Appendix A Simulation runs parameters

In this appendix we present all the parameter data used in each simulation run presented in this thesis.

Data Table A-1

Module A: TTF-210100		
Variable	**Value**	**Units**
Module Inputs		
Forecast Input (FI)	$IOR1_A + IOR2_A$	Products /week
Incoming Ordering Rate 1 (IOR1)	OOR_B	Products /week
Incoming Ordering Rate 2 (IOR2)	OOR_C * *OrderingRatio*	Products /week
Inflow Capacity Limitation (ICL)	10000	Products /week
Outflow Capacity Limitation (OCL)	10000	Products /week
Material Inflow (MI)	OOR_A	Products /week
Main stock and flow structure		
Stock of Material in Transformation (SMT)	*0*	Products
Stock of Transformed Material (STM)	10000	Products
TR material delay order (n)	1	Dimensionless
Unit Multiplier (UM)	1	Dimensionless
Percentage of Material Disposed (PMD)	0	Dimensionless
Time To Transform (TTT)	4	Week
Time To Deliver (TTD)	0.5	Week
Incoming-orders processing 2		
Incoming Orders Backlog1 (IOB1)	$DDD1_A$*$IOR1_A$	Products
Incoming Orders Backlog2 (IOB2)	$DDD2_A$*$IOR2_A$	Products
Desired Deliver Delay1 (DDD1)	0.5	Week
Desired Deliver Delay2 (DDD2)	0.5	Week
Demand forecasting 1		
Time to Average Forecast input (TAF)	4	Week
FD order of smooth (n)	1	Dimensionless
Stock control 1		
Stock of Transformed Material Coverage Time (STMCT)	1+2/3	Week
Stock of Transformed Material Adjustment Time (STMAT)	4	Week
Stock of Material in Transformation Coverage Time (SMTCT)	4	Week
Stock of Material in Transformation Adjustment Time (SMTAT)	4	Week

Module B: TTD-100		
Variable	**Value**	**Units**
Module Inputs		
Incoming Ordering Rate (IOR)	*Demand*	Products /week
Inflow Capacity Limitation (ICL)	10000	Products /week
Material Inflow (MI)	$MO1_A$	Products /week
Main stock and flow structure		
Stock of Material in Transformation (SMT)	*0*	Products
TR material delay order (n)	1	Dimensionless

Unit Multiplier (UM)	1	Dimensionless
Time To Transform (TTT)	1	Week
Incoming-orders processing 1		
Incoming Orders Backlog (IOB)	*0*	Products
Module C: RTTD-000		
Module Inputs		
Inflow Capacity Limitation (ICL)	10000	MaterialA/week
Material Replacement Inflow (MRI)	MO_D+$MO2_A$	Products/week
Material Inflow (MI)	$RepaireReturnRate$	Products/week
Main stock and flow structure		
Stock of Material in Transformation (SMT)	0	Products
Time To Transform (TTT)	1	Week
TR material delay order (n)	1	Dimensionless
Unit Multiplier (UM)	1	Dimensionless
Percentage of Material Disposed	0.25	Dimensionless
Incoming-orders processing 1		
Incoming Orders Backlog (IOB)	*0*	Products
Module D: TTF-P11120		
Variable	**Value**	**Units**
Module Inputs		
Forecast Input (FI)	IOR_D	Products /week
Incoming Ordering Rate (IOR)	OOR_C * (1-*OrderingRatio*)	Products /week
Inflow Capacity Limitation (ICL)	10000	Products /week
Outflow Capacity Limitation (OCL)	10000	Products /week
Material Inflow (MI)	MDR_C + *ReturnRate*	Products /week
Main stock and flow structure		
Stock of Material in Transformation (SMT)	$DSMT_D$	Products
Stock of Transformed Material (STM)	$DSTM_D$	Products
TR material delay order (n)	1	Dimensionless
Unit Multiplier (UM)	1	Dimensionless
Percentage of Material Disposed (PMD)	0.35	Dimensionless
Time To Transform (TTT)	4	Week
Time To Deliver (TTD)	0.5	Week
Incoming-orders processing 1		
Incoming Orders Backlog (IOB)	DDD_D*IOR_D	Products
Desired Deliver Delay (DDD)	0.5	Week
Demand forecasting 1		
Time to Average Forecast input (TAF)	4	Week
FD order of smooth (n)	1	Dimensionless
Material Inflow forecasting 1		
Time to Average Forecast input1 (TAF1)	1	Products
FDR order of smooth (n)	1	Dimensionless
Stock control 2		
Stock of Transformed Material Coverage Time (STMCT)	10	Week
Stock of Transformed Material Adjustment Time (STMAT)	4	Week
Stock of Material in Transformation Coverage Time (SMTCT)	4	Week

