International Journal of Science Academic Research
Vol. 06, Issue 10, pp.10815-10821, October 2025
Available online at http://www.scienceijsar.com

ISSN: 2582-6425

Research Article

INTENSIFYING BOOLEAN MATRIX CONCEPT IN MODELLING CASCADE LIQUEFACTION OF NATURAL GAS

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Received 18th August 2025; **Accepted** 27th September 2025; **Published online** 30th October 2025

Abstract

Technologies for natural gas processing depend on the scope required, composition of the gas, CAPEX and end-use application or utilization. Liquefaction is one of the operations used for the separation of natural before separation into other derivatives. The liquefaction operations that apply cascade models have been used to illustrate its applicability for natural gas processing1. The model is flexible and configuration advanced to different stages – simple, multiple and hybrid cascade models[2-4]. The Boolean Matrix concept enabled us to: simplify binary representation of complex cycles; apply computer-based algorithms (matrix multiplications, graph theory) and modelling; identified dependencies between cycles; facilitate simulation convergence (e.g., detecting recycle loops before solving), generalize and advanced the cased models to complex configurations. The cascade models configurations presented here conform to the Boolean matrix concept, with its application here being fully described and explained. Overall, the Boolean Matrix concept and the modelling approach have enabled the integration of different cascade models into a single train natural gas processing, which allowed the advanced model to evaluate the impact and contribution of each or combination of cascade models to the entire simulation. Over a hundred modelling and simulation have been done to further test and prove the concept and the data supplied used; each simulation converged and gave satisfactory results. The flexibility, reliability and applicability of this model have now been fully demonstrated.

Keywords: Community Land Act, Land tenure, ASALS, Pastoralism, Resource Management.

INTRODUCTION

Scope and concept of natural gas processing

Natural gas can be wet or dry, hence for full processing and greater end-use application, liquefaction/refrigeration are the processes used to separate the various components and deploy same, for specified domestic and industrial uses. The scope for processing of natural gas involves: delivery via metering, and thereafter pre-treatment, dehydration to liquefaction in that sequence; and then to separation into LNG and LPG. Condensate is recovered in the process ***(Figure 1).***

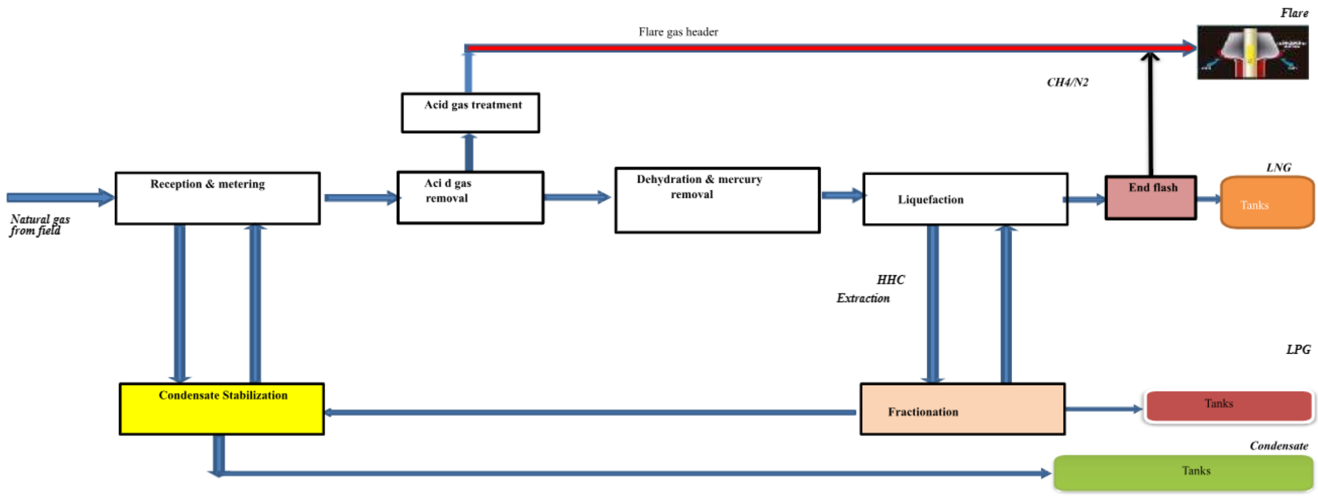

Figure 1. Natural gas processing

The liquefaction section in *Figure 1* is considered as the heart of the process and has been modelled as refrigeration cycles in cascades. A published model[2] with configuration of cascade *(T1C, T2C, 2PC, 2HC, T3C, 3PC and 3HC)* is shown below. Details of these cascade configurations are shown below in *Figure 2* with numbers for streams and codes for equipment defined: *(Cm, compressor, Cn, condenser, JT, JT valve, LN, evaporator here modelled as LNG, FrT, downstream fractionation section).*

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The model starts from *Single (T1C) cycle* with single refrigerant to *double cycle (T2C) cascade* with double refrigerant to *triple cycle (T3C) cascades* with multiple refrigerants. The *double* and *triple* cascades have different configurations and more can be explored depending on requirements for energy optimization.

