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Published version

SAAD, Sameh and BAHADORI, Ramin (2018). Development of an information fractal to optimise inventory in the supply network. International Journal of Service and Computing Oriented Manufacturing, 3 (2/3), 127-150.

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Development of an information fractal to optimise inventory in the supply network

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Abstract: The aim of this research paper is to develop a new conceptual framework for an information fractal to optimise inventory including safety stock, cycle stock and prevent stock out at lowest logistics cost and further enhance integration within the network. The proposed framework consists of two levels; top and bottom level fractals. Fractals in the bottom level analyse demand, optimise safety stock and then transmit output to the top level fractal. Fractals in the top level investigate different replenishment frequencies to determine the optimum cycle stock for each fractal in the bottom level. The proposed conceptual framework and a hypothetical supply network are implemented and validated using mathematical modelling and Supply Chain GURU Simulation Software; in order to optimise inventory in the supply network during the demand test period. Experimental factorial design and statistical techniques (MANOVA) are used to generate and analyse the results.

Keywords: Fractal supply network, supply network modelling, inventory optimisation, simulation, modelling.

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1 Introduction

Inventory control strategies in supply chain management are classified as either centralised inventory control or decentralised inventory control (Nagaraju et al., 2015; Kumar et al., 2016). Members of supply chains are often separate organisations and independent business enterprises. Despite the benefits of integrated decision making; in practice, they are reluctant to follow the decisions made for all of the members and try to optimise their goals instead of the overall system (Giannoccaro and Pontrandolfo, 2004). Many researchers consider a supply chain as a single firm where all policies in the supply chain are defined by single decision maker, who has access to all the necessary information to improve system performance and thus has the power to make decisions. In this case, the members cooperate with each other in accordance with the pre-defined policies (Taleizadeh et al., 2013). This situation is possible when the whole supply chain is under the control of a centralised decision maker who has a high level of coordination and communication with other members in the supply chain. Consequently, this provides better coordination of the inventory replenishments at different levels and different parts of the supply chain and minimises the total system cost which can be the main advantage of using centralised inventory control (Ahsan et al., 2013; Baboli et al., 2008; Marklund, 2002). However, for larger systems with different organisations, centralised control is often not a viable option due to both technical and managerial problems (Andersson and Marklund, 2000). This paper introduces an inventory control system which is a combination of both centralised and decentralised inventory control strategies hence leading to an increase in both collaboration and integration throughout the supply network in fractal environment. Each member in the supply chain has a responsibility to analyse the demand of its downstream customers, determine its safety stock and inventory reorder point and share this with the information centre. This in turn must determine the optimum replenishment frequencies for each member to minimise the logistics costs in the supply chain by integrating both inventory holding costs and transportation costs.

1.1 Information sharing in supply chain

Information sharing as the most basic form of coordination in supply chain has a positive relationship with improving firm performance and enables firms to achieve distinct competitive differentiation in the marketplace by acquiring, analysing, storing, and distributing information both internally and externally through a supply network (Bowersox et al, 1999; Zhao et al, 2001).

Information sharing as an integrating action can be applied for both internal and external integration in supply chain (Lotfi et al., 2013). Internal integration refers to the coordination and collaboration of functional areas within a company whilst, external integration points synchronise with key supply chain members (Chang et al., 2016). This research focuses on information sharing among supply chain members (external integration) and information sharing within the each member during the inventory optimisation process (internal integration).

In general, there are two main research approaches on information sharing. The first is focused on the value of information sharing from quantitative prospective (Lv, 2017; Huang et al., 2017; Sabitha et al., 2016). These studies identify and prove the value of information sharing for managers and discuss how to measure its affective factors.

The second approach is related to the information sharing requirements such as technologies and other factors which are needed to ensure timely and accurate sharing of information with the aim of responding to the managerial needs using a wide range of quantitative-qualitative techniques (Bailey and Francis, 2008; Hernández-Espallardo et al., 2010; Capo-Vicedo et al., 2011).

By reviewing the literature, the vacancy of conceptual modelling for information sharing in the supply chain, is well understood and has been one of the main drivers of this research.

While, information is defined in two strategic and operational categories in the literature, a few studies have distinguished between these two dimensions of information sharing. Strategic information includes long-term corporate issues related to pricing, marketing, logistics and other business strategies. This long-term, qualitative and sensitive information is mainly used to improve coordination between supply chain partners. However, operational information generally includes short-term and quantitative information about logistics activities / daily sales or order status information and inventory levels (Moberg et al., 2002). The latter is mainly used to optimise inventory and improve customer service and has hence, received authors' focus in this study.

1.2 Fractal capabilities

Fractal concept attracts many of industrialists because of its capabilities which include self-similarity, self-optimisation, self-organisation, goal orientation, and dynamics (Warnecke, 1993).

Self-similarity means each fractal unit is similar to another fractal unit while they can have their own structure (Attar and Kulkarni, 2014). Although, fractal units may have a different condition and internal structure in comparison to another, they can have a same target in the system. Therefore, in the fractal supply network, fractals are self-similar if they can achieve goals in the system with different internal structure while inputs and outputs are the same (Ryu et al, 2013). Higher self-similarity in the supply network can increase the information sharing, operation coordination and degree of integration among the fractal units and decrease the complexity of the system to allow the supply network to be understood and managed clearly (He, 2010).

Self-optimisation means each fractal unit is an independent unit with the ability to improve its performance continuously. Fractals choose and use suitable methods to optimise operation and decision making processes with coordination of the whole system to achieve the goals (Attar and Kulkarni, 2014; He, 2010; Ryu et al, 2013).

Self-organisation (dynamic restructuring) refers to supporting the reconfiguration of the network connections between fractals and the reorganisation of fractals in the system (Ryu and Jung, 2003). It means each fractal is free to make a decision about the organisation's dimension which is require for special performance with regards to environmental parameter and the goals (He, 2010) without external intervention (Leitão and Restivo, 1999). In fact, self- organisation, as a kind of supply chain organisation, converts irregular conditions into regular conditions without outer monitoring and control to offer products and services to customers constantly (Fan and Chen, 2008).

Goal orientation enables the system goals to be achieved from the goals of individual fractals (Warnecke, 1993). Fractal units perform a goal-formation process to generate their own goals by coordinating processes with the participating fractals and modifying goals if necessary (Ryu and Jung, 2003).

Dynamics refer to cooperation and coordination between self- organising fractals which are characterised by high individual dynamics and an ability to restructure their processes to meet and adapt to the dynamically changing environment (Ryu and Jung, 2003).

2 The proposed framework for the Information Fractal Supply Network (IFSN)

Figure 1 displays the new proposed framework of an IFSN through the supply network with two levels including an *information fractal-centre* as a top level fractal and the *information fractal-supplier's facility*, *information fractal-manufacturer*, *information fractal-distribution hub* and *information fractal-retailer* as bottom level fractals. For each of these information fractals, there are five function models namely: observer, analyser, resolver, organiser and reporter to form the basis of the information fractal unit structure (Ryu et al, 2013).

Figure 2 demonstrates this structure and clearly explains the internal relationships amongst these five function models. Saad and Bahadori (2016) mentioned that in the bottom level, observers in the sourcing fractals trace and receive the demand from the outer fractal gate, which it could be a customer order; the observer transmits the demand data to analysers and notifies resolvers by receiving the demand at same time. Analysers use an appropriate method to analyse current demands based on a set of demand statistics to determine demand class and then transmit it to resolvers. The demand class enables resolvers to recognise different types of demands and allocate an appropriate method to calculate and optimise safety stock. Organisers in all the fractals, including top and bottom level fractals; observe, control and manage the fractal structure to adapt to the continuous change in the environment. Reporters have a responsibility to report fractal outputs to outer fractals. Resolvers' decisions made at the bottom level fractal regarding the expected safety stock and reorder point should be transmitted through reporters to the fractal in the top level.