Stock of Material in Transformation Adjustment Time (SMTAT)	4	Week

Module E: Custom made		
Variable	**Value**	**Units**
Main stock and flow structure		
Products disposed by the company	0	Products
Products disposed by customers	0	Products
Products in use	0	Products
Demand	Figure 6	Products/week
End of lifetime	150	Week
Time to damage	50	Week
Percentage returned	0 or 0.5 for each simulation run	Dimensionless
Ordering ratio	1: simulation run 1 0.5: simulation run 2 0: simulation run 3	Dimensionless

Data Table A-2

TTF-110100		
Variable	**Value**	**Units**
Module Inputs		
Forecast Input (FI)	*IOR*	Widgets/week
Incoming Ordering Rate (IOR)	100 + STEP(20,5)	Widgets /week
Inflow Capacity Limitation (ICL)	10000	Widgets /week
Outflow Capacity Limitation (OCL)	10000	Widgets /week
Material Inflow (MI)	*OOR*	Widgets /week
Main stock and flow structure		
Stock of Material in Transformation (SMT)	*DSMT*	Widgets
Stock of Transformed Material (STM)	*DSTM*	Widgets
TR material delay order (n)	3	Dimensionless
Unit Multiplier (UM)	1	Dimensionless
Percentage of Material Disposed (PMD)	0	Dimensionless
Time To Transform (TTT)	8	Week
Time To Deliver (TTD)	2	Week
Incoming-orders processing 1		
Incoming Orders Backlog (IOB)	100	Widgets
Desired Deliver Delay	4	Week
Demand forecasting 1		
Time to Average Forecast input (TAF)	8	Widgets
FD order of smooth (n)	1	Dimensionless
Stock control 1		
Stock of Transformed Material Coverage Time (STMCT)	4	Week
Stock of Transformed Material Adjustment Time (STMAT)	8	Week
Stock of Material in Transformation Coverage Time (SMTCT)	8	Week
Stock of Material in Transformation Adjustment Time (SMTAT)	2	Week

Data Table A-3

TTF-P01120		
Variable	**Value**	**Units**
Module Inputs		
Forecast Input (FI)	*IOR*	MaterialB/

		week
Incoming Ordering Rate (IOR)	50 + STEP(50,10)	MaterialB/ week
Inflow Capacity Limitation (ICL)	10000	MaterialA/ week
Outflow Capacity Limitation (OCL)	10000	MaterialB/ week
Material Inflow (MI)	200 + STEP(100,35)	MaterialA/ week
Main stock and flow structure		
Stock of Material in Transformation (SMT)	200	MaterialA
Stock of Transformed Material (STM)	250	MaterialB
TR material delay order (n)	1	Dimensionl ess
Unit Multiplier (UM)	1	MaterialB/ MaterialA
Percentage of Material Disposed (PMD)	0.2	Dimensionl ess
Time To Transform (TTT)	4	Week
Time To Deliver (TTD)	4	Week
Demand forecasting 1		
Time to Average Forecast input (TAF)	4	MaterialB
FD order of smooth (n)	1	Dimensionl ess
Material Inflow forecasting 1		
Time to Average Forecast input1 (TAF1)	1	MaterialB
FDR order of smooth (n)	1	Dimensionl ess
Stock control 2		
Stock of Transformed Material Coverage Time (STMCT)	5	Week
Stock of Transformed Material Adjustment Time (STMAT)	4	Week
Stock of Material in Transformation Coverage Time (SMTCT)	4	Week
Stock of Material in Transformation Adjustment Time (SMTAT)	4	Week

Appendix B Modules' description and naming convention

In Appendix B, Table B-1 presents a general description for each mini-module type, the versions developed for these mini-modules, along with specific description for each version, and the modules each version is compatible with. In addition, Table B-2 presents the naming convention used in this study for the developed modules.