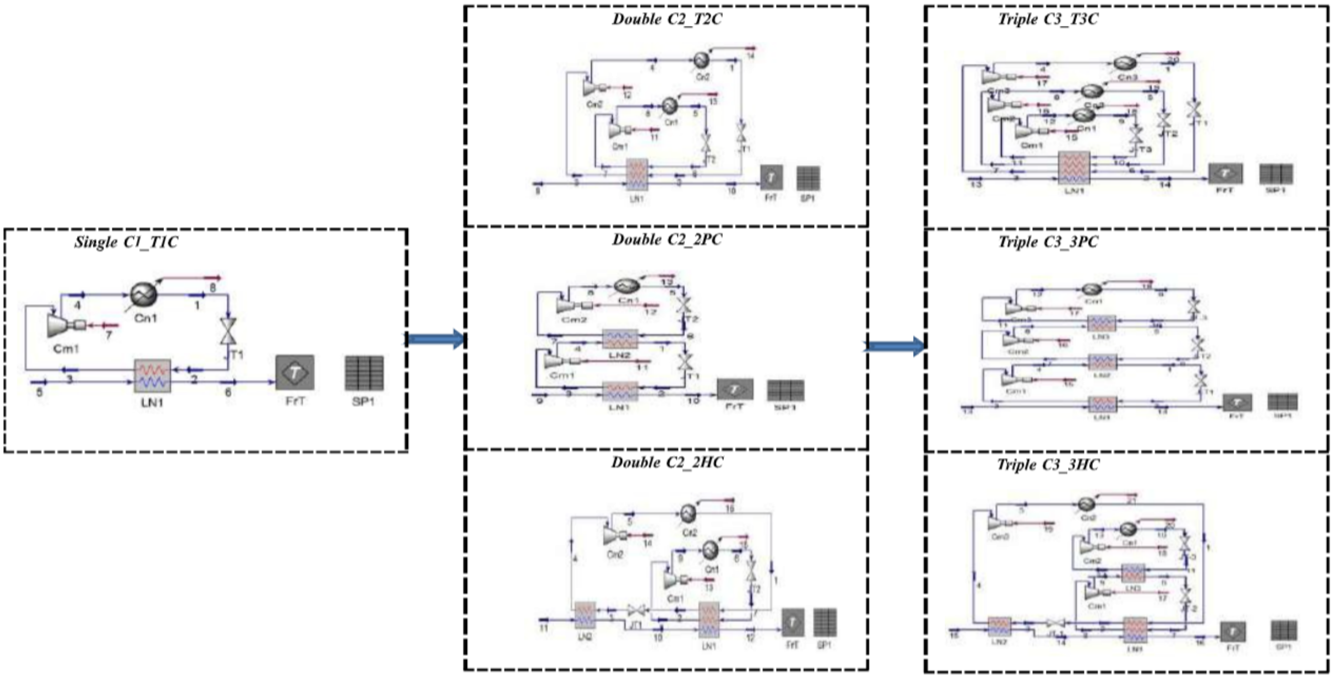


Figure 2. Independent Cascade models

Advanced Cascade Liquefaction models for natural gas processing

The cascade liquefaction models in *Figure 2* have been advanced and generalized for n cascades (where n is number of cascades modelled in different configuration) as shown below in *Figure 3*. The model complexities are listed in *Figure 4:* shows matrices representing the cascade configurations for the three groups, namely, simple, multiple and hybrid cascades. The tables show the complexities with *from 1 to n cascades and the system unit operations: cascade cycles (Cas cycle); Cooler; JT Valve; LNG Exchanger (LNG Exch);* and *Compressor (Compr)*. The number of each of the unit operations in each *i cascade model (i=1,2, n),* in the context of complexities, is contained in *Figure 4*. These are now described in the context of Boolean Matrix