In the top level fractal, the observer traces and receives decisions which are made by each fractal in the bottom level (e.g. Retailer), transmits them to analysers and then notifies resolvers. Analysers investigate and analyse the different replenishment frequencies on the transportation costs and inventory holding costs for each fractal in the bottom level. Resolvers integrate inventory holding costs and transportation costs based on analysers' reports to achieve an optimum replenishment frequency with the lowest logistics cost for each fractal in the bottom level. In the top level fractal, reporters report resolvers' decisions regarding optimum replenishment frequency to the fractals in the bottom level. This research paper concentrates on two main functions, analyser and resolver, to optimise both the safety stock and replenishment frequency in the supply network.

[Figure 1 near here]

[Figure 2 near here]

2.1 Bottom level fractals

It is important to determine how much inventory must be held against the variability in both demand and lead times. Therefore, understanding the demand variability is essential to calculate safety stock. Analysers in the bottom level fractal use an appropriate method to analyse demand based on a set of demand statistics. During the demand analysis process, demand is aggregated, outliers are recognised and a set of demand statistics are provided. Analysers use demand statistics and demand classification threshold values to determine the demand classification (e.g. Slow, Lumpy, Erratic and Smooth). Analysers perform the following steps to analyse current demand:

- Step 1: Determine aggregate demand for the specified aggregation period which can be based on a daily, weekly and monthly demand.
- Step 2: Provide a set of demand statistics to classify the demand.
- Step 3: Classify the demand based on the demand's statistics which are provided in step 2.

To set up a demand class, analysers use a set of demand classification thresholds that affect how demand is classified and how analysers determine the appropriate approach for safety stock calculation. Demand classification thresholds include demand frequency, intermittency and dispersion which are determined by a non-zero demand count (M_{NZ}), inter-demand interval mean (p) and squared coefficient of variation of non- zero demand (CV^2_{NZ}), respectively. Outlier, variability and clumpiness are specified by a non-zero demand standard division (σ_{NZ}). Demand classification threshold values are determined based on the firm's conditions (see Figure 3).

[Figure 3 near here]

An extremely slow class will occur when the demand count is lower than the demand count adjusted in the demand classification thresholds. This class has a large inter-demand interval mean.

Analysers recognise outliers based on the non-zero demand standard division and the non-zero demand mean values during the demand classification process:

- If (σ_{NZ}) is less than the default number in the demand classification threshold, analysers ignore the outlier recognising process and continue to demand classification.
- If (σ_{NZ}) is greater or equal to the default number in the demand classification threshold, the outlier recognising process is initialised. Analysers consider the aggregation period with the largest demand size and determine it as an outlier if it is greater or equal to (σ_{NZ}) in the demand classification threshold *(μ_{NZ}) from the rest of the demand.

There are two options for analysers, when handling the outliers:

- Outliers are considered in the demand statistics where they were recognised.
- Replace outliers with the demand mean of the rest of the demands which are smaller than the outlier and recalculate the non-zero demand standard deviation and return to the first step of the process.

Intermittency specifies how frequently demand occurs, based on the average time between adjacent demands.

- If the average time between the demands is lower than the intermittency threshold, it is known as non-intermittent demand. It means that demand happens regularly with a few exceptions during the demand period. If (CV^2_{NZ}) is greater than the default number in the threshold, this demand is classified as erratic and if (CV^2_{NZ}) is less, the demand is classified as smooth.

- If the average time between the demands is greater than the intermittency threshold, it is known as intermittent demand. It means that there is irregularity of when the demand happens during the demand period. Intermittent demand can be considered as a low or high variable, and is slow or lumpy. Low variable demand has a lower (σ_{NZ}) in comparison to highly variable demand, and slow demand has a lower (CV^2_{NZ}) in comparison to lumpy demand.

Clumpiness shows how demand points are close to each other and have a reasonably fixed demand with variability close to zero. The demand size for unit-sized demand is always one, and there is no variability for this demand class.

Once analysers have finished the demand analysis, resolvers start to specify the required safety stock by considering demand and lead-time variability. Resolvers use a target service level to calculate optimum safety stock. Service level is a measure to indicate a fractal's ability to provide products to downstream fractals. There are different types of service level which are used in industry, including type 1 (probability of not stocking out), type 2 (fill rate) and type 3 (ready rate). In this research paper, service level type 1 is used. Resolvers in the bottom level fractal determine the safety stock level, inventory policy and reorder point as part of the safety stock optimisation.

There are three models to calculate safety stock and reorder point which may happen during the demand period (Heizer & Render, 2014):

The following notations are adopted:

SS =Safety stock

σ_{dLT} = Standard division of demand during the lead time

σ_d= Standard deviation of demand per day

LT=Lead time

Z= Service level

ROP= Reorder point

μ_{dLT}= Demand mean during the lead time

μ_d= Average daily demand

d_D= Daily demand

σ_{LT}= Standard deviation of lead time in days

μ_{LT}= Average lead time

- Demand is variable and lead time is constant:

$$SS = Z\left(\sigma_d \times \sqrt{LT}\right) \quad (1)$$

And

$$ROP = \mu_d \times LT + ZZ\left(\sigma_d \times \sqrt{LT}\right) \quad (2)$$

- Lead time is variable and demand is constant:

$$SS = Z \times d_D \times \sigma_{LT} \quad (3)$$

And

$$ROP = (d_D \times \mu_{LT}) + Z \times \sigma_{LT} \quad (4)$$

- Both lead time and demand are variable:

$$SS = Z\sqrt{(\mu_{LT} \times \sigma_d^2) + (\mu_d)^2 \times \sigma_{LT}^2} \quad (5)$$

And

$$ROP = (\mu_d \times \mu_{LT}) + Z \times \sigma_{LT} \quad (6)$$

2.2 Top level fractals

As part of the replenishment frequencies optimisation in the supply network (Saad and Bahadori, 2015), analysers of the fractals in the top level have to calculate the inventory holding costs for both components and products and analyse transportation costs by investigating different days between replenishment (*DBR* = *1,…, x*) during the demand period. Therefore, a mathematical formulation governing the problem of inventory holding costs and transportation costs (Saad and Bahadori, 2016) are presented in equations (7 and 8) respectively and the following notations are adopted:

DBR = days between replenishment

TDj = Total demand of component/product j.

j = Index number of different component/product

T = Period time

IHC = inventory holding cost of components/ products

t = Transportation time

V = Component or product value,

$I_{(cc)\%}$ =Inventory carrying cost percentage

$T_{(c)}$ = Transportation cost from source fractal to customer fractal

td =Travel distance,

A(c) = Average transportation cost per mile

$$IHC = \left\{ SS_j + DBR \times \left(\frac{\sum_{j=1}^{n} SS_j \sum_{j}^{n} TD_j}{2T} \right) + \frac{\left(\sum_{j=1}^{n} SS_j \sum_{j}^{n} TD_j \right) t}{T} \right\} \times V \times \frac{T}{365} \times I_{(cc)\%} \qquad (7)$$

$$T_{(c)} = td \times \frac{\sum_{j=1}^{n} SS_j \sum_{j}^{n} TD_j}{DBR \times \mu_d} \times A_{(C)} \qquad (8)$$

where:

$DBR = 1, \dots, x$

Since, different numbers of days between replenishments were investigated among fractals by analysers, resolvers integrate both inventory holding costs and transportation costs to achieve lower total logistics cost among fractals (see equation 9) to choose the best match and find the optimum amount of replenishment cycle stock (Saad and Bahadori, 2017).

$$Min\left(\left\{SS_j + DBR \times \left(\frac{\sum_{j=1}^{n} SS_j \sum_{j}^{n} TD_j}{2T}\right) + \frac{\left(\sum_{j=1}^{n} SS_j \sum_{j}^{n} TD_j\right) t}{T}\right\} \times V \times \frac{T}{365} \times I_{(cc)\%} + td \times \frac{\sum_{j=1}^{n} SS_j \sum_{j}^{n} TD_j}{DBR \times \mu_d} \times A_{(C)}\right) \qquad (9)$$

where:
$DBR = 1, \dots, x$

3 Application of the proposed information fractal structure using LlamaSoft

3.1 The hypothetical supply network

In this paper, we assume a supply network in the electronic industry. The main manufacturer (M) is located in Lyon, France and deals with different types of electronic device which in this research comprises of just one type of laptop (with value of $300 per product) made from different components. Components are supplied from seven suppliers (S) from different regions to the main manufacturer, including Japan (CD-ROM and RAM chip with values of $50 and $6 per component, respectively), Hong Kong (video cards and microprocessor with values of $20 and $30 per component, respectively), China (power supplier with a value of $10 per component), Malaysia (floppy drive with a value of $10 per component), Taiwan (cooling fan, monitor and network card with values of $4, $30 and $5 per component, respectively), Singapore (SCSI card and disk device with values of $8 and $30 per component, respectively) and Turkey (keyboard and soundcards with values of $15 and $20 per component, respectively). Due to long lead times from suppliers to manufacturer, each supplier built a facility (F) close to the manufacturer, located in Monaco, France, 219.3 miles away (Japan facility); Barcelona, Spain, 388.34 miles away (Hong Kong facility); Nantes, France, 376.38 miles away (China facility); Royan, France, 413.212 miles away (Malaysia facility); Agde, France, 212.51 miles away (Taiwan facility); Genoa, Italy, 257.47 miles away (Singapore facility) and Montpellier, France, 181.62 miles away (Turkey facility). Moreover, there are four distribution hubs (Dh), dealing with finished products located in Madrid, Spain (661.49 miles away) with two retailers (R) (Porto, Portugal and Malaga, Spain at 305.11 and 1062.79 miles distance, respectively); Paris, France (286.07 miles away) with two retailers (Tours, France and Ghent, Belgium at 152.84 and 187.89 miles distance, respectively); Milan, Italy (246.13 miles away) with three retailers (Bologna and Udine, Italy and Bern, Switzerland with 145.52, 154.07 and 233.11 miles distance, respectively) and Frankfurt, Germany (410 miles away) with four retailers (Bremen, Berlin and Homburg, Germany and Randers, Denmark at 238.68, 304.25, 298.86 and 284.38 miles distance, respectively).

3.2. Simulation modelling of the supply network

Figure 4 displays a snap shot of the supply chain GURU simulation model, created for the considered hypothetical supply network using LlamaSoft (2017). LlamaSoft allows an agent based representation of the supply chain infrastructure and their behaviour and interactions while enabling a process oriented approach to represent orders as in a discrete event simulation. Therefore, the agents here are the observer, analyser, resolver, organiser and reporter; however, as mentioned before in section 2, this research paper focuses on two main functions, analyser and resolver.

[Figure 4 near here]

The amount of demand quantity at each fractal in the bottom level is dictated by customer demand (e.g. retailers). The required level of inventory at each upstream fractal is determined by observing retailers' demand, and retailers' demand requirements are propagated through the multi-echelon network. Therefore, as shown in table 4 retailers' demand for the one type of product (laptop) during the period test of seven days (from 01/09/2016 to 07/09/2016) has been assumed.

[Table 1 near here]

The lead time required for product and components to be replenished at the fractals from the upstream fractals is assumed to be eight days for the Malaysia facility, seven days for the Japan, Hong Kong, China, Taiwan and Singapore facilities, three days for the Turkey facility and two days for the main manufacturer, distribution hubs and retailers. Moreover, an average transportation cost per mile ($A_{(c)}$) and percentage of inventory carrying cost ($I_{(cc)}\%$) are assumed to be \$1 and 12 percent, respectively, and there is no limit for transportation assets in terms of capacity. The demand aggregation period was based on daily demand over seven days per week. In terms of demand outlier's determination, outliers were considered in the demand statistics when they were recognised. Moreover, demand classification threshold values were adjusted as default values as follows:

- Demand Frequency (M_{NZ}) = 3
- Intermittency (p) = 1.32
- Dispersion (CV^2_{NZ}) = 0.49
- Outlier = 10
- Variability (σ_{NZ}) = 200
- Clumpiness = 0.1

3.3 Experimental design

This section provides the design of experiments, which allow us to find out the impact of the uncertainties in the demand and days between replenishment (*DBR*) on the performance of whole supply network, consisting of 22 sites including retailers, distribution hubs, main manufacture and supplier's facilities (see Figure 4). Four performance measures (dependent factors) namely transportation costs, inventory holding costs, cycle stock and total logistics costs are considered in this study.

After conducting pilot experiments, the two independent factors with their levels are identified and displayed in Table 2. Based on a full factorial experimental design, a total of 616 experiments are required to gather enough data and to allow the authors to draw a valid conclusion from this study.

[Table 2 near here]

4 Results analysis and discussion

A full statistical factorial MANOVA technique was used to analyse the results obtained from GURU Simulation Software at 95% confidence interval. Table 3 displays the obtained results and the following can be concluded:

- Days between replenishment (*DBR*) and demand have a significant relationship with transportation costs, inventory holding costs, total logistics costs and cycle stock.
- Interaction of the days between replenishment and demand (*DBR* * *Demand*) show that there is a significant relationship with performance measures except for transportation cost.

[Table 3 near here]

4.1 Results analysis of bottom level fractal optimisation

According to the demand classification diagram (see Figure 3) and based on adjusted demand classification threshold values, shown at the end of section 3 above, analysers in the information fractals in bottom level classified the demand at different days between replenishment (*DBR*) from one day to seven days and the obtained results from GURU Software are presented in Table 4.

As can be seen, there are the classifications as follows:

1) Smooth: when the average time between demand is less than intermittency p=1.32, the demand should be a non-intermittent and then if (CV^2_{NZ}<0.49), the demand is finally classified as smooth.

2) Slow low variable: when the average time between demand is greater than intermittency p=1.32, the demand should be intermittent and if (σ_{NZ} < 200), the demand characterised as low variable, then is finally classified a slow low variable when (CV^2_{NZ}<0.49).

3) Slow high variable: when the average time between demand is greater than intermittency p=1.32, the demand should be intermittent and if (σ_{NZ} > 200), the demand characterised as high variable, then is finally classified a slow low variable when (CV^2_{NZ}<0.49).

[Table 4 near here]

Since demand was variable and lead time was constant, resolvers used equations 1 and 2 to calculate required safety stock with a service level of 0.95 percent and reorder point during the demand period test of seven days for each site. It has been noticed that the safety stock and the reorder points for all the retailers (Rs) are the same and do not change with the days between replenishment (*DBR*) (see Tables 5 and 6).

