12].

6.2 Simulation Solution Development

Simulation development has an own process due to the system information accuracy level, which has to be qualitatively high for the simulation to fulfill its goal of giving insight on the system.

In the first steps of a simulation, a model of the system is created; first a "word model" followed by a formal model, e.g. in UML. The goals are formulated and key variables are identified. Since understanding the system is so vital, interviews with subject matter experts is emphasized. This contributes to the suitability of the model, to the verification of the model and to the validation of the implementation.

Experiments are designed and the simulations are run. The results are analyzed and insight won.

Simulation development is very iterative - especially the validation process - and has to be planned accordingly.

The MSCO[27] gives following definition for validation in *A Practitioner's Perspective on Simulation Validation*[28]: "Validation is the process of determining the degree to which a model or simulation is an accurate representation of the real world from the perspective of the intended uses of the model or simulation."

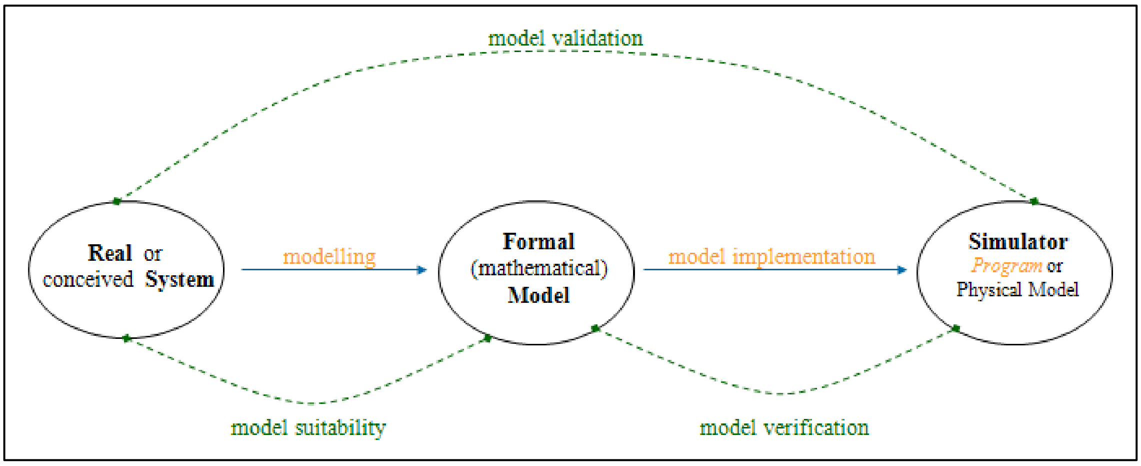
Though validation is a key part of the simulation process and cannot completely be considered as a sub process, the details of validation exceed the scope of this thesis.

To develop a valid and credible simulation the following list, which is by no means complete, gives an good overview of what should be done according to Rinkel[31] and the MSCO[27][28]

- Understand the system
  - Interview subject matter experts
- Be clear about the goals – this will direct the outcome. Identify following:
  - Variables to be measured
  - Input variables
  - Resources
  - Activities
  - Events
- Formulate the model representation in words - precisely
- Translate into modeling software
- Perform a structural walk-through of the conceptual model[28]
- Document the model
- Verify that computerized representation represents the conceptual model faithfully
- Validate the model
- Design the experiments
- Run the experiments
- Analyze results
- Get insight

Below we see a schema, which describes the simulation solution development process. Characteristic for the development process is the back coupling, where information from "control" mechanisms flows "back" to be processed once again; the model is questioned for its suitability, the simulation is verified against the model and validated against the system to model. The analysis of the *real system* is implicitly part of the schema; the circular processes could be planned iterative as mentioned.

A explanative schema from Rinkel[31], illustrates the simulation development process



Simulation Process – Overview [31]

The process components:

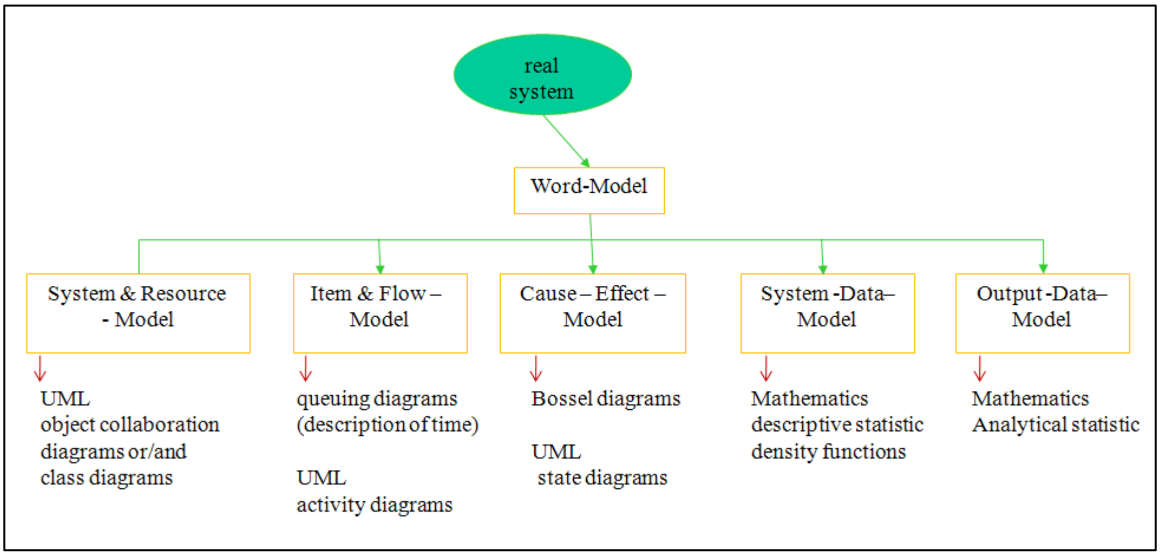
Real System

If we are implementing a simulation for a real system, we collect *input and output data* where applicable to use during the validation and simulation process. For a virtual system, the quality of the data and understanding its origin is significant to the validation process according to Law and Kelton. [24]

Modeling

In a first step the *real system* is analyzed and a *model* of it is specified. The level of abstraction depends on the goal of the simulation. The modeling can be done in a general programming language like UML, a Visio[32] chart or in Mathematica [33]. The resulting *formal model* is checked for its *suitability* against the real system.

The modeling process according to Rinkel [31]



Modeling steps as part of simulation development process

Implementation

After the system has been abstracter to a model, the *model is implemented* in a *simulator.* The simulator contains the *physical model,* which has to be *verified* against the formal model.

Model Validation

Conclusions need to be reached from a valid system to achieve the set objectives. The validation process determines that the simulation (physical model) is a most appropriate representation of the real system from the perspective of the intended use of the physical model or simulation. Validation is a continuous process during the development and can not only be done after development has concluded.

Essentially the validation part of the development process assesses and improves the physical model (simulation), which has to best represent the real system. Law and Kelton found that the documentation of the model, including the model logic and assumptions and a structured walk through the simulation belongs to the validation process.