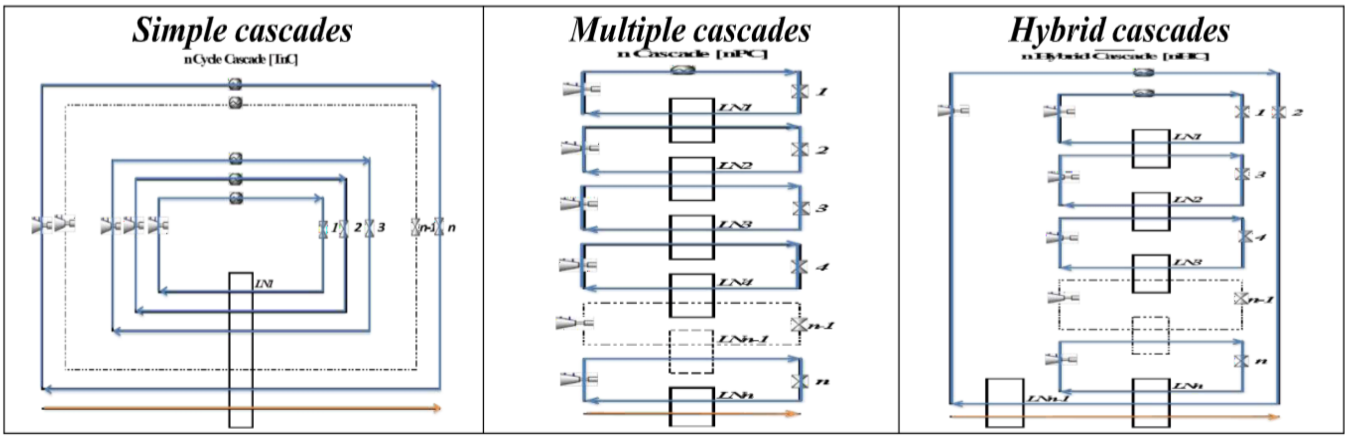


Figure 3. 'n' cascade model generalized configuration

Cas cycle
Cooler JT
Valve
LNG Exch
Compr

	Simple cascade (i=1,….,n)							Multiple cascade (i=1….,n)							Hybride cascade (i=1,….,n)					
	1	*2*	*3*	*4*	*n-1*	*n*		*1*	*2*	*3*	*4*	*n-1*	*n*		*1*	*2*	*3*	*4*	*n-1*	*n*
Cy	1	2	3	4	n-1	n	Cy	1	2	3	4	n-1	n	Cy	1	2	3	4	n-1	n
Cn	1	2	3	4	n-1	n	Cn	1	1	1	1	1	1	Cn	1	1	2	3	n-2	n-1
JT	1	2	3	4	n-1	n	JT	1	2	3	4	n-1	n	JT	1	2	3	4	n-1	n
LNG	1	1	1	1	1	1	LNG	1	2	3	4	n-1	n	LNG	1	2	3	4	n-1	n
Cm	1	2	3	4	n-1	n	Cm	1	2	3	4	n-1	n	Cm	1	2	3	4	n-1	n

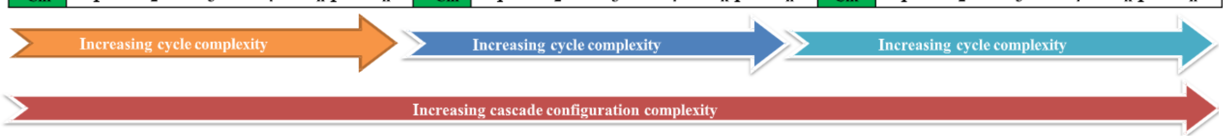


Figure 4. System unit operations in the 'i'(i=1,2, n) cascade model

Aspen HYSYS was used to model the cascades, incorporating the Boolean Matrix concept; generate several sensitivity studies, optimizations and other process analysis. The cascade model configurations featuring the Boolean Matrix concept in the simulations has been fully demonstrated and applied as shown in the analysis below.

- **Boolean Matrix Description of Cascade Models Background: Process Flowsheet Analysis**

A process flow sheet represents how material and energy flow between units (reactors, heat exchangers, separators, etc.) in a chemical or process plant. For systematic analysis—like identifying connectivity, recycle loops, or sequencing operations, engineers often need a mathematical representation. A Boolean matrix is a rectangular array of binary entries: 1 (True), indicates the presence of a relationship/connection, or, 0 (False), indicates the absence of a relationship/connection. In process flowsheet analysis, the Boolean matrix is used to capture which units are connected to which. The construction of Boolean Matrices in cascade model has enable us to describe for: n cycles in the cascade model, so that there will be n × n matrix [B], where: row *i* corresponds to a source equipment and column *j* corresponds to a destination equipment. Hence: B(i, j) = 1 if output of unit *i* flows to input of unit *j*, and, B(i, j) = 0, if otherwise. This is essentially the adjacency matrix of the flowsheet network. This approach has enabled us to: simplify binary representation of complex cycles; apply computer-based algorithms (matrix multiplications, graph theory); identifies dependencies between cycles; facilitates simulation convergence (e.g., detecting recycle loops before solving) and, generalize and advanced the cased models to complex configurations.