[Table 5 near here]

[Table 6 near here]

4.2 Results analysis of top level fractal optimisation

As part of the replenishment frequencies optimisation in the supply network, the analyser located in top level fractal calculated the inventory holding costs (*IHC*) and total transportation costs *T*(*c*) for fractals in the bottom level with different days of replenishment (from one day to seven) using equations 7 and 8 - the results are reported in Appendix 1. To achieve a lower total logistics cost throughout the supply network, the resolver uses the analyser results to integrate both inventory holding costs and transportation costs with respect to different days of replenishment among fractals to choose the best match using equation 9.

The results proved that the days between replenishment (*DBR*) for the minimum total logistics cost between distribution hubs and retailers were two days, except for Madrid (Dh) to Malaga (R) and Frankfurt (Dh) to Randers (R) which were five and three days respectively (See figure 5). Figure 6 displays that the *DBR*, which resulted in a minimum total logistics cost between manufacturers and distribution hub was one day with the exception of Lyon (M) to Madrid (Dh) which was two days. Finally, figure 7 shows the reported minimum total logistics cost between the supplier facilities to the main manufacturer were two days between replenishment (*DBR*) apart from both Hong Kong (F) and Singapore (F) to Lyon (M).

[Figure 5 near here]

[Figure 6 near here]

[Figure 7 near here]

7 Conclusions

The unique contribution of this paper was the proposed framework for the information fractal with two levels named top and bottom level fractals to manage and optimise inventory in the supply network. Fractals in the bottom level traced, observed and analysed its downstream fractal demand and determined optimum safety stock and inventory policy whilst sharing this with fractal information centres in the fractal. Based on this information, information fractal-centre of the top level fractal achieved the lowest total logistics cost among fractals of the bottom level by integrating both inventory holding costs and transportation costs, in addition to determining and sharing optimum replenishment frequencies for each fractal.

The proposed framework was applied on the hypothetical supply network using mathematical modelling and LlamaSoft Supply Chain GURU Simulation Software with results being analysed and validated using a statistical test (MANOVA).

Application of the proposed framework has clearly introduced an inventory control system, in which both centralised and decentralised inventory control strategies were combined and has led to enhancing both collaboration and integration through the supply network. Moreover, and from a managerial and planning point of view, it provides a systematic procedure through which practitioners should be able to decide upon the demand analysis and optimise both safety stock and replenishment frequencies to achieve the lowest total logistics cost through the supply network.

Many areas of our work can be extended, therefore for future work; the authors recommend that the availability of the transportation asset capacity, a complete analysis of CO_2 emissions and impact of different fleet designs should be considered as a road map for future research.

Acknowledgements

The study was partially supported by Sheffield Hallam University, and authors thank the reviewers for their invaluable comments.

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Table 1: Retailers' demand during a period test of seven days

Retailer	01/09/16	02/09/16	03/09/16	04/09/16	05/09/16	06/09/16	07/09/16
Porto	719	734	1434	1926	1433	589	1097
Malaga	1265	1714	1619	1776	1344	1161	1028
Tours	831	966	421	855	1420	536	882
Ghent	1874	570	1753	1675	457	1698	1354
Bologna	595	1429	1096	582	697	771	1208
Odine	979	1967	1984	839	406	1612	1078
Bern	1538	774	1813	801	1122	590	1443
Bremen	907	1950	742	1221	558	1653	1814
Berlin	1479	893	419	620	1330	650	867
Homburg	1852	555	1058	1733	539	1576	1913
Randers	1073	1095	1381	1766	1020	744	1431

Table 2: Independent factors with their levels

Factor	**Levels**						
Demand	1000	Normal (1000,100)	Normal (1000,200)	Normal (1000,300)	-	-	-
(*DBR*)	1 Day	2 Days	3 Days	4 Days	5 Days	6 Days	7 Days

Table 3: Full factorial MANOVA results

Dependent variables	Independent variables	F	P	Significant
DBR	Transportation costs	110.008	.000< .005	Yes
	Inventory holding costs	215.503	.000< .005	Yes
	Total logistics costs	88.695	.000< .005	Yes
	cycle stock	50688297.593	.000< .005	Yes
Demand	Transportation costs	8.382	.000< .005	Yes
	Inventory holding costs	110.442	.000< .005	Yes
	Total logistics costs	91.323	.000< .005	Yes
	cycle stock	74342799.832	.000< .005	Yes
*DBR * Demand*	Transportation costs	.651	1.000>.005	No
	Inventory holding costs	3.505	.000< .005	Yes
	Total logistics costs	2.684	.000< .005	Yes
	cycle stock	4191481.369	.000< .005	Yes

Table 4: Demand class in the bottom level fractals at different DBR (1day to 7days)

Sites	**1day**	**2days**	**3 days**	**4 days**	**5 days**	**6 days**	**7days**
Porto (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Malaga (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Tours (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Ghent (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Bologna (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Odine (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Bern (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Bremen (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Berlin (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Homburg (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Randers (R)	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Madrid (Dh)	Smooth	Smooth	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow Highly Variable
Paris (Dh)	Smooth	Smooth	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable
Milan (Dh)	Smooth	Smooth	Smooth	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable
Frankfurt (Dh)	Smooth	Smooth	Smooth	Smooth	Smooth	Slow-Highly Variable	Slow-Highly Variable
Lyon (M)	Smooth	Smooth	Smooth	Smooth	Smooth	Slow-Highly Variable	Slow-Highly Variable
Japan (F)	Smooth	Slow-Low Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable

Hong Kong(F)	Smooth	Slow-Low Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable
China (F)	Smooth	Slow-Low Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable
Malaysia (F)	Smooth	Slow-Low Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable
Taiwan(F)	Smooth	Slow-Low Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable
Singapore (F)	Smooth	Slow-Low Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable
Turkey (F)	Smooth	Slow-Low Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable	Slow-Highly Variable

Table 5: Safety stock optimisation results in the bottom level fractals at different DBR (1 day to 7 days)

Sites	**Product / Component**	**1day**	**2days**	**3 days**	**4 days**	**5 days**	**6 days**	**7days**
Porto (R)	laptop	1139	1139	1139	1139	1139	1139	1139
Malaga (R)	laptop	674	674	674	674	674	674	674
Tours (R)	laptop	749	749	749	749	749	749	749
Ghent (R)	laptop	1366	1366	1366	1366	1366	1366	1366
Bologna (R)	laptop	774	774	774	774	774	774	774
Odine (R)	laptop	779	779	779	779	779	779	779
Bern (R)	laptop	1398	1398	1398	1398	1398	1398	1398
Bremen (R)	laptop	1064	1064	1064	1064	1064	1064	1064
Berlin (R)	laptop	1283	1283	1283	1283	1283	1283	1283
Homburg (R)	laptop	898	898	898	898	898	898	898
Randers (R)	laptop	1388	1388	1388	1388	1388	1388	1388
Madrid (Dh)	laptop	4692	5981	8779	10240	11511	12639	13652
Paris (Dh)	laptop	4273	5245	7682	8956	10063	11044	11924
Milan (Dh)	laptop	5260	6542	7971	11007	12416	13683	14839
Frankfurt (Dh)	laptop	6326	7746	9421	10876	12160	16010	17394
Lyon (M)	For each Component	29820	30014	30109	32334	36151	47871	51965
Japan (F)	CD-ROM	115378	180304	225590	225180	180302	123542	123542