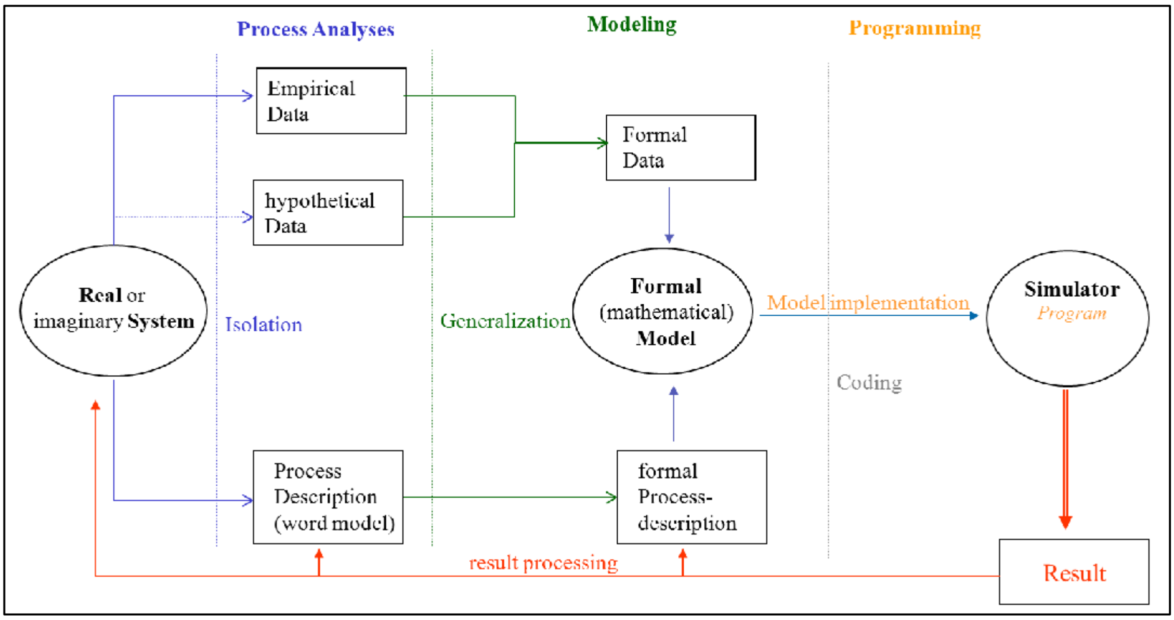
- Is the level of abstraction correct?
- Are the approximations meaningful?
- Is the output comprehendible?
  The removing of the probability from the system makes the system constant and reduces the level of complication. In this case the output should be most apparent.
- Does the output correspond with the input?
- Can meaningful conclusions be drawn with relatively high confidence?

If an existing system is simulated, the output of the simulation would have to correspond with the output of the real system, when the relevant input data and parameters have been used.

6.2.1 Analyses, Modeling and Programming

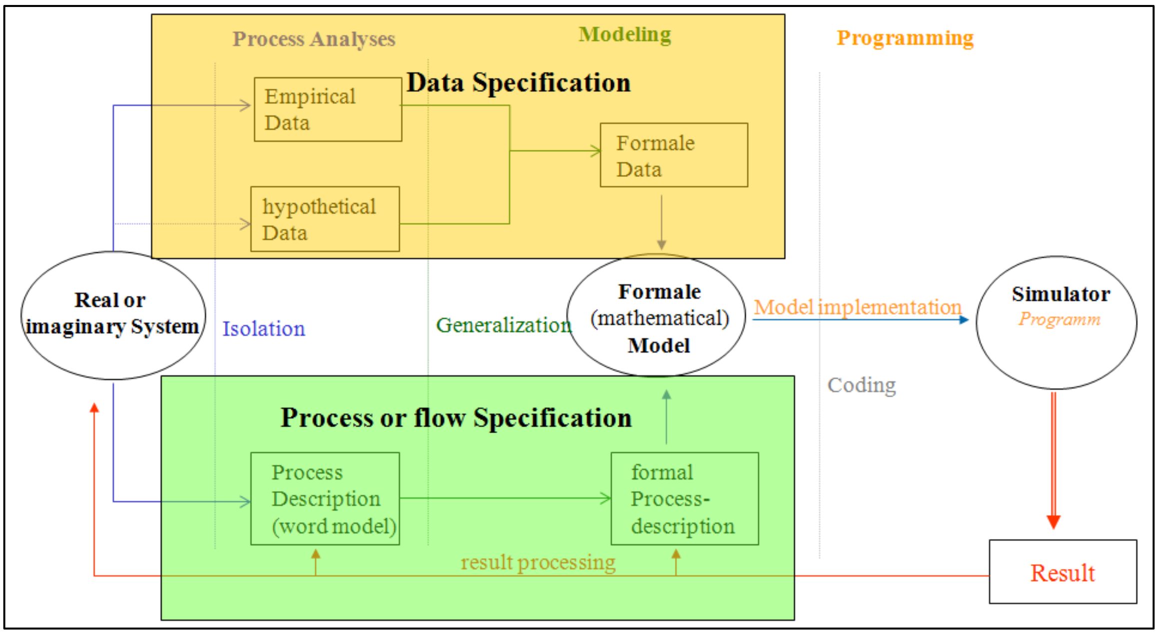
Below the development process is shown in three phases, Process Analyses, Modeling and Programming, producing the artifacts as illustrated in the schema *Simulation Process – Overview.* The phases are overlapping and the development iterative.

Note the differentiation between data analysis and process analysis in the process analysis and modeling phases.



Analyses, Modeling and Programming [31]

The *Data Specification* is done during the Process Analyses and Modeling and the result is Empirical Data, Hypothetical Data and Formal Data. The Process or Flow Specification is done during the same phases, in the steps Word Model and Formal Process Description.



Data Specification – Process Specification [31]

It is important to note, that the outline described above is an iterative process and that it could be embossed by the validation process.

6.3 Simulation Result

A simulation produces a result, which is analyzed and processed. The model is adjusted and the experiments are repeated or new ones are run.

The goal of the simulation indirectly specifies the result processing steps: If just confirmation was needed for a system, the design or model is hereby confirmed or demented. With a system where an optimal solution is part of the goal, as in our supply chain, an optimization process is included in the result processing. The system is optimized and experiments are run again with the optimized model until with necessary accuracy a solution has been found. The iterative validation process is part of result processing and is integrated in the Data Specification as well as in the Process Specification.

7 The Beer Distribution Game Simulation

To stay true to the idea of the game, this implementation does not have information sharing or any of the other Bullwhip Effect countering remedies. The model has been implemented to enable the simulation of the four layered supply chain with delays on order or delivery handling and transit. The ordering mechanism has been kept trivial simple and can be replaced in the implementation.

The emphasis has been placed on the model, which is comprehendible but complex and unpredictable concerning a solution.

With delays, a closer to real life situation has been achieved, without increasing the complexity of the rest of the game.

7.1 The Model

The Beer Game or Beer Distribution Game is originally a board game. Since we are simulating, the game does not have an internal clock representing the rounds of a game. Rather, it has distributions, for generation of customers, for demand size allocation to the retailer and for delivery delays.

The goal of the game is to have a minimal running cost for the 4 layered supply chain, with the cost resulting from storage and the penalty fees for backlog. The supply chain's generated cost is a benchmark for the efficiency.

Each businesses cost is calculated independently and targets a minimal cost.

The 4 layers are

1. Retailer
2. Wholesaler
3. Regional Dealer
4. Factory

The retailer orders and receives stock from the wholesaler; the wholesaler from the regional dealer and the regional dealer from the factory.

The retailer does not have a backlog like the other three sites - the clients leave empty handed or with partial deliveries -a backlog is not caused. The retailer has a penalty for not fulfilling demand - the other sites has a backlog cost as penalty.

The factory has a production, which receives the factories order and where the production delay can be set.

Cost generation per Business, per case of beer, per minute is as following*:

- Out of stock and cannot supply: 2
- For storage: 1
- Retailer penalty: 15
  This value is chosen high, since the system should intend to deliver and not reduce overall cost by not ordering at all.

*This as a difference to the board game, where cost is generated per round and the retailer has a backlog.

Each business orders for itself. The game is without information sharing, since this represents a close image of the real world situation where demand is complex. Consequently we generate demand, which only the retailer receives.

Partial deliveries are allowed.