Boolean Matrix: Simple Cascade *(i=1,….,n)*

							To								
		Cn1	.	*Cnn-1*	*Cnn*	*JT1*	.	*JTn-1*	*JTn*	*LN1*	*Cm1*	.	*Cmn-1*	*Cmn*	*FrT*	*EqB*
	Feed	0	.	0	0	0	.	0	0	1	0	.	0	0	0	*1*
	Cn1	0	.	0	0	1	.	0	0	0	0	.	0	0	0	*1*
	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Cnn-1	0	.	0	0	0	.	1	0	0	0	.	0	0	0	*1*
	Cnn	0	.	0	0	0	.	0	1	0	0	.	0	0	0	*1*
	JT1	0	.	0	0	0	.	0	0	1	0	.	0	0	0	*1*
	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
From	*JTn-1*	0	.	0	0	0	.	0	0	1	0	.	0	0	0	*1*
	JTn	0	.	0	0	0	.	0	0	1	0	.	0	0	0	*1*
	LN1	0	.	0	0	0	.	0	0	0	1	.	1	1	1	*4*
	Cm1	1	.	0	0	0	.	0	0	0	0	.	0	0	0	*1*
	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Cmn-1	0	.	1	0	0	.	0	0	0	0	.	0	0	0	*1*
	Cmn	0	.	0	1	0	.	0	0	0	0	.	0	0	0	*1*
	StB	*1*	.	*1*	*1*	*1*	.	*1*	*1*	*4*	*1*	.	*1*	*1*	*1*	

Boolean Matrix: Multiple Cascade *(i=1,….,n)*

							To								
		Cn1	*JT1*	.	*JTn-1*	*JTn*	*LN1*	.	*LNn-1*	*LNn*	*Cm1*	.	*Cmn-1*	*Cmn*	*FrT*	*EqB*
	Feed	0	0	.	0	0	1	.	0	0	0	.	0	0	0	1
	Cn1	0	0	.	0	1	0	.	0	0	0	.	0	0	0	1
	JT1	0	0	.	0	0	0	.	0	0	0	.	0	0	0	0
	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	JTn-1	0	0	.	0	0	0	.	0	0	0	.	0	0	0	0
	JTn	0	0	.	0	0	0	.	0	1	0	.	0	0	0	1
	LN1	0	0	.	0	0	0	.	0	0	1	.	0	0	1	2
From	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	LNn-1	0	1	.	0	0	0	.	0	0	0	.	1	0	0	2
	LNn	0	0	.	1	0	0	.	0	0	0	.	0	1	0	2
	Cm1	0	0	.	0	0	0	.	1	0	0	.	0	0	0	1
	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Cmn-1	0	0	.	0	0	0	.	0	1	0	.	0	0	0	1
	Cmn	1	0	.	0	0	0	.	0	0	0	.	0	0	0	1
	StB	*1*	*1*	.	*1*	*1*	*1*	.	*1*	*2*	*1*	.	*1*	*1*	*1*	

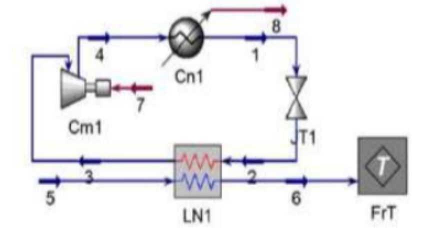
Boolean Matrix: Hybrid Cascade *(i=1,….,n)*

From \ To	*Cn1*	.	*Cnn-1*	*JT1*	.	*JTn-1*	*JTn*	*Ln1*	.	*LNn-1*	*LNn*	*Cm1*	.	*Cmn-1*	*Cmn*	*FrT*	*EqB*
Feed	0	.	0	0	.	0	0	0	.	1	0	0	.	0	0	0	1
Cn1	0	.	0	0	.	0	1	0	.	0	0	0	.	0	0	0	1
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cnn-1	0	.	0	0	.	0	0	1	.	0	0	0	.	0	0	0	1
JT1	0	.	0	0	.	0	0	0	.	1	0	0	.	0	0	0	1
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
JTn-1	0	.	0	0	.	0	0	1	.	0	0	0	.	0	0	0	1
JTn	0	.	0	0	.	0	0	0	.	0	1	0	.	0	0	0	1
From *Ln1*	0	.	0	1	.	0	0	0	.	0	0	1	.	0	0	1	3
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
LNn-1	0	.	0	0	.	0	0	1	.	0	0	0	.	0	1	0	2
LNn	0	.	0	0	.	1	0	0	.	0	0	0	.	1	0	0	2
Cm1	0	.	0	0	.	0	0	0	.	0	1	0	.	0	0	0	1
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Cmn-1	1	.	0	0	.	0	0	0	.	0	0	0	.	0	0	0	1
Cmn	0	.	1	0	.	0	0	0	.	0	0	0	.	0	0	0	1
StB	*1*	.	*1*	*1*	.	*1*	*1*	*3*	.	*2*	*2*	*1*	.	*1*	*1*	*1*	