	RAM chip							
Hong Kong (F)	video cards microprocessor	115378	180304	225590	225180	180302	123542	123542
China (F)	power supplier	57689	90152	112795	112590	90151	61771	61771
Malaysia (F)	floppy drive	61673	95767	119810	119593	95766	65672	65672
Taiwan (F)	cooling fan monitor network card	173067	270456	338385	337770	270453	185313	185313
Singapore (F)	SCSI card disk device	115378	180304	225590	225180	180302	123542	123542
Turkey (F)	keyboard soundcards	75534	122840	153020	152752	122838	84086	84086

Table 6: Reorder Point results in the bottom level fractals at different DBR (1 day to 7 days)

Sites	**Product / Component**	**1day**	**2days**	**3 days**	**4 days**	**5 days**	**6 days**	**7days**
Porto (R)	laptop	3405	3405	3405	3405	3405	3405	3405
Malaga (R)	laptop	3505	3505	3505	3505	3505	3505	3505
Tours (R)	laptop	2438	2438	2438	2438	2438	2438	2438
Ghent (R)	laptop	4047	4047	4047	4047	4047	4047	4047
Bologna (R)	laptop	2597	2597	2597	2597	2597	2597	2597
Odine (R)	laptop	3210	3210	3210	3210	3210	3210	3210
Bern (R)	laptop	3931	3931	3931	3931	3931	3931	3931
Bremen (R)	laptop	3372	3372	3372	3372	3372	3372	3372
Berlin (R)	laptop	3810	3810	3810	3810	3810	3810	3810
Homburg (R)	laptop	2686	2686	2686	2686	2686	2686	2686
Randers (R)	laptop	4024	4024	4024	4024	4024	4024	4024
Madrid (Dh)	laptop	9788	11078	13875	15336	16607	17735	18748
Paris (Dh)	laptop	8643	9614	12051	13325	14432	15413	16293
Milan (Dh)	laptop	12047	13328	14757	17793	19202	20469	21625
Frankfurt (Dh)	laptop	15586	17006	18681	20136	21420	25270	26654
Lyon (M)	For each Component	55333	55526	55622	57847	61663	73383	77477
Japan (F)	CD-ROM RAM chip	293966	358892	404178	403768	358890	302130	302130

Hong Kong (F)	video cards microprocessor	293966	358892	404178	403768	358890	302130	302130
China (F)	power supplier	146983	197817	202089	201884	179445	151065	151065
Malaysia (F)	floppy drive	163723	179446	221860	221643	197816	167722	167722
Taiwan (F)	cooling fan monitor network card	440949	538338	606267	605652	538335	453195	453195
Singapore (F)	SCSI card disk device	293966	358892	404178	403768	358890	302130	302130
Turkey (F)	keyboard soundcards	152072	199376	229556	229288	199374	160622	160622

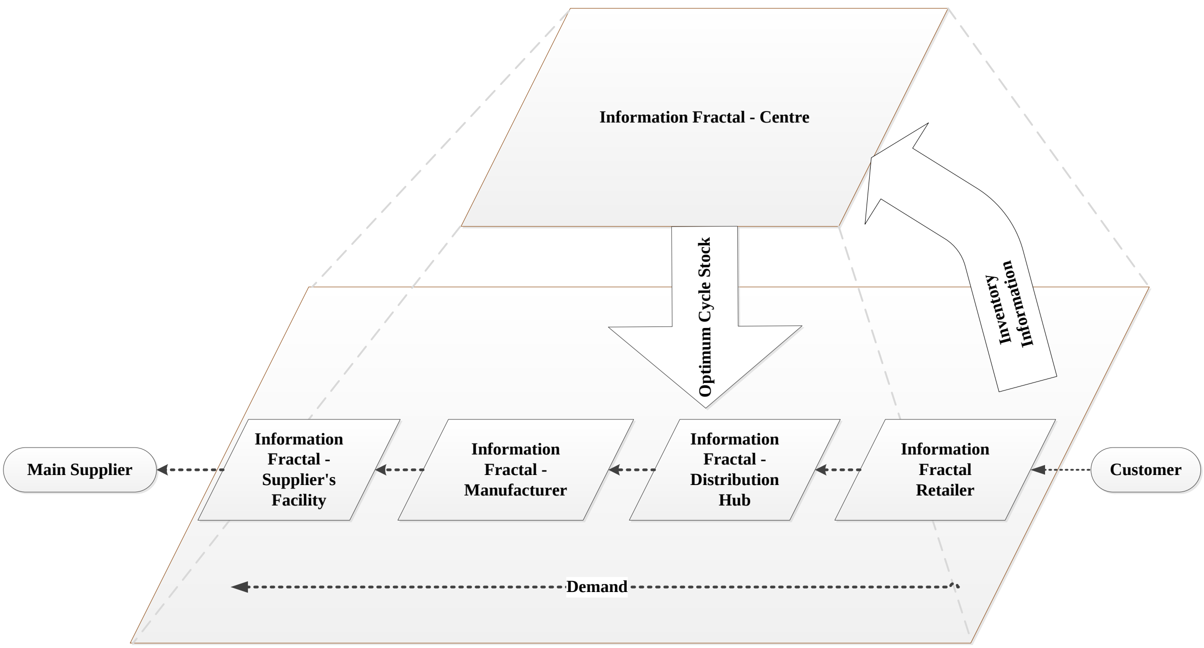


Figure 1: The proposed framework for an Information Fractal Supply Network (IFSN)