Table B-1: Mini-modules' description

Version number	Specific description	Compatibility
Incoming-orders processing: responsible for keeping track of incoming orders, and initiating the desired material outflow.		
1	Takes orders from one module and supplies materials to it accordingly	ALL
2	Takes orders from two different modules and supplies materials to both of them accordingly	ALL
Forecasting: responsible for forecasting whether it is demand, disposal rate, or material inflow.		
Demand forecasting 1	Forecasting demand	TTF TTF-P
Disposal forecasting 1	Forecasting disposal rate	TTF TTF-P
Material inflow forecasting 1	Forecasting material flow	TTF-P
Stock control: responsible for controlling Stocks calculating the desired material inflow		
1	Controls *Stock of Materials in Transformation* and *Stock of Transformed Materials*	TTF
2	Controls *Stock of Materials in Transformation* and *Stock of Transformed Materials*	TTF-P
Outgoing-orders processing: responsible for keeping track of the outgoing orders.		
1	Responsible for keeping track of the outgoing orders.	TTF TTD/RTTD
2	Responsible for keeping track of the outgoing orders and correcting for the upstream supply line while tracking orders	TTF

Since there are multiple versions of mini-modules used in the main modules, there would be many possible formulations of each developed module. Although this creates flexibility in adapting the modules to different needs, it might confuse the reader. For this reason, we have developed a naming convention that will aid the reader in identifying which mini-modules are used within the specified module. The naming convention is presented in Table B-2.

Table B-2: Modules naming convention

	Incoming-orders processing	Demand forecasting	Disposal/Material-inflow forecasting	Stock control	Outgoing-orders processing
TTF-	0 1	0 1	0 1	1	0 1 2
TTF-P	0 1	0 1	0 1	2	
TTD-	0 1				0 1
RTTD-	0 1				0 1

First you specify the module type (e.g. TTF), then you insert a dash then you insert a series of numbers that specify the version of the mini modules used or not used (if 0). For example, TTF-11010 would mean the transfer-to-forecast module which has the following mini-modules: Incoming-orders processing mini-module version 1, demand forecasting version 1, and stock control version 1; and does not have the following mini-modules: disposal forecasting, and outgoing-orders processing.

Appendix C Modules' validity

The modules developed are formulated using previously used and validated supply chain models in system dynamics as well as qualitative descriptions of the modules' functions. The TTF/TTD/RTTD modules' main stock and flow structure is well representative of a transformation process. Obviously there could be certain transformation processes that need a more detailed stock and flow structure, but this would not serve the purpose of this article. The modules developed have adequate detail and boundary to remain general yet representative to a useful degree for most transformation processes.

Many of the modules developed are based on widely used and well-validated system dynamics models. For example, the TTF module structure is based on Sterman's (2000, Chapter 18) Production Inventory model. Some versions of the RTTD stock and flow structure are used in modelling reverse supply chains in system dynamics (e.g. Das & Dutta, 2013b; Georgiadis & Athanasiou, 2010; Poles, 2013; Vlachos et al., 2007). For example, Das and Dutta (2013b) represent reverse supply chain processes (i.e. Collection, product remanufacturing and component remanufacturing) using a variant of the RTTD module.

The TTD module is based on a qualitative description of the transformation process. The TTD module as described previously represents the process of transforming material based on customer demand. The behaviour of the module replicates the expected behaviour of a TTD process; for example, the expected time of product delivery is equal to the transformation time.

We have tested the module's structure and behaviour rigorously to eliminate the possibility of modelling errors. In that aspect, all formulations of the modules are dimensionally consistent. Also various extreme condition tests were passed. For example, in TTF when the *Incoming Orders Rate* is set to zero, the *Transformation start rate* and the *Outgoing Orders Rate* goes to zero after some delay (due to the forecasting delay); and the *Incoming Orders Backlog* stock depletes to zero, indicating that all the orders were met. This shows that the modules respond well to an extreme value of *Outgoing Orders Rate.*

Another validity test is the boundary-adequacy test, which evaluates if a model's stock and flow structure is adequate for representing the critical and important endogenous dynamics of the system. If a model includes all the necessary endogenous structures of a system while reproducing its behaviour, it is said to have an adequate boundary. In that aspect, each module represents the structure of its corresponding supply chain process, including incoming orders tracking, heuristics for ordering or disposing materials, outgoing orders tracking, and material flows within the supply chain. The advantage of using modules to model supply chains is that one can assess the right boundary to represent the system under investigation and decide on the number of modules to be integrated. This allows the modeller to test if the boundary is adequate by adding or removing modules while observing the model's behaviour in comparison to the real system. This adds flexibility and ease to the modelling process and saves considerable time in contrast to expanding and contracting a model built from scratch.

Another important validity test is the behaviour reproduction test, which is used to assess if a model reproduces the behaviour of a system. The behaviour of TTF and RTTD were compared with previously developed and well-established models. For example the behaviour of TTF-11010 module was compared with Sterman's (2000, Chapter 18) Production Inventory model. The module was parameterized in accordance with Sterman's (2000: 721) model; the module parameters are presented in Data Table A-2 in Appendix A. Figure 10 shows the behaviour of the module and the model. As shown in the figure the module's behaviour slightly differs from Sterman's model in transient state (due to a slight difference in modelling the *Material Outflow*[1]) and is identical to it in steady state. The same test was performed on RTTD against the models by Das and Dutta (2013a) and Georgiadis and Athanasiou (2010).