Application of the generalized model algorithm and Boolean Matrix representation: showing the matrix and the cascade liquefaction configuration model from Aspen HYSYS.

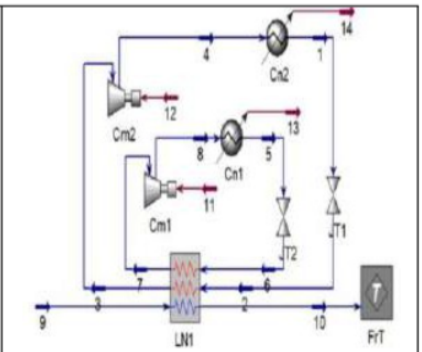
Simple Cascade (n=1)

From \ To	*Cn1*	*JT1*	*LN1*	*Cm1*	*FrT*	*EqB*
Feed	0	0	1	0	0	*1*
Cn1	0	1	0	0	0	*1*
From *JT1*	0	0	1	0	0	*1*
LN1	0	0	0	1	1	*2*
Cm1	1	0	0	0	0	*1*
StB	*1*	*1*	*2*	*1*	*1*	*6*



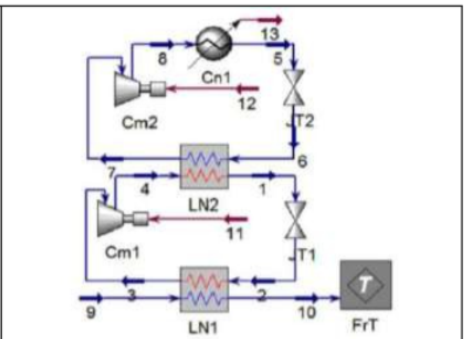
Simple Cascade (n=2)

From \ To	*Cn1*	*Cn2*	*JT1*	*JT2*	*LN1*	*Cm1*	*Cm2*	*FrT*	*EqB*
Feed	0	0	0	0	1	0	0	0	*1*
Cn1	0	0	1	0	0	0	0	0	*1*
Cn2	0	0	0	1	0	0	0	0	*1*
JT1	0	0	0	0	1	0	0	0	*1*
From *JT2*	0	0	0	0	1	0	0	0	*1*
LN1	0	0	0	0	0	1	1	1	*3*
Cm1	1	0	0	0	0	0	0	0	*1*
Cm2	0	1	0	0	0	0	0	0	*1*
StB	*1*	*1*	*1*	*1*	*3*	*1*	*1*	*1*	*10*



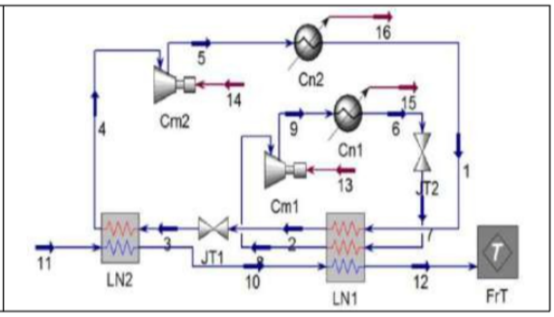
Multiple Cascade (n=2)

From \ To	*Cn1*	*JT1*	*JT2*	*LN1*	*LN2*	*Cm1*	*Cm2*	*FrT*	*EqB*
Feed	0	0	0	1	0	0	0	0	1
Cn1	0	0	1	0	0	0	0	0	1
JT1	0	0	0	0	0	0	0	0	0
JT2	0	0	0	0	1	0	0	0	1
From *LN1*	0	0	0	0	0	1	0	1	1
LN2	0	1	0	0	0	0	1	0	2
Cm1	0	0	0	0	1	0	0	0	1
Cm2	1	0	0	0	0	0	0	0	1
StB	*1*	*1*	*1*	*0*	*2*	*1*	*1*	*1*	*8*