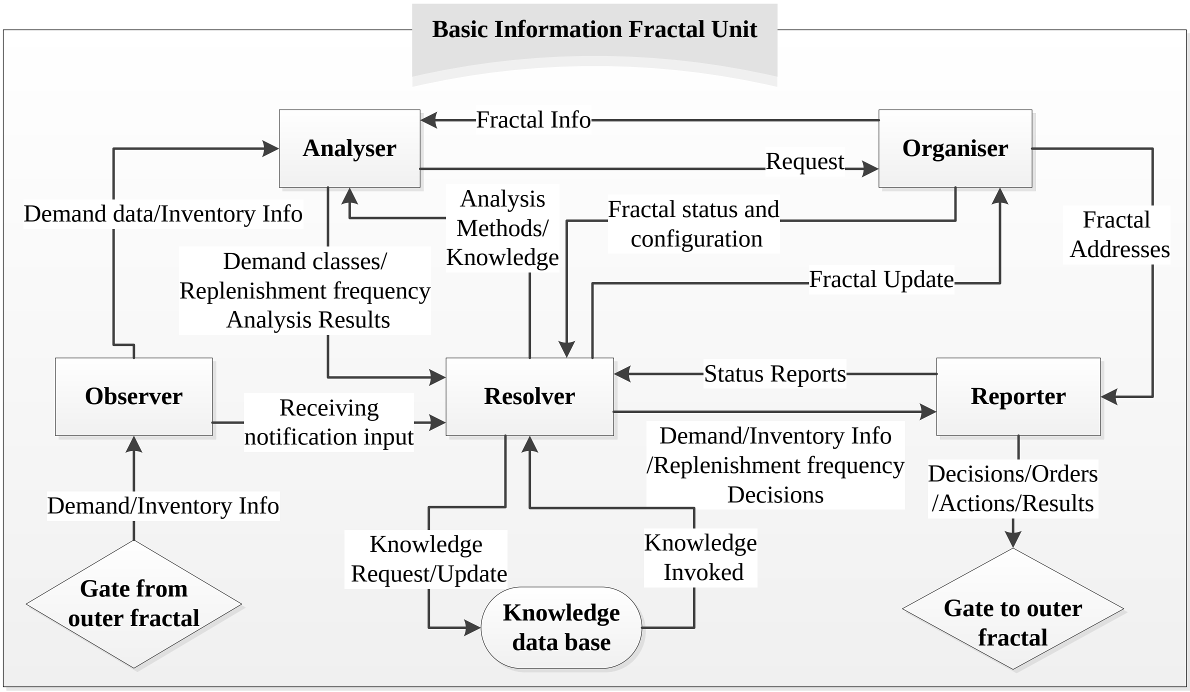


Figure 2: Basic Information Fractal Unit Structure

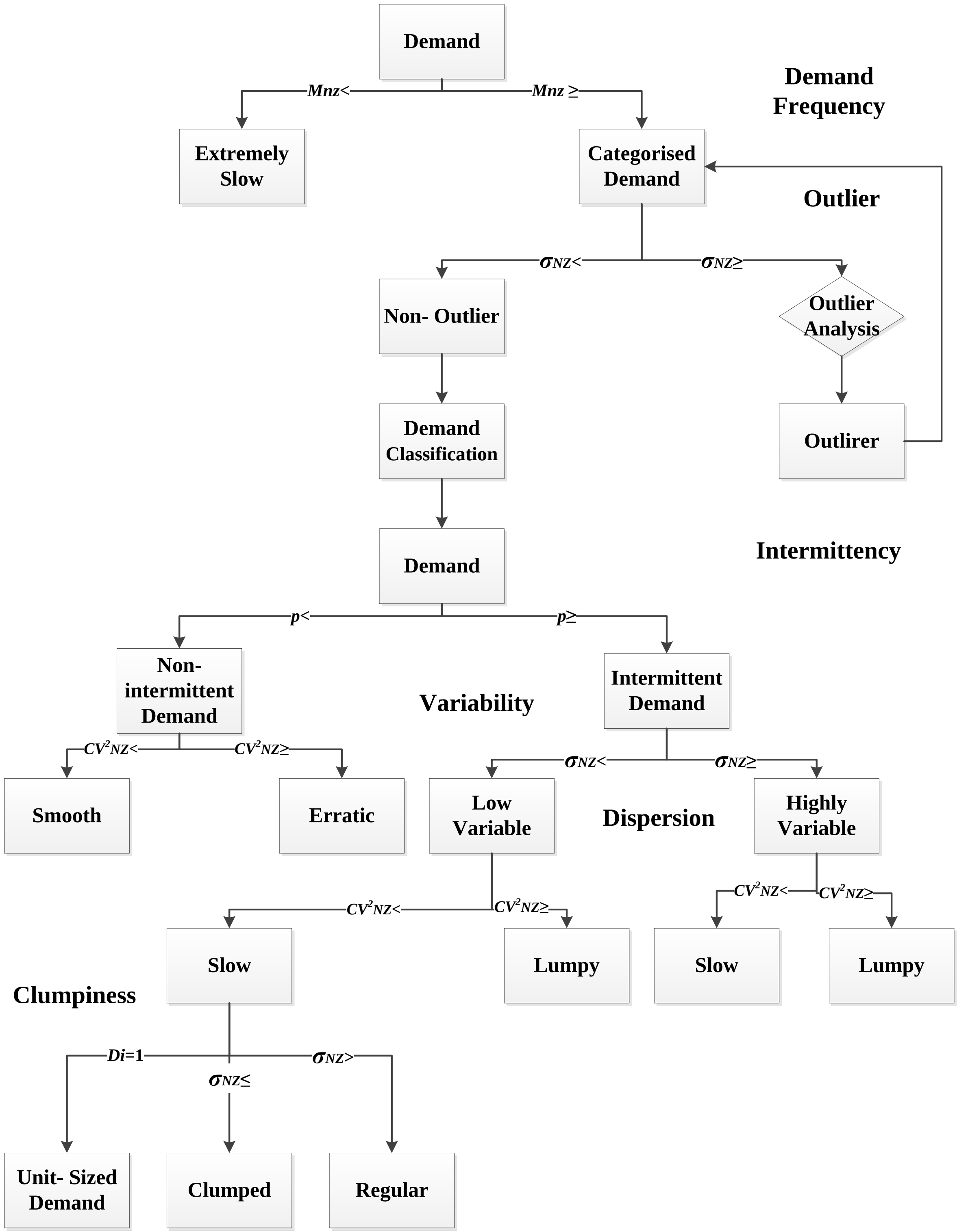


Figure 3: Demand classification diagram (Saad and Bahadori, 2016).