[1] Sterman determines the *Material Outflow* by multiplying the *Desired Material Outflow* with an *Order Fulfillment Ratio*. The *Order Fulfillment Ratio* is a nonlinear graphical function that depends on the ratio of *Desired Material Outflow* and *Maximum Material Outflow* (which equals *Stock of Transformed Materials/Time to Deliver)*. The graphical function allows the modeler to create a custom graphical function for *Order Fulfillment Ratio.* Instead we decided to use a simpler version that directly determines the *Material Outflow* by comparing the *Desired Material Outflow* with the *Maximum Material Outflow*, such that if the *Desired Material Outflow* is less than the *Maximum Material Outflow* then the *Material Outflow* will be equal to the *Desired Material Outflow,* and if otherwise the *Material Outflow* is equal to the *Maximum Material Outflow.* This simpler version assumes that the decision maker is always trying to satisfy orders with maximum capacity without any desire to limit *Material Outflow* (i.e. shipments to orders) for unexpected high ordering rates or low current levels of inventory.

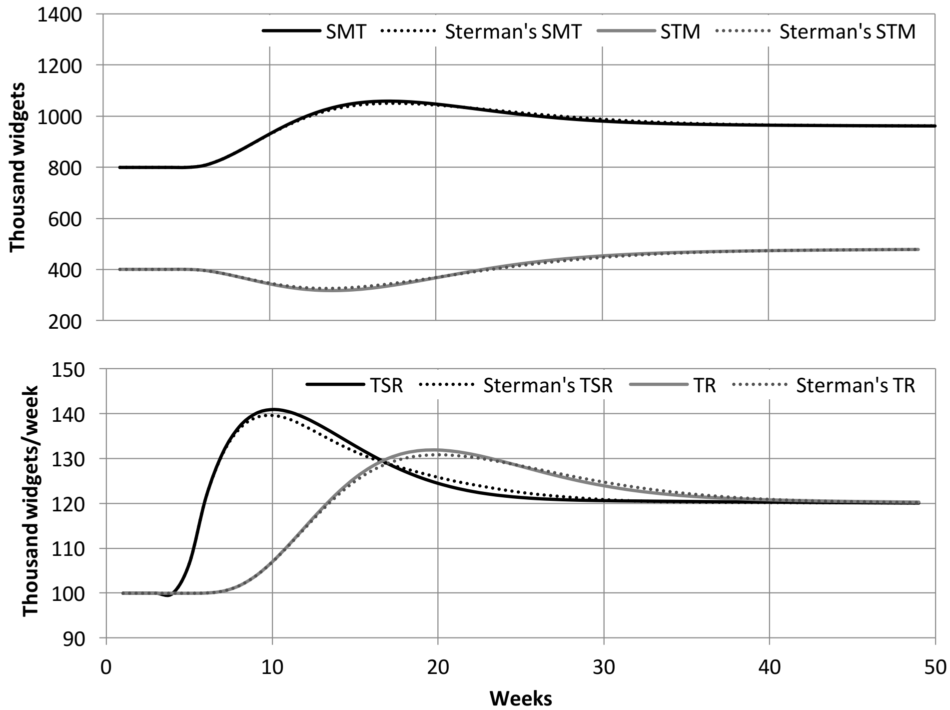

Figure 10: TTF-110100 module's behaviour versus Sterman's Production inventory model behaviour

Behaviour prediction tests are used in system dynamics to determine if a model's behaviour matches the predicted future behaviour of the system under study. We have documented the TTF-P module's test assessment as an example, however the test was performed for all the modules resulting in a similar assessment as the ones presented. The TTF-P module is essentially the same as the TTF, except that controlling the stock is done by disposing excess material, and so there is no *Outgoing Ordering Rate* to satisfy the *Incoming Ordering Rate*, instead the *Material Inflow* is pushed into the module. We expect that the behaviour is similar to TTF except that the stock control is done through adequate *Material Disposal Rate*. Figure 11 shows TTF-P0112 module's behaviour for a step increase in the *Incoming Ordering Rate.* The modules parameters for this run are presented in Data Table A-3 in Appendix A. As shown in the figure the module is initialized in equilibrium, and a 100% step increase in *Incoming Orders Rate* is introduced after ten weeks. In this module we see that the *Desired Material Outflow* is equal to the *Incoming Ordering Rate* since the incoming-orders processing mini-module is inactive, and so any orders that are not satisfied are lost.