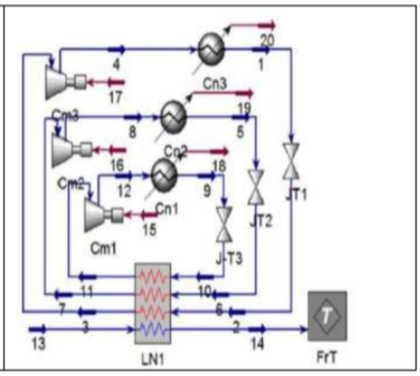
Hybrid Cascade (n=2)

From	Cn1	Cn2	JT1	JT2	LN1	LN2	Cm1	Cm2	FrT	EqB
Feed	0	0	0	0	0	1	0	0	0	1
Cn1	0	0	0	1	0	0	0	0	0	1
Cn2	0	0	0	0	1	0	0	0	0	1
JT1	0	0	0	0	0	1	0	0	0	1
JT2	0	0	0	0	1	0	0	0	0	1
LN1	0	0	1	0	0	0	1	0	1	3
LN2	0	0	0	0	1	0	0	1	0	2
Cm1	1	0	0	0	0	0	0	0	0	1
Cm2	0	1	0	0	0	0	0	0	0	1
StB	1	1	1	1	3	2	1	1	1	12



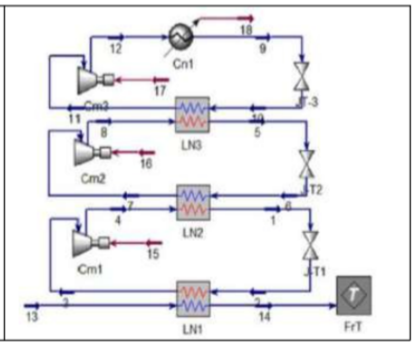
Simple Cascade (n=3)

From	Cn1	Cn2	Cn3	JT1	JT2	JT3	LN1	Cm1	Cm2	Cm3	FrT	EqB
Feed	0	0	0	0	0	0	1	0	0	0	0	1
Cn1	0	0	0	1	0	0	0	0	0	0	0	1
Cn2	0	0	0	0	1	0	0	0	0	0	0	1
Cn3	0	0	0	0	0	1	0	0	0	0	0	1
JT1	0	0	0	0	0	0	1	0	0	0	0	1
JT2	0	0	0	0	0	0	1	0	0	0	0	1
JT3	0	0	0	0	0	0	1	0	0	0	0	1
LN1	0	0	0	0	0	0	0	1	1	1	1	4
Cm1	1	0	0	0	0	0	0	0	0	0	0	1
Cm2	0	1	0	0	0	0	0	0	0	0	0	1
Cm3	0	0	1	0	0	0	0	0	0	0	0	1
StB	1	1	1	1	1	1	4	1	1	1	1	14



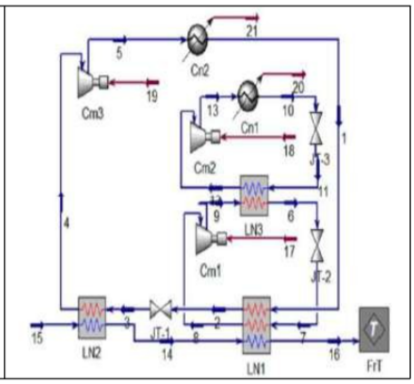
Multiple Cascade (n=3)

From	Cn1	JT1	JT2	JT3		LN1	LN2	LN3	Cm1	Cm2	Cm3	FrT	EqB
Feed	0	0	0	0	1	0	0	0	0		0	0	1
Cn1	0	0	0	1	0	0	0	0	0		0	0	1
JT1	0	0	0	0	0	0	0	0	0		0	0	0
JT2	0	0	0	0	0	0	0	0	0		0	0	0
JT3	0	0	0	0	0	0	1	0	0		0	0	1
LN1	0	0	0	0	0	0	0	1	0		0	1	2
LN2	0	1	0	0	0	0	0	0	1		0	0	2
LN3	0	0	1	0	0	0	0	0	0		1	0	2
Cm1	0	0	0	0	0	1	0	0	0		0	0	1
Cm2	0	0	0	0	0	0	1	0	0		0	0	1
Cm3	1	0	0	0	0	0	0	0	0		0	0	1
StB	1	1	1	1	1	1	2	1	1		1	1	12



Hybrid Cascade (n=3)