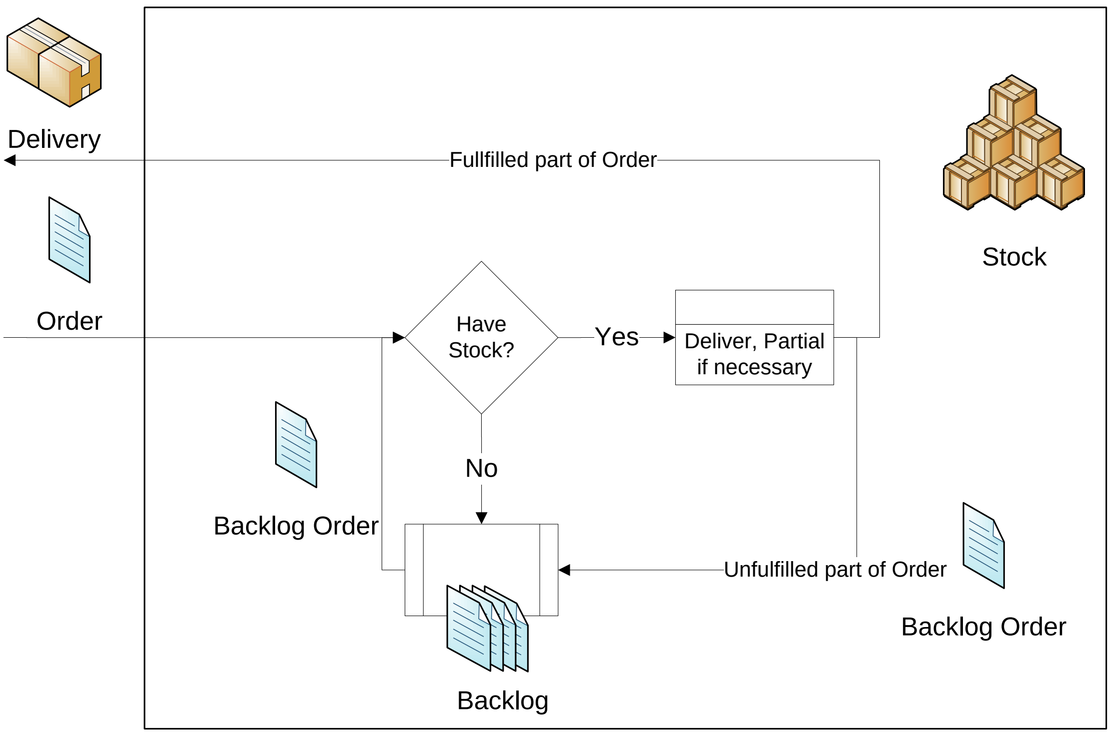
The retailer does not backlog unfulfilled deliveries.

Rules
- Orders cannot be terminated, nor changed.

For each Business, only following is known:
- Own Stock
- Own Backlog
- Outstanding Orders

The stock and data flow
Orders are placed with the upstream business. The order is delayed. If the order can be met, the order is subtracted from the stock and is returned, with a delay. If a order cannot be met, in partial or in full, a backlog results, which continues to exist until met; with exception of the retailer, which returns what can be met, with a resulting penalty for what could not be met.
Backlogs are handled when stock enters.

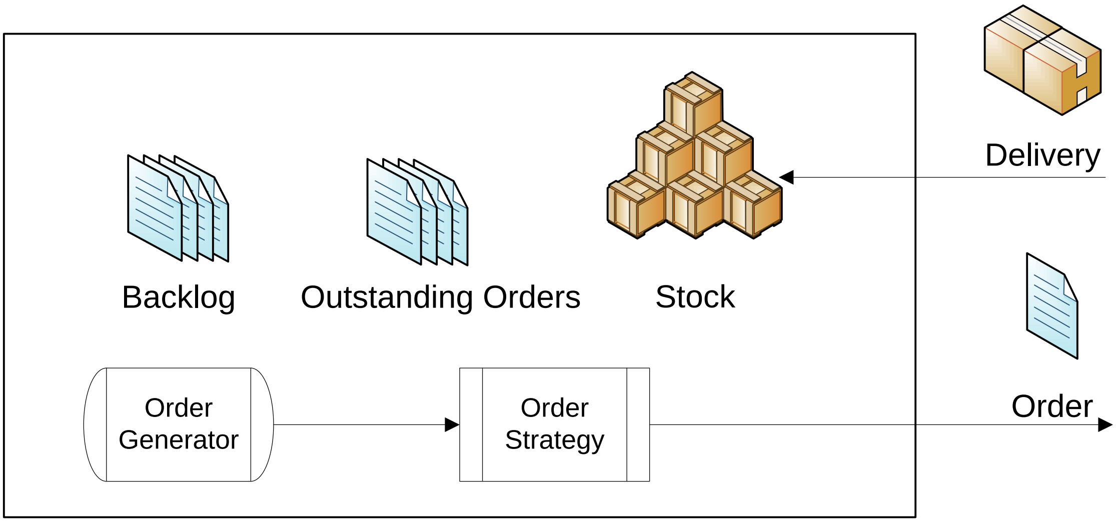
Order Handling



Order handling*

*With exception of the retailer: has no backlog.
The Backlog is handled as a single entity and do not reference the original delivery.

Order Strategy
An order strategy determines the order size. Taken into account is the stock on hand, the outstanding orders, the lead times of the different orders and the forecasted future demand.



Cost Calculate
Cost for each Business is calculated from their

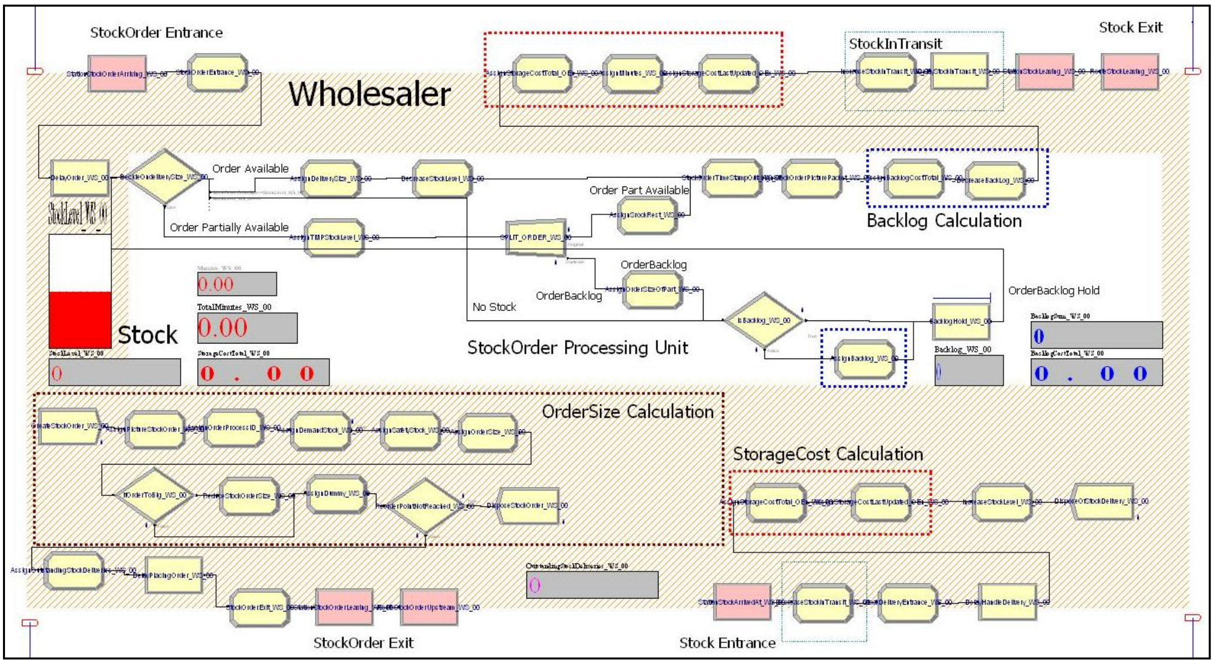
- Stock
- Backlog (Excl. Retailer)
- Not fulfilling Demand (only Retailer)

7.1.1 The Implementation

The four layered supply chain consists out of a

- Retailer
- Wholesaler
- Regional Dealer
- Factory

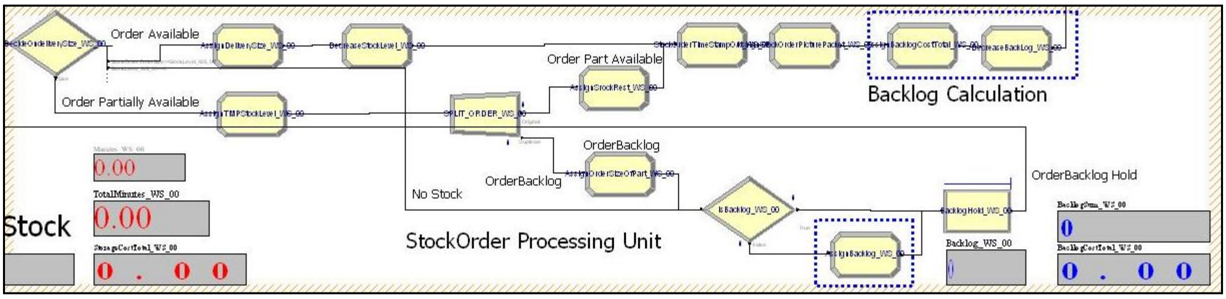
Below the Wholesaler is shown.