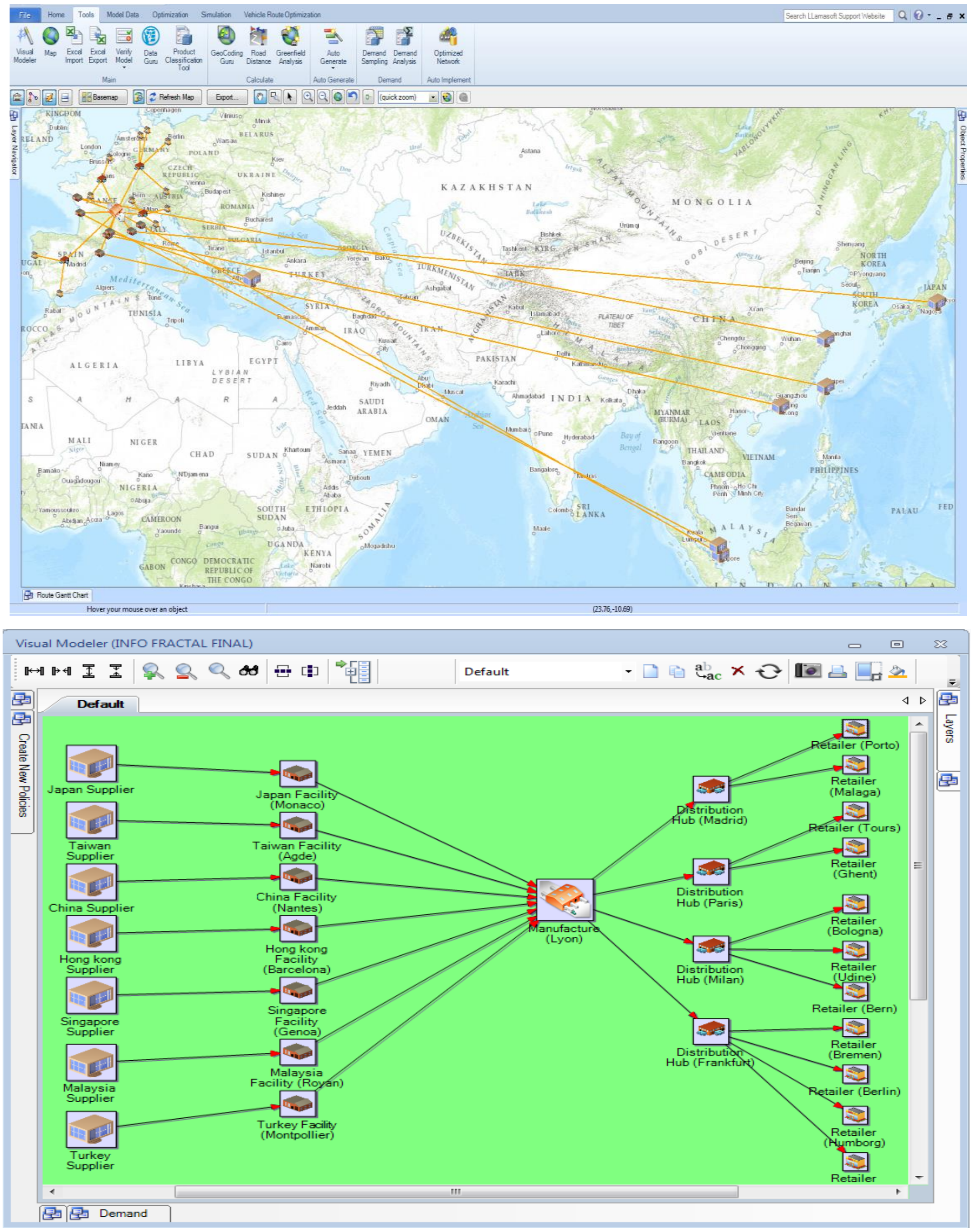
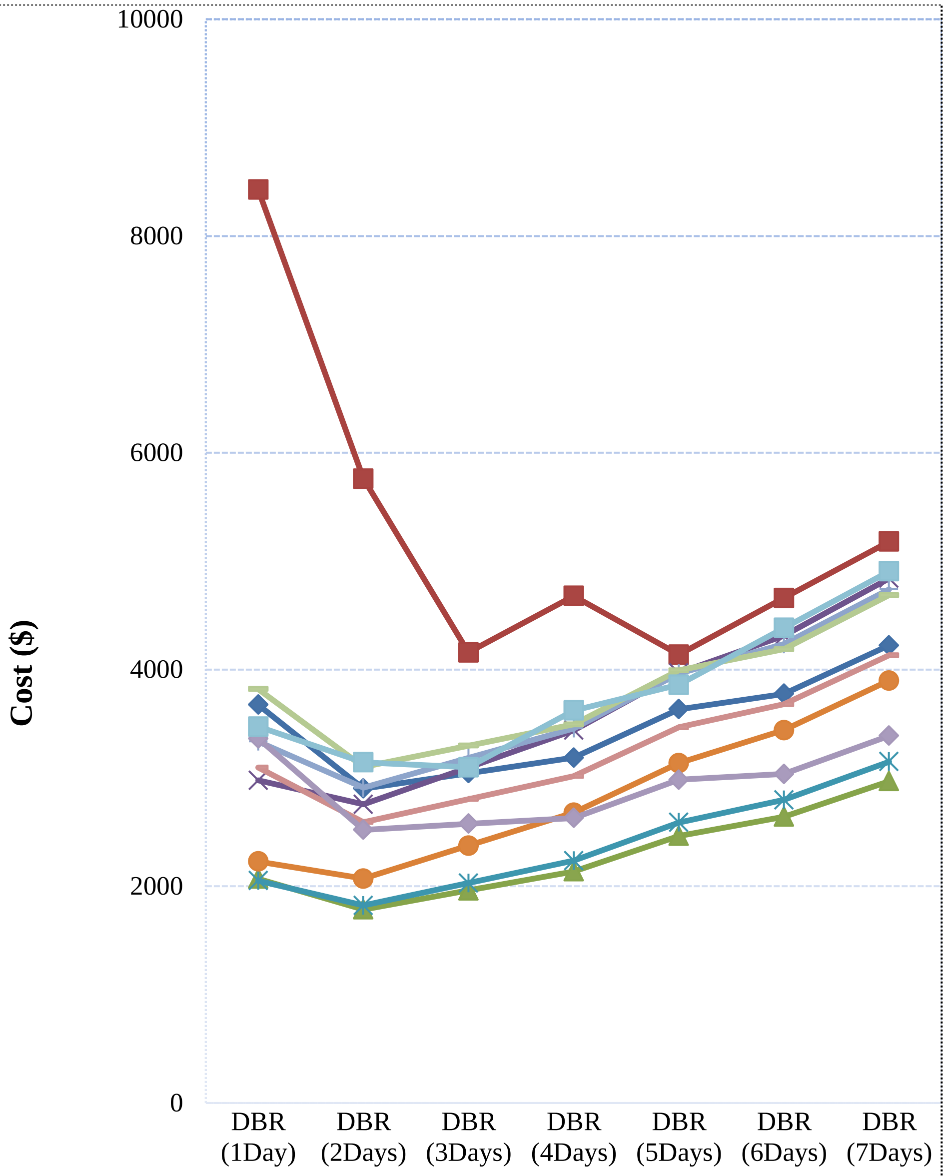
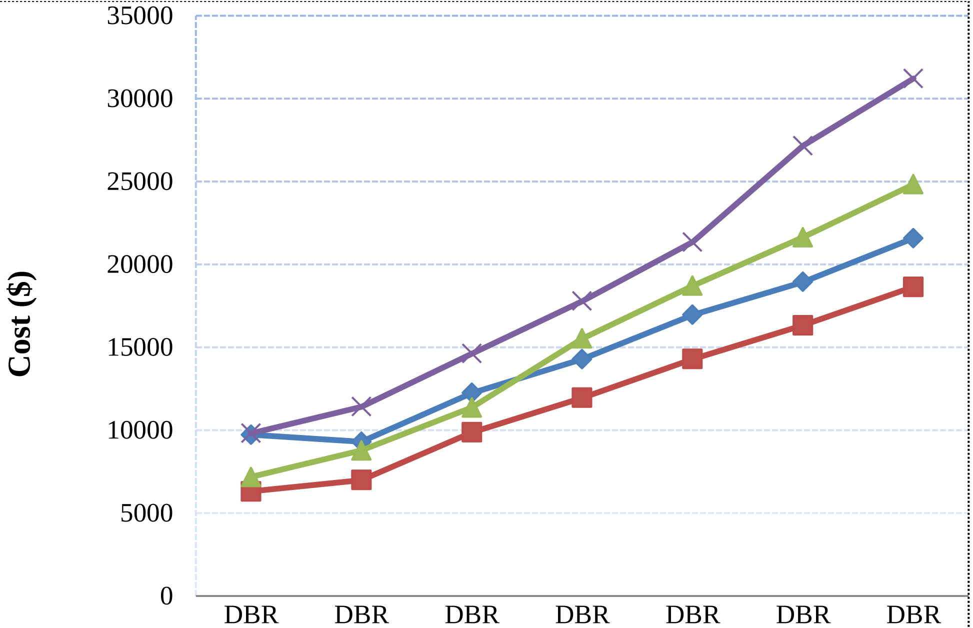