From	Cn1	Cn2	JT1	JT2	JT3	LN1	LN2	LN3	Cm1	Cm2	Cm3	FrT	EqB
Feed	0	0	0	0	0	0	1	0	0	0	0	0	1
Cn1	0	0	0	0	1	0	0	0	0	0	0	0	1
Cn2	0	0	0	0	0	1	0	0	0	0	0	0	1
JT1	0	0	0	0	0	0	1	0	0	0	0	0	1
JT2	0	0	0	0	0	1	0	0	0	0	0	0	1
JT3	0	0	0	0	0	0	0	1	0	0	0	0	1
LN1	0	0	1	0	0	0	0	0	1	0	0	1	3
LN2	0	0	0	0	0	1	0	0	0	0	1	0	2
LN3	0	0	0	1	0	0	0	0	0	1	0	0	2
Cm1	0	0	0	0	0	0	0	1	0	0	0	0	1
Cm2	1	0	0	0	0	0	0	0	0	0	0	0	1
Cm3	0	1	0	0	0	0	0	0	0	0	0	0	1
StB	1	1	1	1	1	3	2	2	1	1	1	1	16



- **Integrating the Cascade Models into Single Train Modelling of Natural Gas Processing**

The earlier cascade models of natural gas are included in the liquefaction section as independent and employed to do specific sensitive studies. We have advanced and integrated the three stages of cascade models – simple, multiple and hybrid, as shown in Figure 2 here into an integrated network of cascade models, designed to use for in-depth evaluation of the liquefaction process and impacts of its parameters in the entire upstream and downstream of the simulation. Figures 5, below show the flowsheets for both the upstream (integrated cascade models for liquefaction), and the downstream (fractionation into products). The integrated cascade model is represented as Aixi where A represent the cascade model, x (0-1), the contribution of cascade A in the liquefaction process *'i' = 1,…,m* (here for this simulation, *'m'= 7,* as shown in Table 1 below).

Table 1. Integrated Cascade Model description and identification

Ai	*Cascade Model Description*	*Model Identification*	*Modelled 'xi'*
A1	Single cascade model *(n=1)*	C1_T1C.1	0.2
A2	Multiple cascade model *(n=2)* hybrid	C2_2HC.1	0.1
A3	Multiple cascade model *(n=2)* double 1	C2_2PC.1	0.2
A4	Multiple cascade model *(n=2)* double 2	C2_T2C.1	0.1
A5	Multiple cascade model *(n=3)* hybrid	C3_3HC.1	0.2
A6	Multiple cascade model *(n=3)* Triple 1	C3_3PC.1	0.1
A7	Multiple cascade model *(n=3)* Triple 2	C3_T3C.1	0.1