Wholesaler Site Complete

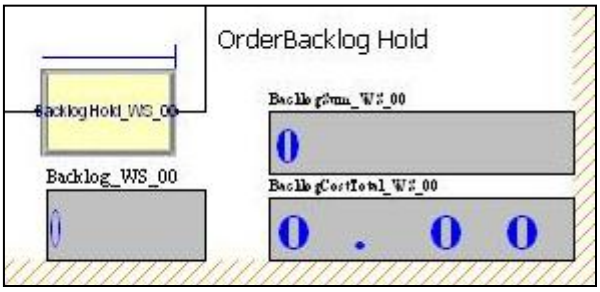
In essence the four supply chain links are identical, as they each consists out of following units

- Order processing unit
  Processes orders from a downstream component

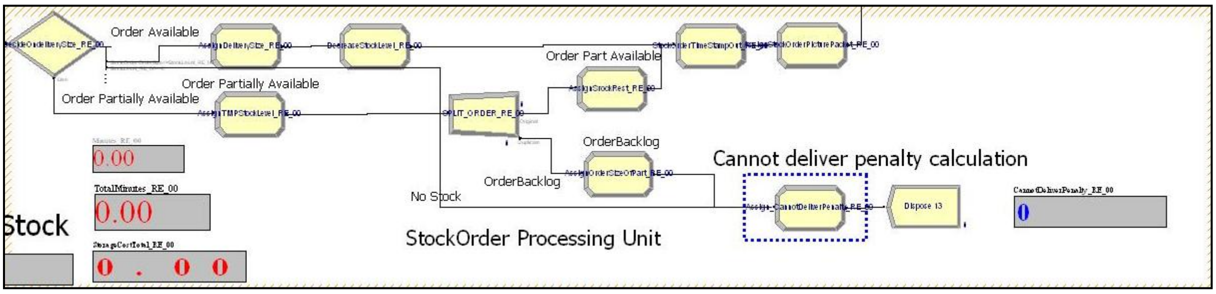


Order Processing Unit (Excl. Retailer)

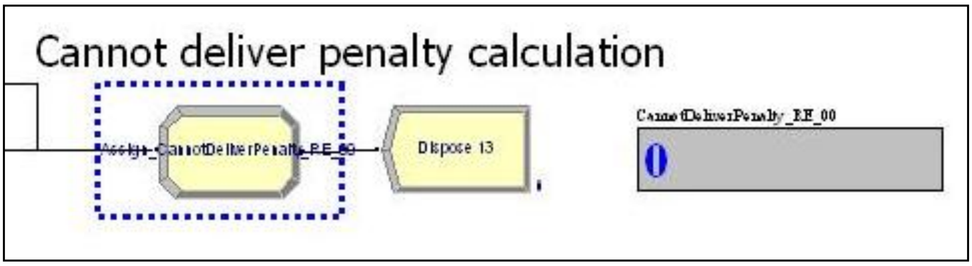
Here it is determined if the order can be fulfilled, in whole or in part. For the part of the order, which cannot be delivered, an backlog is created, which is then added to the total backlog of the site. Once a delivery enters a site, the BacklogHold queue is triggered by the increase in stock level. The system then releases a order, representing a backlog to be processed by the system in the same way a new order would be processed. Below, the backlog queue can be seen.



Backlog Queue



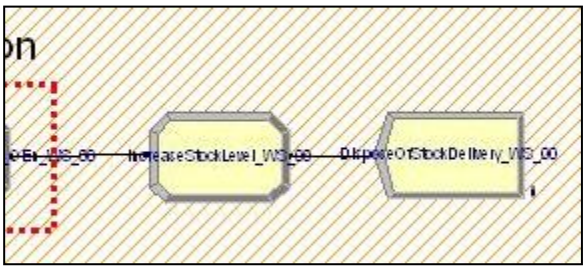
Retailer Order Processing Unit



Retailer unfulfilled order Disposal

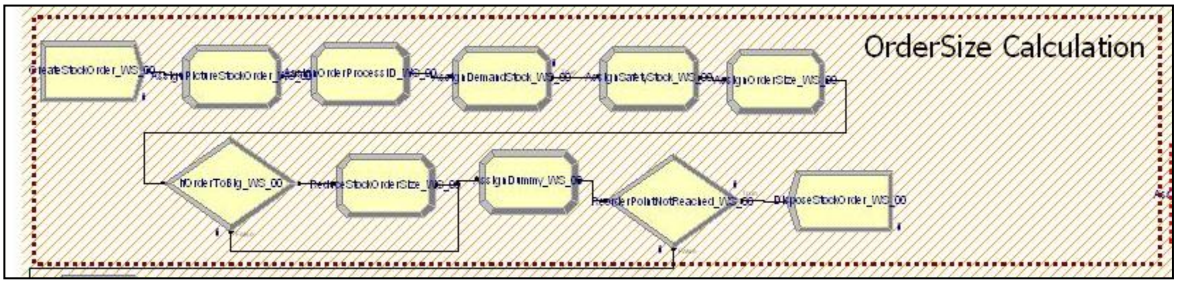
The Retailer disposes of unfulfilled orders. The rest of the order processing has been left unchanged.

- Stock delivery processing unit
  Adds a stock delivery, received from an upstream unit, to the stock by incrementing the stock level with the delivery size, after which the event is disposed of.



Stock delivery processing

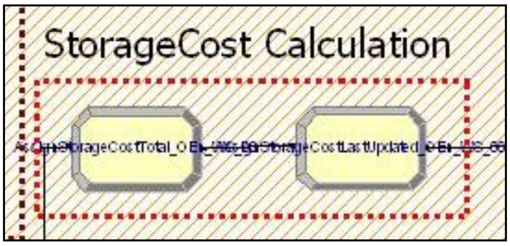
- Order unit
  Calculates and generates an order to a upstream unit

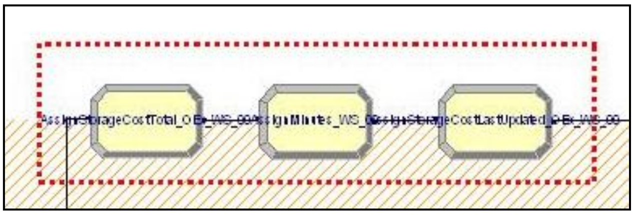


Ordering Unit

With order strategies being one of the central issues to be examined, the order processing unit can be replaced by different implementations.