Figure 4: Supply Chain Guru screen shot of the considered supply network



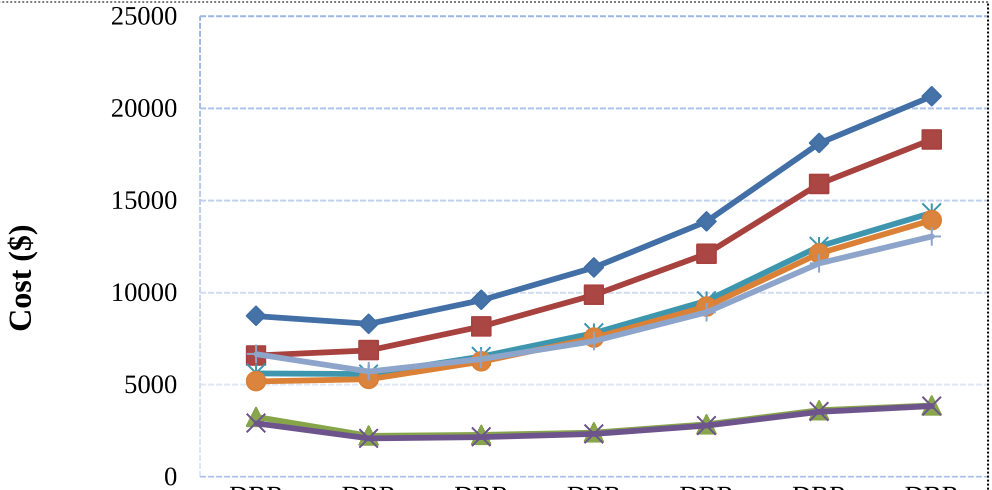
	DBR (1Day)	DBR (2Days)	DBR (3Days)	DBR (4Days)	DBR (5Days)	DBR (6Days)	DBR (7Days)
Madrid(Dh)→Porto(R)	3675	2901	3043	3186	3633	3775	4223
Madrid(Dh)→Malaga(R)	8427	5760	4157	4679	4137	4659	5181
Paris(Dh)→Tours(R)	2069	1785	1961	2137	2465	2641	2969
Paris(Dh)→Ghent(R)	2976	2755	3097	3439	3969	4311	4841
Milan(Dh)→Bologna(R)	2051	1822	2029	2236	2589	2797	3149
Milan(Dh)→Odine(R)	2229	2070	2374	2678	3136	3440	3898
Milan(Dh)→Bern(R)	3336	2909	3183	3456	3962	4235	4741
Frankfurt(Dh)→Bremen(R)	3095	2592	2804	3016	3467	3680	4131
Frankfurt(Dh)→Berlin(R)	3819	3102	3297	3493	3992	4187	4686
Frankfurt(Dh)→Homburg(R)	3364	2521	2576	2630	2982	3036	3389
Frankfurt(Dh)→Randers(R)	3473	3143	3098	3621	3859	4383	4906

Figure 5: Total logistics cost at different *DBR* (1 day to 7 days) from distribution hubs to retailers



	DBR (1 Day)	DBR (2 Days)	DBR (3 Days)	DBR (4 Days)	DBR (5 Days)	DBR (6 Days)	DBR (7 Days)
Lyon(M)→Madrid(Dh)	9732	9304	12251	14289	16954	18942	21583
Lyon(M)→Paris(Dh)	6308	6999	9874	11956	14293	16329	18644
Lyon(M)→Milan(Dh)	7177	8781	11371	15530	18710	21643	24832
Lyon(M)→Frankfurt(Dh)	9812	11418	14618	17787	21354	27164	31214

Figure 6: Total logistics cost at different DBR (1 day to 7 days) from main manufacturer to distribution hubs



	DBR (1 Day)	DBR (2 Days)	DBR (3 Days)	DBR (4 Days)	DBR (5 Days)	DBR (6 Days)	DBR (7 Days)
Japan(F)→Lyon(M)	8730	8300	9595	11359	13864	18107	20654
Hong Kong(F)→Lyon(M)	6587	6873	8165	9873	12110	15898	18308
China(F)→Lyon(M)	3252	2235	2277	2405	2852	3610	3876
Malaysia(F)→Lyon(M)	2909	2082	2163	2329	2776	3534	3838
Taiwan(F)→Lyon(M)	5619	5575	6529	7809	9553	12508	14334
Singapore(F)→Lyon(M)	5187	5304	6265	7544	9244	12123	13934
Turkey(F)→Lyon(M)	6659	5722	6398	7367	8932	11584	13043

Figure 7: Total logistics cost at different DBR (1 day to 7 days) from supplier facilities to main manufacturer

Appendix 1: Analyser calculation results in top level fractal

- Inventory holding cost ($) results for the bottom level fractal at different DBR (1 day to 7 days)

Sites	Product / Component	1 day	2 days	3 days	4 days	5 days	6 days	7 days
Porto (R)	laptop	1234	1681	2128	2576	3023	3470	3918
Malaga (R)	laptop	987	1509	2031	2553	3074	3596	4118
Tours (R)	laptop	846	1174	1502	1831	2159	2488	2816
Ghent (R)	laptop	1473	2003	2533	3063	3593	4123	4653
Bologna (R)	laptop	887	1240	1592	1945	2298	2651	3003
Odine (R)	laptop	996	1454	1912	2370	2828	3286	3744
Bern (R)	laptop	1471	1977	2484	2990	3496	4002	4508
Bremen (R)	laptop	1186	1637	2088	2539	2990	3441	3892
Berlin (R)	laptop	1385	1885	2384	2884	3383	3883	4382
Homburg (R)	laptop	973	1326	1679	2032	2384	2737	3090
Randers (R)	laptop	1482	2005	2529	3052	3575	4099	4622
Madrid (Dh)	laptop	4440	6658	10267	12966	15631	18281	20922
Paris (Dh)	laptop	4019	5855	9016	11384	13721	16043	18358
Milan (Dh)	laptop	5208	7796	10633	15038	18218	21397	24586
Frankfurt (Dh)	laptop	6506	9765	13378	16961	20528	26751	30801
Lyon (M)	CD-ROM RAM chip	5235	6747	8430	10582	13087	17330	20266
Lyon (M)	video cards microprocessor	4674	6023	7527	9448	11685	15473	18095
Lyon (M)	power supplier	935	1205	1505	1890	2337	3095	3619
Lyon (M)	floppy drive	935	1205	1505	1890	2337	3095	3619
Lyon (M)	cooling fan monitor network card	3645	4698	5871	7370	9114	12069	14115
Lyon (M)	SCSI card disk device	3552	4578	5720	7181	8881	11760	13752
Lyon (M)	keyboard soundcards	3272	4216	5269	6614	8179	10831	12667

- Total transportation costs ($) among sites at different DBR (1 day to 7 days)

Source Site	Destination Site	1 day	2 days	3 days	4 days	5 days	6 days	7 days
Madrid(Dh)	Porto(R)	2441	1220	915	610	610	305	305
Madrid(Dh)	Malaga(R)	7440	4251	2126	2126	1063	1063	1063
Paris(Dh)	Tours(R)	1223	611	459	306	306	153	153
Paris(Dh)	Ghent(R)	1503	752	564	376	376	188	188
Milan(Dh)	Bologna(R)	1164	582	437	291	291	146	146
Milan(Dh)	Odine(R)	1233	616	462	308	308	154	154
Milan(Dh)	Bern(R)	1865	932	699	466	466	233	233
Frankfurt(Dh)	Bremen(R)	1909	955	716	477	477	239	239
Frankfurt(Dh)	Berlin(R)	2434	1217	913	609	609	304	304
Frankfurt(Dh)	Homburg(R)	2391	1195	897	598	598	299	299
Frankfurt(Dh)	Randers(R)	1991	1138	569	569	284	284	284
Lyon (M)	Madrid(Dh)	5292	2646	1984	1323	1323	661	661
Lyon (M)	Paris(Dh)	2289	1144	858	572	572	286	286
Lyon (M)	Milan(Dh)	1969	985	738	492	492	246	246
Lyon (M)	Frankfurt(Dh)	3306	1653	1240	826	826	413	413
Japan(F)	Lyon (M)	3495	1553	1165	777	777	777	388
Hong Kong (F)	Lyon (M)	1913	850	638	425	425	425	213
China (F)	Lyon (M)	2317	1030	772	515	515	515	257
Malaysia (F)	Lyon (M)	1974	877	658	439	439	439	219
Taiwan (F)	Lyon (M)	1974	877	658	439	439	439	219
Singapore (F)	Lyon (M)	1635	726	545	363	363	363	182
Turkey (F)	Lyon (M)	3387	1506	1129	753	753	753	376