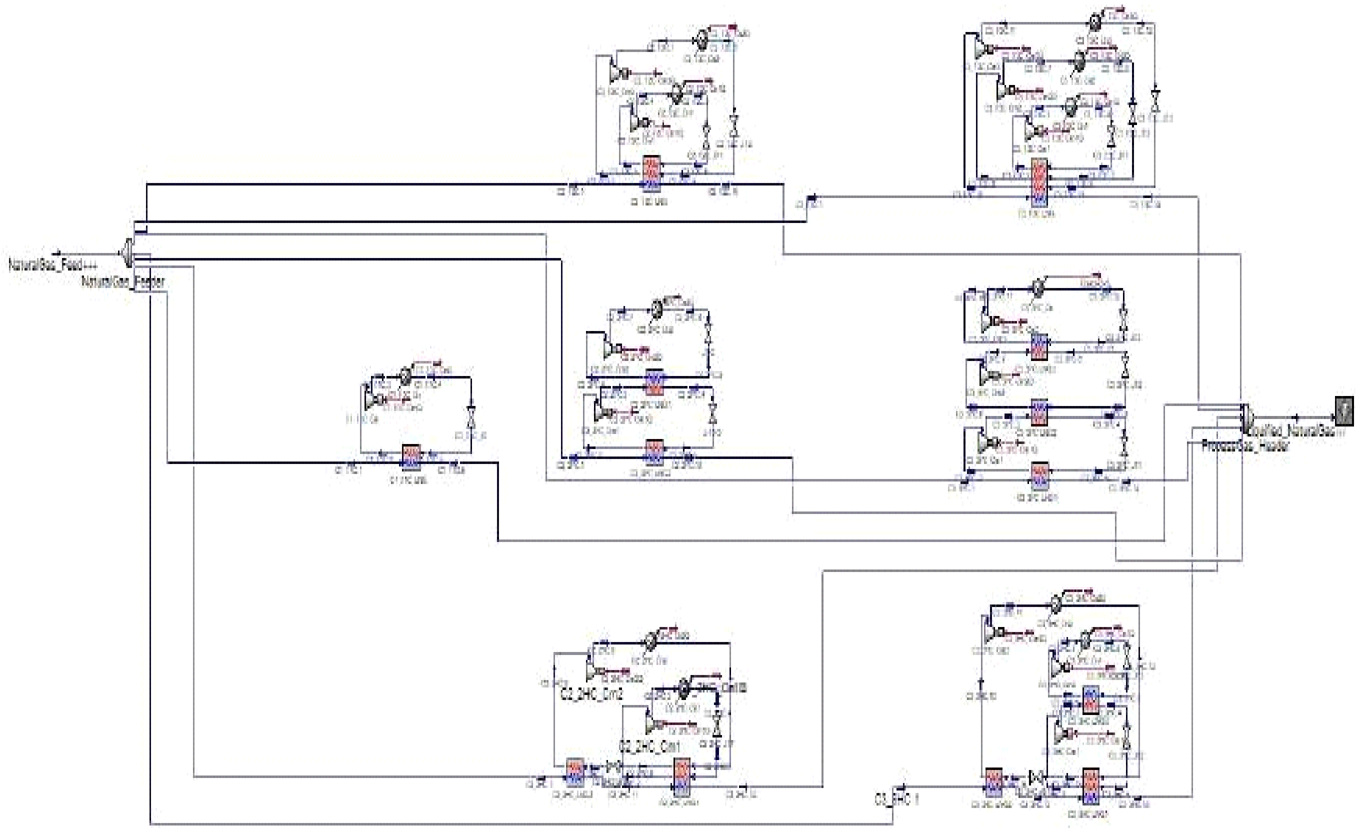


Figure 5a. Integrated Cascade Models in a Single Train Simulation Model – Upstream Liquefaction Section

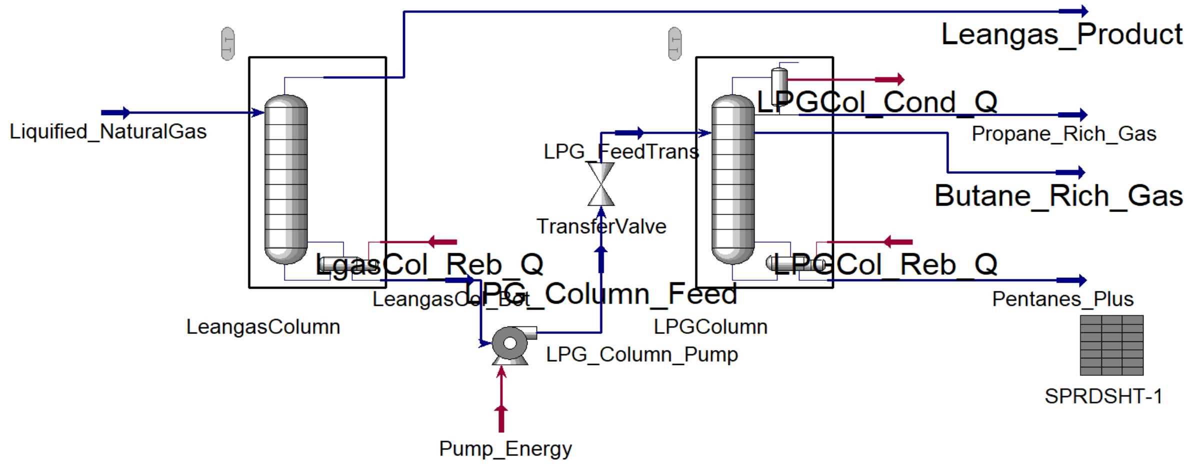


Figure 5b. Integrated Cascade Models in a Single Train Simulation Model – Downstream Fractionation Section

Conclusion

Overall, the Boolean Matrix concept and the modelling approach have enabled the integration of different cascade models into a single train natural gas processing, which allowed the advanced model to evaluate the impact and contribution of each or combination of cascade models to the entire simulation. Over a hundred modelling and simulation cases have been done to further test and prove the concept and the data supplied used; each simulation converged and gave satisfactory results. The flexibility, reliability and applicability of this model have now been fully demonstrated.

Nomenclature

CAPEX Capital Expenditure
LNG Liquefied Natural Gas
LPG Liquefied Petroleum Gas
N2 Nitrogen
JT Joule Thompson
Cn Cooler in the cascade cycle
Cm Compressor in the cascade cycle
Cni ***'i'*** represent the count on the number of Cn in the model
Cmi ***'i'*** represent the count on the number of Cm in the model **Feed** Natural gas feed from the field
FrT Fractionation node showing the model to fractionation section
LN LNG/Liquefied Natural Gas model used for cascade liquefaction
LNi ***'i'*** represent the count on the number of LN in the model
StB Total summation of the row parameters in the Boolean Matrix
EqB Total summation of the column parameters in the Boolean Matrix

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