- Storage Cost Calculation

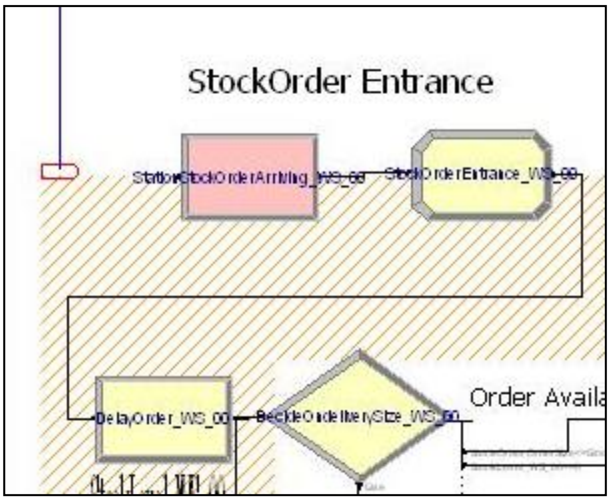




Storage Cost Calculation

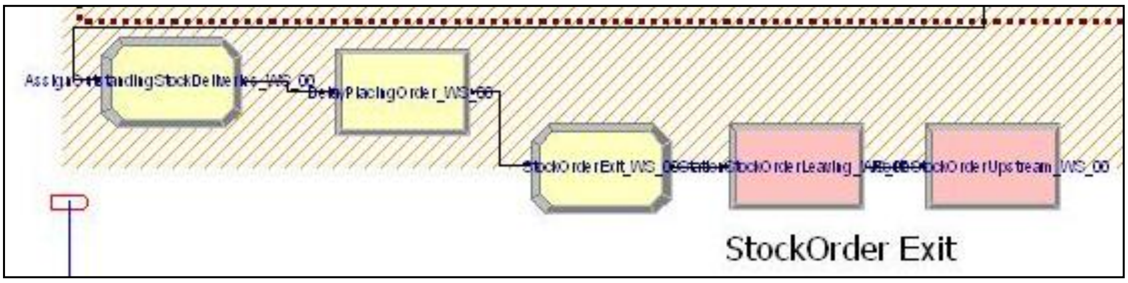
The storage cost is calculated upon changes to the stock level: when stock leaves the site (left image) and when stock enters the site (right image). The cost is calculated in relation to time: 1 cost unit per minute per unit n stock.

- Stock Order Entrance
  An order is delayed upon entrance with DelayOrder



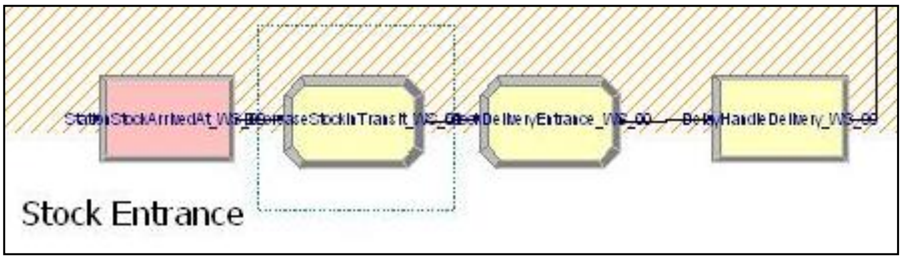
Stock Order Entrance

- Stock Order Exit
  An outgoing order is delayed with DelayPlacingOrder



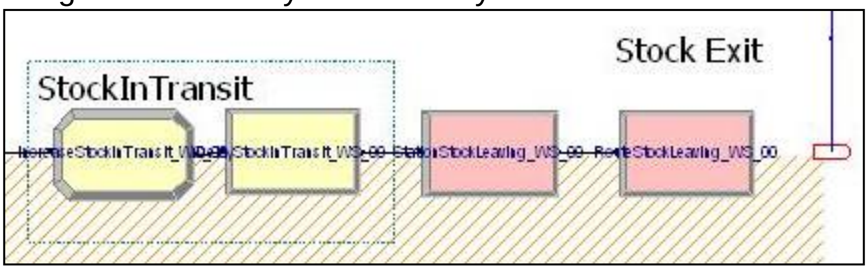
Stock Order Exit

- Stock Entrance
  An incoming stock delivery is delayed with DelayHandleDelivery



Stock Entrance

- Stock Exit
  Stock leaving the site s delayed with DelayStockInTransit

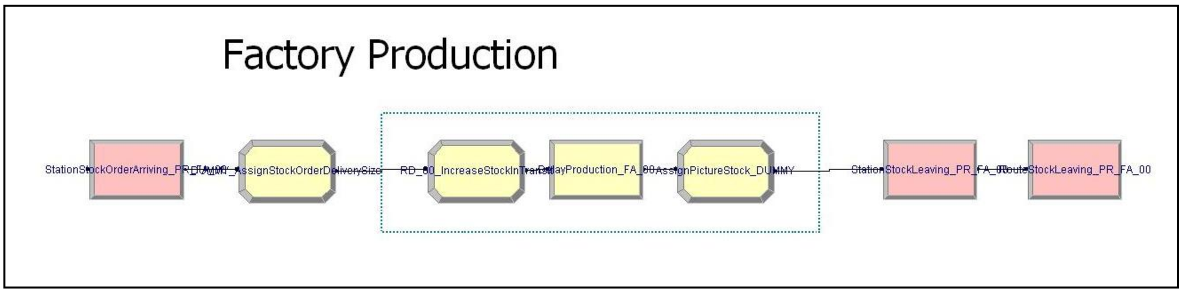


Stock Exit

Note that each site has its own delays for specific events.

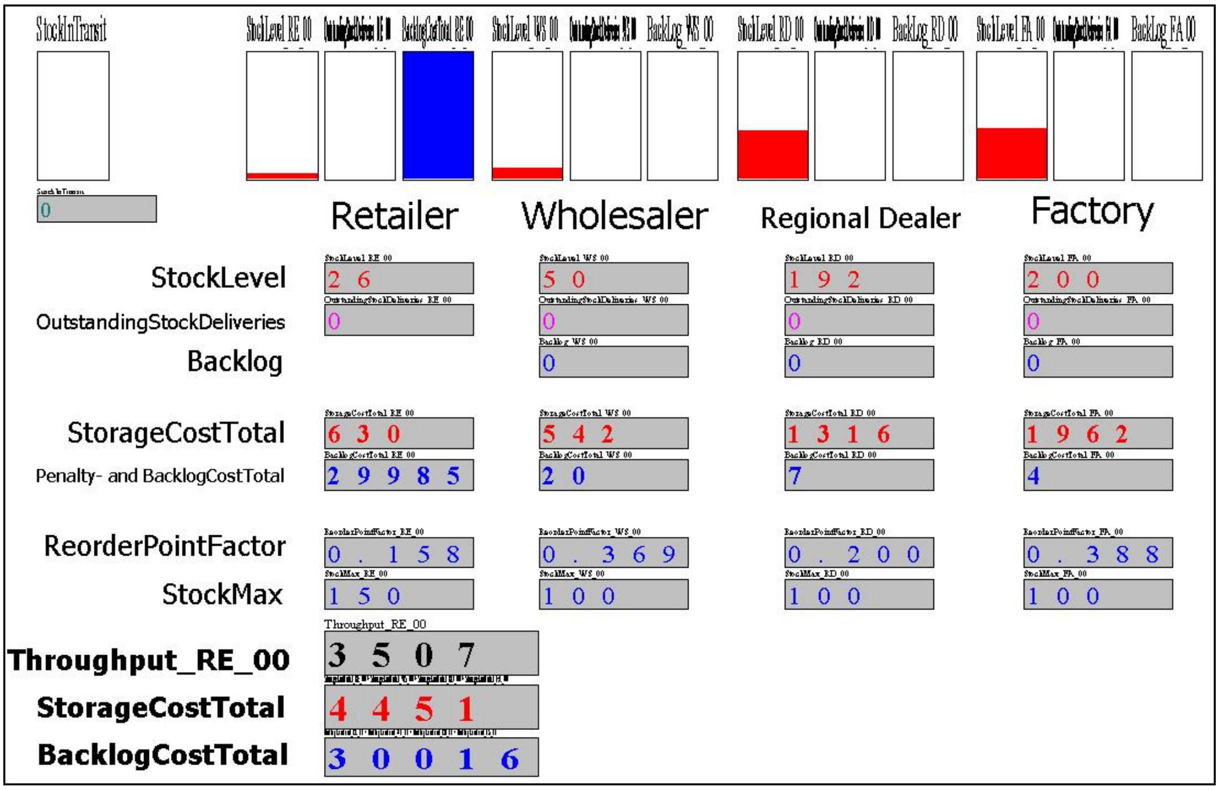
- Stock delivery
  There is no stock delivery unit. The reason for this is the structure of the game, being a four leveled supply chain with a single unit on each echelon. It does not make sense not to fulfill an order when possible. Consequently orders are processed as they arrive and backlog is decreased as soon as possible, which is when a deliver is received. The movements are done with the named events.