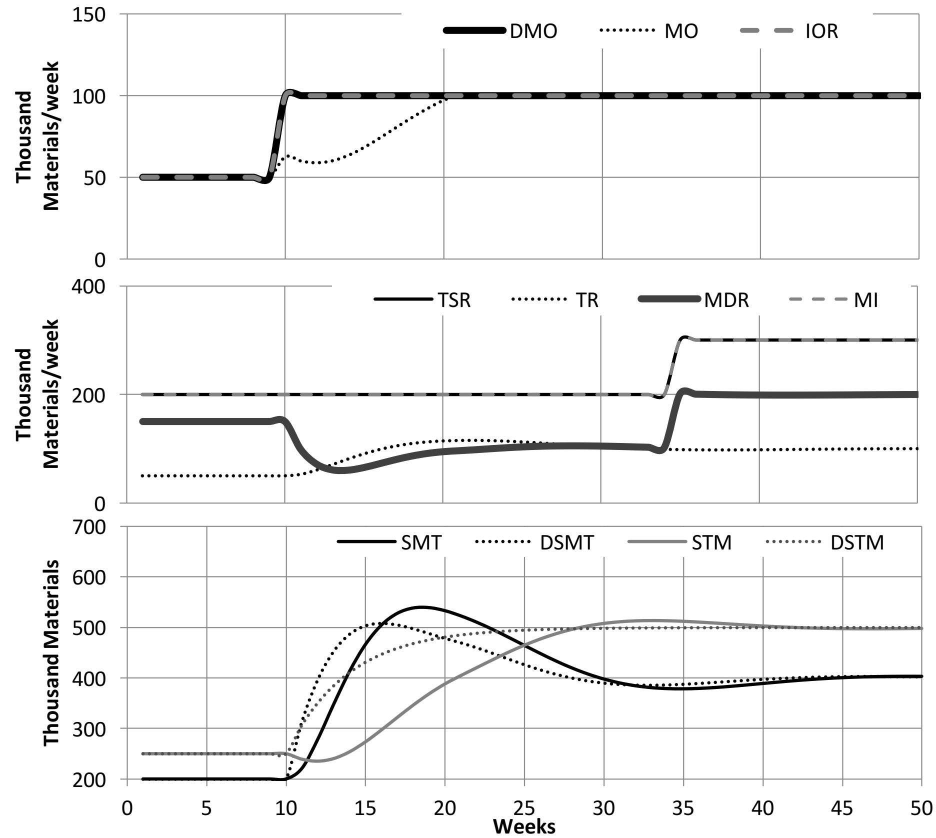

Figure 11: TTF-P01120 module's simulation behaviour for step increase in incoming ordering rate and in Material Inflow

In response to the higher demand the *Material Disposal Rate* decreases which leads to an increase in the *Transformation Rate*, leading to higher *Stock of Transformed Materials* after its initial dip due to the sudden increase in demand. With the increase of *Stock of Transformed Materials* the *Material Outflow* increases to match the *Desired Material Outflow.* The difference between the *Material Outflow* and *Desired Material Outflow* are lost orders. It takes *Material Outflow* ten weeks to match the *Desired Material Outflow.* At week 35 a sudden 50% increase in *Material Inflow* is introduced as material is pushed into the system. We see that the *Transformation Start Rate* is equal to the *Material Inflow* since there is no capacity limitation, and as expected the 50% increase in *Material Inflow,* simply leads to 50% increase in *Material Disposal Rate* to keep the *Stock of Transformed Material* at the desired level.

The TTF-P module matches the predicted behaviour in response to sudden disturbances; the behaviour prediction test was performed on all other modules, as well, with similar disturbances introduced to the system. In all cases the modules have passed the test.

The validity tests performed indicated multiple mathematical and structural errors in most modules, which have been fixed. The development of these modules were an iterative process where the tests were performed, errors were discovered and fixed, and then tested again. As Forrester and Senge (1980, p. 4) put it:

> "There is no single test which serves to 'validate' a system dynamics model. Rather, confidence in a system dynamics model accumulates gradually as the model passes more tests and as new points of correspondence between the model and empirical reality are identified."

In that aspect these modules have passed the tests mentioned in this section, building confidence in them, and as we use the modules more, the confidence in them increases. In summary, we have tested these modules rigorously within our capacity, allowing us to develop modules that can be used by modellers in developing system dynamics models: their use will also increase confidence and possibly improve the modules as such.