- Factory - Production Unit
  The factory has a single production unit, which is delayed. In this implementation there is no production threshold.



Factory Production Unit

- Cockpit View



In the cockpit view an overview of the systems values are provided.

In red, the stock level data, in blue the backlog and penalty cost, in pink, the outstanding stock orders.

The gauges indicate the current level, with the values below. Note that the Retailer’s penalty gauge’s max is 10’000. The rest of the gauges maximum are 500.

7.1 Changeable Variables

For all four sites, following Variables can be manipulated in the system: All time units are in hours.

- StockMax_
  The size of the sites storage.

- DemandPerHour_
  The demand forecast - the estimated demand per hour of the site.

- LeadTime_
  Expected time delay between ordering and receiving delivery

- ReOrderPointFactor_
  Specifies when to reorder as factor of the sites storage size. [0;1]

- SafetyStockFactor_
  Specifies the amount of safety stock a site expects to need as a factor of the Stockmax_

The purpose of an order unit is to place orders, not just that the demand can be fulfilled, but that the total running cost is minimized. The running cost is generated by the StockLevel and Penalty or Backlog. Consequently excess stock and unfilled orders is what as to be minimized.

The reorder frequency has to be managed by the order unit. If the stock level drops below the reorder point, the site orders stock from upstream.

The goal is to fulfill demand - keep the running as low as possible.

7.2 Terms

Term	Description
Demand	Concrete Customer demand
Backlog	Received orders, which could not be fulfilled and has to be delivered with delay
Backlog Cost	The penalty fee paid for not being able to fulfill an order per measured time unit
Echelon	Tier, Layer or warehouse
Storage Cost	The cost generated by stock on hand

Demand Forecast	Estimated demand for a certain period
Lead Time	Expected time delay between ordering and receiving delivery to fulfill demand
Delay	A delay associated with an certain action
Reorder frequency	Frequency with which the stock is checked, to see if it is needed to order
Reorder Point	The level beneath which, if the stock falls, a order is placed
Order Strategy	A strategy which makes an tradeoff between having safety stock and causing a backlog, by not being able to fulfill an order
Outstanding Stock Orders	Placed orders, which are still in the pipeline.
Supply Chain Link	Generalized term for Retailer, Wholesaler, Regional Dealer or Factory
Stock Level	The amount of stock on hand

7.3 Variables

A helpful variable, which influences a specific OrderSize:

- OutstandingStockOrders

7.4 Values to optimise

- TotalStorageCost
- TotalBacklogCost / Penalty Cost

7.5 Cost Causing Variables

- CostStoragePerMinute_ 1
- CostBacklogPerMinute_ 2
- CostRetailerCannotDeliver 15

7.6 Delays

- Transportation Delays Product flow affected
- Delivery Processing Delays Prodect flow affected
- Order Processing Delays Information flow affected
- Order Placing Delays Information flow affected

7.7 Safety Stock

As a demand forecast is based on statistics, forecast errors are given. Safety stock is kept as a buffer, to satisfy demand, when e.g. the demand increases or deliveries are not made, when expected – needed. Safety stock is an financial outlay (stock and storage), which guarantees a certain service level. To minimize the financial drain, the safety stock needs to be minimized and a reasonable strategy for its calculation is needed. A inadequate reordering strategy has the Bullwhip Effect and other problems as consequences.

7.8 Delays and Lead Time

The lead time is the expected time delay between ordering and receiving delivery to fulfill demand. The lead time is created by delays is the system.

With the following conditions, we estimate the lead time of the retailer below:

- The retailer orders once a day – thus every 24 hours.
- The delivery process stars when a site has or receives stock.
- The delivering site, the wholesaler has stock for the deliveries

A site could estimate its lead time as follow, by sample of the retailer by summing the following details:

Nr.	Excel Sheet Coordinates	Delay value description
1	C6	The time interval in which it orders. The retailer orders every 24 hours.
2	E9	The site's order delay
3	E12	The time the site delivering it needs to process the order
4	G12	The transport time from the delivering site, the wholesaler, to the retailer
5	G9	The delivery handling time of the retailer itself

Below a visual overview of the retailers lead time calculation.

SUM | =E9+E12+G12+G9+C6

	A	B	C	D	E	F	G	H
3		CreateCustomerfrequency	0.05	NORM(0.05, 0.5)	3			
4		CustomerDemandAllocation	12	ANINT(NORM(12, 0.5))			0.05	
5		DEMAND_PER_HOUR	240	NORM(0.5, 0.5)	DelayOrder		DelayHandleCustomerDelivery	NORM(0.05, 0.1)
6		CreateStockOrder	24			RE		
7		LEAD_TIME	=E9+E12+G12+G9+C6					
8		DemandStock	7080	NORM(1, 0.2)	DelayPlacingOrder		DelayHandleDelivery	NORM(1, 0.5)
9		DemandStock	DEMAND_PER_HOUR_RE_00 * LEAD_TIME_RE_00		1		1	
10								
11								
12					0.5		3	
13		DEMAND_PER_HOUR	300	NORM(0.5, 0.5)	DelayOrder		DelayStockInTransit	NORM(3, 0.1)
14		CreateStockOrder	12			WS		
15		LEAD_TIME	17.5					
16		DemandStock	5250	NORM(1, 0.2)	DelayPlacingOrder		DelayHandleDelivery	NORM(1, 0.5)
17					1		1	
18								

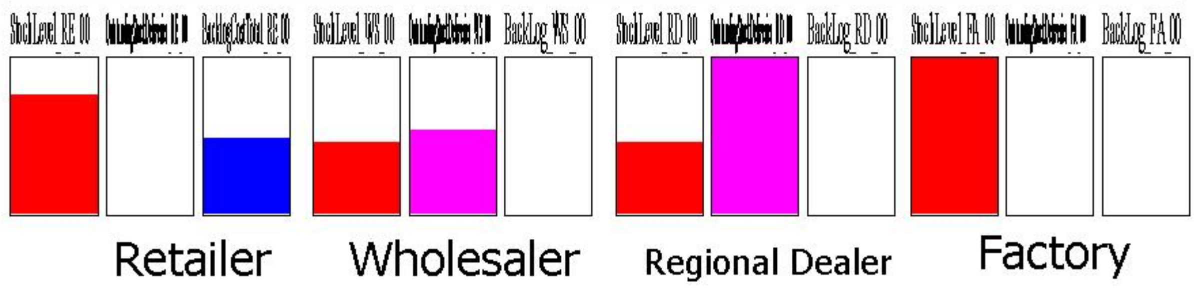
Simplified lead time estimation

Using these values, as also can be seen in the output, produces following result.

Variable	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Backlog_FA_00	16.7735	3.77	13.3101	21.4200	0.00	1000.00
Backlog_RD_00	13.8244	9.49	4.7191	21.6209	0.00	1000.00
Backlog_RE_00	0.00	0.00	0.00	0.00	0.00	0.00
Backlog_WS_00	6.4654	1.33	5.6601	8.2634	0.00	500.00
BacklogCostTotal_FA_00	1.4694	0.47	1.1488	1.8886	0.00	3.6152
BacklogCostTotal_RD_00	1.6076	0.27	1.3489	1.9142	0.00	3.7037
BacklogCostTotal_RE_00	6690.63	1'541.59	5080.15	8098.38	0.00	15450.00
BacklogCostTotal_WS_00	0.8649	1.01	0.4647	2.3259	0.00	5.4430
BacklogSum_FA_00	2572.00	114.11	2458.82	2709.26	0.00	3520.00
BacklogSum_RD_00	1466.86	449.41	1047.99	1916.47	0.00	2985.00
BacklogSum_RE_00	0.00	0.00	0.00	0.00	0.00	0.00
BacklogSum_WS_00	502.42	26.02	492.46	539.90	0.00	603.00
DEMAND_PER_HOUR_FA_00	500.00	0.00	500.00	500.00	500.00	500.00
DEMAND_PER_HOUR_RD_00	400.00	0.00	400.00	400.00	400.00	400.00
DEMAND_PER_HOUR_RE_00	240.00	0.00	240.00	240.00	240.00	240.00
LEAD_TIME_RD_00	12.5000	0.00	12.5000	12.5000	12.5000	12.5000
OutstandingStockDeliveries_FA_00	54.7819	3.07	51.7086	58.2931	0.00	1000.00
OutstandingStockDeliveries_RD_00	56.2600	5.45	49.5008	60.4934	0.00	1500.00
OutstandingStockDeliveries_RE_00	32.2826	1.13	30.9887	33.5213	0.00	500.00
OutstandingStockDeliveries_WS_00	58.9705	6.14	50.3428	62.6291	0.00	1000.00
StockLevel_FA_00	857.85	54.47	799.84	892.56	0.00	1000.00
StockLevel_RD_00	623.77	167.62	504.76	793.22	0.00	1500.00
StockLevel_RE_00	226.86	15.53	215.85	248.39	0.00	978.00
StockLevel_WS_00	466.64	42.57	421.34	516.14	0.00	1000.00
StorageCostTotal_FA_00	7404.17	319.92	7044.80	7630.97	0.00	18127.73
StorageCostTotal_RD_00	6248.08	1'446.22	4965.89	7573.77	0.00	15856.97
StorageCostTotal_RE_00	2448.98	325.93	2296.66	2916.08	0.00	5166.48
StorageCostTotal_WS_00	4375.26	442.91	3945.71	4775.53	0.00	9817.75
Throughput_RE_00	3307.25	135.92	3175.68	3428.32	0.00	6753.00

System output after 5 replications – before optimization

In a normal simulation with roughly estimated values, the Bullwhip Effect can be seen clearly- Large orders ripple through the supply chain – caused costs can be seen above.



Stock Levels viewed at an instance in time

These values will be used as initial values for the optimization. It is clear, that the system setup is not near optimal and in a normal analysis process these values would have been estimated more accurately. Consequently the optimization will show more effect.

8 Simulation Tool - ARENA of Rockwell Automation

Arena of Rockwell Automation is the chosen simulation tool for this thesis. The choice of a simulation tool can be cumbersome if all requirements to the tool are not known at project start. Since simulation tools proves to have mentionable differences [7], the simulation tool's characteristics have to be taken into account, when the physical model is designed. With ARENA, the findings of M.H. Jansen-Vullers and M. Netjes [7], has shown to be accurate: simple issues can become complex. Templates enable the reuse of code which is powerful, in systems with recurrences.

8.1 The Development Process

The development process in a simulation tool is different; compare it to programming in Java or C#: the productivity rate in relation seems lower. The comparison may not be quite fair, since the simulation model has a very high information level and it would be expected to have mentionable less code in the representation level if compared to a normal application.

8.2 Optimization with OptQuest for Arena

Optimization is an intelligent brute force process. The task of the optimizer was to reduce the sum of the cost caused by storage and backlog penalties:

Minimize(BacklogCostTotal + StarageCostTotal)

ARENA's simulation model is used by "OptQuest for ARENA" of Optimization Technologies, Inc.[25] during the result processing for optimization.

The Controls:

For all four sites they are the same:

- StockMax_
  The size of the sites storage.

- DemandPerHour_
  The demand forecast - the estimated demand per hour of the site.

- LeadTime_
  Expected time delay between ordering and receiving delivery

- ReOrderPointFactor_
  Specifies when to reorder as factor of the sites storage size. [0;1]

- SafetyStockFactor_
  Specifies the amount of safety stock a site expects to need as a factor of the Stockmax_

The goal is to fulfill demand - keep the running as low as possible:

Minimize(BacklogCostTotal + StarageCostTotal)

Minimize(

[BacklogCostTotal_FA_00] + [BacklogCostTotal_RD_00] +
[BacklogCostTotal_RE_00] + [BacklogCostTotal_WS_00] +
[StorageCostTotal_FA_00] + [StorageCostTotal_RD_00] +
[StorageCostTotal_RE_00] + [StorageCostTotal_WS_00]

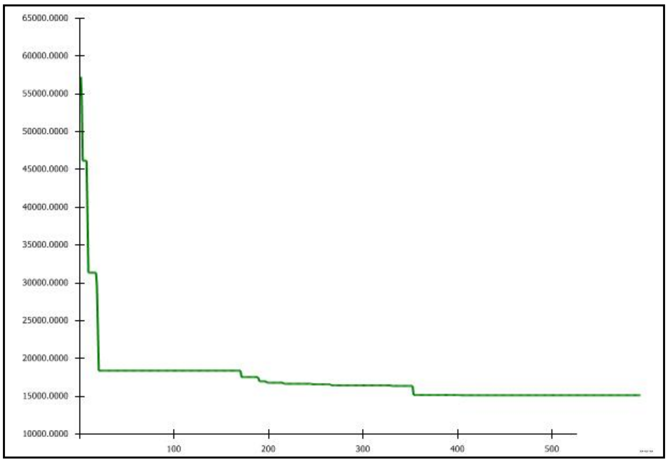
)

After the first optimization

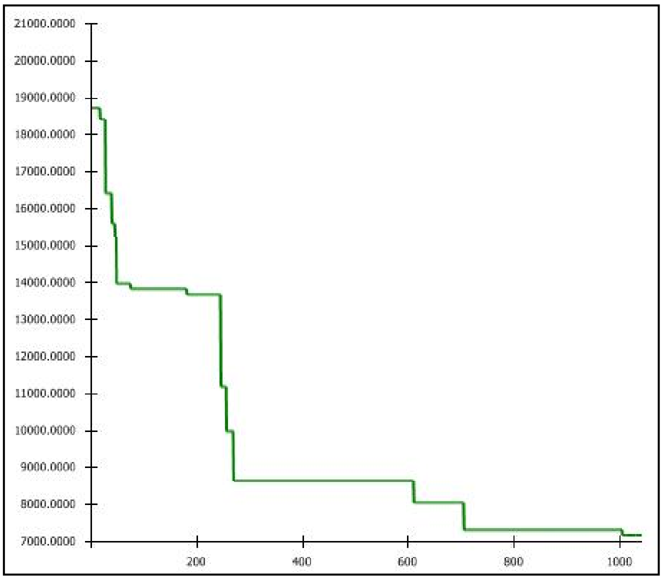
The systems performance showed improvement - the variation was extremely reduced. The result was processed and the simulation was run again with OptQuest – this was done 5 times. The reason for the repeats were not just to optimize the process, but also to speed up the optimization by choosing the variable values types more carefully, including their stepping size; by specifying the stepping size and by reducing the value domains a little at a time reduced the variability in possibilities to be simulated. This was done without affecting the outcome of the simulation: Not just does it make sense to define the storage size stepped; the storage size is multiplied with the reorder point factor; hens does not reduce the overall result.

Below a typical OptQuest optimization graphs. This shows how the equation value is reduced by choosing the input parameters more suitable.

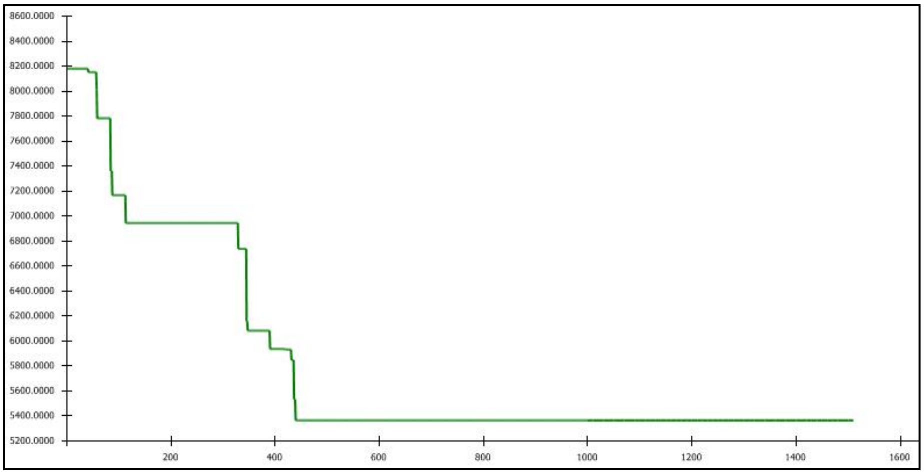
The first simulation has the value of 55'500, the last optimized run 5'300



Simulation optimization course with roughly estimated values



Simulation optimization course – second run



Simulation optimization course – third run

The optimization is set to minimize or maximize an equation. In this case it was to minimize the sum of the storage cost and backlog penalties. The cost drops during the optimization every time a better configuration is found.

Below the equation values of the 3 optimization runs can be seen. A single optimization run can be a few thousand simulations and takes time. One can save time here by logically examination the input value dependencies. To speed up the simulation after the first run, the DEMAND_PER_HOUR variable type was changed to integer and the StockMax was corrected to integer. The step size of StockMax was additionally set to 10, then to 5.

Below we can see how the running cost of the system could be reduced within 3 optimization runs from 55500 to 5300: The first run was set with

- a estimated max lead time for each site
- an estimated demand for each site

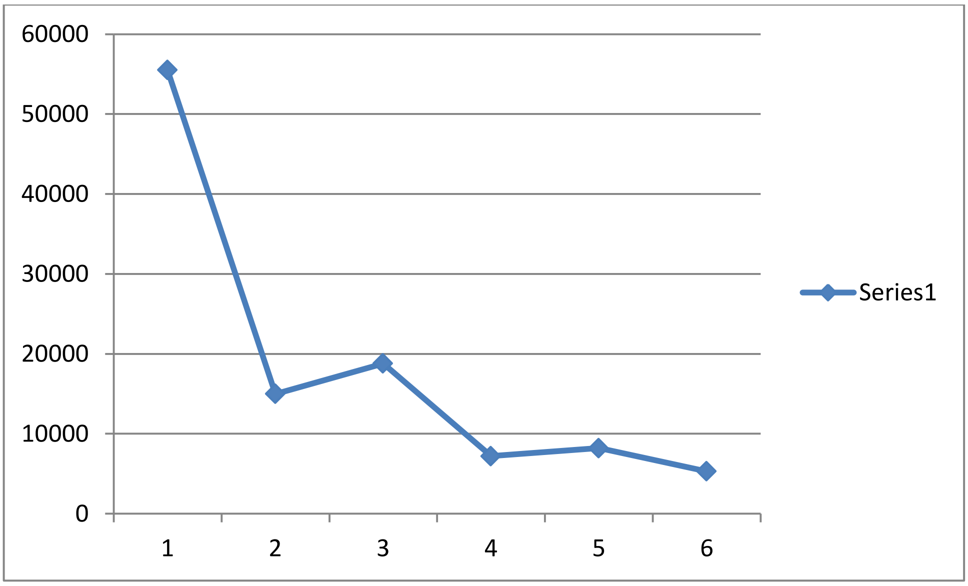
Leaving the first run out of the calculation, we consider the following 2 in which the cost was reduced from 15000 to 5300. Note that the actual value is not of interest to us, but rather the factor, which is nearly 3, achieved with optimization.

Minimize		
	Objective Value	Status
Best Value	15139.782874	Feasible

Minimize		
	Objective Value	Status
Best Value	7158.829453	Feasible

Minimize		
	Objective Value	Status
Best Value	5365.788936	Feasible

Optimization Best Values



Optimization Best Values Chart

The variable values for the best run

Controls	
Control Name	**Best Value**
DEMAND_PER_HOUR_FA_00	5
DEMAND_PER_HOUR_RD_00	4
DEMAND_PER_HOUR_RE_00	4
DEMAND_PER_HOUR_WS_00	5
LEAD_TIME_FA_00	9.001531
LEAD_TIME_RD_00	12.363797
LEAD_TIME_RE_00	27.877372
LEAD_TIME_WS_00	15.988554
ReorderPointFactor_FA_00	0.341655
ReorderPointFactor_RD_00	0.194645
ReorderPointFactor_RE_00	0.212898
ReorderPointFactor_WS_00	0.249216
SafetyStockFactor_FA_00	0.552077
SafetyStockFactor_RD_00	0.459647
SafetyStockFactor_RE_00	0.339976
SafetyStockFactor_WS_00	0.602062
StockMax_FA_00	75
StockMax_RD_00	120
StockMax_RE_00	700
StockMax_WS_00	220

Variable Values of Optimization

The functionality of OptQuest is explained in detail in its users guide [26].

Once the mechanisms of Arena have been learnt, it has shown to very powerful, also in the optimization of processes.

9 Conclusion

By thoroughly understanding the inherence of supply chains and the underlying causes of The Bullwhip Effect, which results from rational decision making by members in the supply chain, effective counteractions are possible.

Victory by comprehension…

The iterative validation process is part of result processing and is integrated in the Data Specification as well as in the Process Specification. The simulation development process needs a high quality of data to perform its task, which adds focus to the validation process of simulation models.

ARENA has proven to be very powerful, not just in the simulation model building but also in the optimization. ARENA additionally provides process analyzing and specialized packaged, for supply chains as well. In depth knowledge of the models domain is provided up front and need not be built by oneself. This contributes to the development speed as well as the model quality and in the end to the simulation result.

The simulation of supply chains
is evidently an interdisciplinary research area
with much potential.

10 Next Readings

Because of the vastness of the research area involved in the simulation of supply chains, the scope of this thesis does not go in depth into all areas involved. Consequently, a list of subjects and areas to explore accumulates and would be next steps. This chapter is an accumulation of references and ideas as a next step and should help to share the gained knowledge as a whole.

10.1 Simulation

Behavioral equivalence in simulation modeling:
http://www.sciencedirect.com/science/article/pii/S1569190X06000633

MSCO. See "Credits" for involved organizations.
The MSCO [27] provides a very informative view and list practical aspects related to validation and its importance, which makes it mentionable here.
http://vva.msco.mil

The visualization of the optimization process could be interesting to see, following paper; Accelerating Scientific Discovery Through Computation and Visualization, James S. Sims, John G. Hagedorn, Peter M. Ketcham, Steven G. Satterfield, Terence J. Griffin, William L. George, Howland A. Fowler, Barbara A. am Ende, Howard K. Hung, Robert B. Bohn, John E. Koontz, Nicos S. Martys, Charles E. Bouldin, James A. Warren, David [32]

10.2 Supply Chains

ECR: Efficient Consumer Response initiative [22]: Tried to redefine how grocery supply chains should work.
CPFR: Collaborative Planning Forecasting and Replenishment 1997

10.2.1 Contemporary solutions

How do our peers solve their problems? Apple, Dell, Amazon, major retail store chains. The list is long, but to understand one's own supply chain best and to find an optimal strategy, the leading peers and competitors' supply chains should be studied.

- The Gartner Supply Chain Top 25, http://www.gartner.com/technology/supply-chain/top25.jsp
- CRP (Continuous Replenishment Program)

http://www.lean-manufacturing-japan.com/scm-terminology/crp-continuous-replenishment-program.html

"CRP is used combined with the ordering point method in which an economic amount of orders will be calculated for order placement when the inventory level reaches the ordering point or with the replenishment ordering system that aims to return the inventory level to the basic inventory."

10.2.1 Digital Supply Chains

In addition to the physical supply chain, digital supply chains have become part of the circle and pose different problems. Apple with ITunes, Disney with films in hard and soft copies are but only the first two examples.

Which variabilities are relevant for digital supply chains and how do the two supply chains cohere?

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