SUPPLY CHAIN PERFORMANCE MEASUREMENT USING SIMULATION: AN OVERALL EQUIPMENT EFFECTIVENESS BASED ANALYSIS

M. ESSAID, F. GRIMAUD, P. BURLAT

Ecole Nationale Supérieure des Mines de Saint-Etienne
158, Cours Fauriel
42023 Saint-Étienne cedex 2
essaid@emse.fr , grimaud@emse.fr , burlat@emse.fr

Abstract
Nowadays, more and more companies are involved in manufacturing networks. Supply chain management is a significant element of business strategy and operations management. Managing manufacturing network operations is a difficult task; therefore the need for modelling approaches is crucial to study such complex systems. The simulation is one of the most appropriate methods to analyse the dynamic nature of supply chains. The purpose of this paper is to investigate the behaviour of supply chains in terms of material flow connectivity with a focus on the local efficiency of the manufacturing capabilities. A simulation model is developed to evaluate supply chain performance where manufacturers of dissimilar production process capabilities and heterogeneous control and planning policies collaborate in a serial supply chain. The simulation experiment is based on the Overall Equipment Effectiveness (OEE) as an aggregate metric to characterize the enterprise efficiency level. The advantage of this approach is that by changing parameters of this dynamic system one can examine the influence of the efficiency of individual enterprises on the overall network performance. Thus, both the performance losses due to the lack of process connectivity and those caused by a local inefficiency can be analysed in the same simulation model.

Key-words: supply chain, simulation, Overall Equipment Effectiveness, enterprise efficiency level

1. Introduction

In today's global market, managing the entire supply chain becomes a key factor for a successful business. The dynamic nature of supply chains makes simulation necessary for studying the time-varying behaviour of supply chains.
In this paper, we use simulation methods to investigate behaviour of the supply chain, when enterprises of different production efficiency levels are called to perform in manufacturing network. We deal precisely with the use of local efficiency information metrics to develop simulation scenarios. First, using an aggregate efficiency metric (Overall Equipment Effectiveness for instance) may be useful to profile an enterprise's efficiency. This provides a simple and meaningful scheme to classify manufacturing systems. Second, such a tool is an aid in enterprise modelling and also in supply chain model parameterization. Indeed, the overall efficiency metric is decomposed into factors (availability, performance and quality), which also are decomposed into variables such as set-up and breakdown times, scrap ratio, etc. These variables constitute input data for the simulator.
Some of the questions relevant to this issue are as follows: (i) Does the position, in the supply chain, of the less adequate enterprise affect the level of logistic performance in terms of inventory and customer service levels? (ii) What enterprise combinations are the better trade-offs to achieve supply chain objectives? (iii) What is the degree of supply chain losses due to the inefficiency at the local level of the supply chain operations?
Another source of potential supply chain management failure is the use of heterogeneous planning and control systems by the different actors. This issue of a manufacturing network decision making system, combined with the misalignment of differing local manufacturing capabilities may damage the flow connectivity in the supply chain. Therefore, we have incorporated in our model different production management policies. In this study, we focus mainly on a make to stock demand response strategy (MTS), and a replenishment stock production policy (ROP).

This paper is organized as follows: section 2 presents a non exhaustive supply chain simulation modelling state of the art, which helps to position our work. Section 3 describes the generic supply chain model. Section 4 demonstrates the Overall Equipment Effectiveness factors and explains our simulation experiment approach. Section 5 highlights some important results and their implications. Section 6 discusses the simulations and provides some research perspectives.

2. Supply chain simulation state of the art

Simulation is the process of designing and creating a model of a real or proposed system, using abstract objects in an effort to replicate the behaviour of their real-world equivalents (Kim et al, 2004).
Supply chain simulation based methods are tools by which a comprehensive supply chain model can be analyzed considering both its strategic and operational elements. The dynamic nature of supply chains makes simulation necessary for studying their time-varying behaviour (Chang and Makatsoris, 2004). Kleijnen (2005) provides a general survey of supply-chain simulation work, identifying four useful types of simulation: spreadsheet, system dynamics (continuous), discrete-event and business games. Discrete-event simulation is the method adopted for this research.
(Feigin et al. 1996), (Kumar et al. 1993), (Maloni and Benton 1997) and (Towill, et al. 1992) used simulation techniques to evaluate effects of various supply chain strategies on demand amplification. (Tzafestas and Kapsiotis, 1994) utilized a combined analytical/simulation model to analyze supply chains. (Swaminathan, et al, 1995) utilized a simulation to study the effect of sharing supplier's available-to-promise information.
Making it possible to explore policies and operating procedures is one of the greatest advantages of simulation (Banks, 1998). This ability to evaluate "what if" scenarios with a variety of inputs could make simulation a useful technique for analyzing supply chains (Hellström, and Johnsson, 2002). (Terzi and Cavalieri, 2004), (Wyland et al, 2000) argue that the increasing popularity of simulation as a tool in supply chain management is due to its excellent capacity to evaluate system variation and interdependencies. This enables a decision-maker to assess changes in part of the supply chain and visualise the impact of those changes on the other parts of the system, and ultimately on the efficiency of the entire supply chain.
Simulation has been used to model supply chains in various industrial sectors including mobile communication systems (Persson and Olhager, 2002), food (Reiner and Trcka, 2004), apparel (Al-Zubaidi and Tyler, 2004), and the aerospace industry (Bilczo et al, 2003).
(Chan and Rossetti, 2003) have developed an object-oriented modelling approach to implement a platform for the simulation of supply chains. The tool can generate, from components, various scenarios of supply chains. (Hung et al, 2004) have developed an approach using generic blocks (generic nodes) and test various types of operations management policies. (Byrne and Heavy, 2004) simulated supply chain management policies in the field of SME networks. (Enns and Suwanruji, 2006) summarized simulation studies comparing replenishment strategies under various demand patterns and different levels of uncertainty and capacity constraints. (Pundoor and Herrmann, 2006) proposed a generic model using the Supply Chain Operations Reference (SCOR) methodology. (Labarthe et al., 2007) have developed a methodological framework for agent-based modelling and simulation of supply chains in mass customization environments.
Some of these simulation models are applicable to specific industrial fields; most of them deal with particular supply chain issues. Therefore, the lack of generality makes the simulation results not enough generalizable (Swaminathan, 1998).
Another major limitation for supply chain models is the fact that local efficiency is not explicit enough. This raises and important question: which is the root cause for the supply chain inefficiency, incompetent actor or unsatisfactory connectivity of two actors? Thus, we consider that the use of performance measurement based on the manufacturing capability may help to render explicit the local efficiency aspects when modelling a manufacturing network.
From this perspective, the focus is on the use of the Overall Equipment Effectiveness as an efficiency metric to characterize the performance of a manufacturing system. Then, once a planning and control policy is set, an enterprise profile can be constructed. The simulation study is conducted to analyse the behaviour of a supply chain which is composed of manufacturers with different efficiency profiles which are collaborating in *on demand* production environment.

3. Generic enterprise model for the supply chain

The supply chain simulation approach is developed by using a conceptual enterprise model. This model is composed of:
- Two macro-processes which reproduce the physical transformation processes from raw material to semi-finished goods and then into finished goods. The production process can be a transfer, assembly, or postponement operation. In addition, production resources are modelled within this process.
- Three potential planning points: these are found in flow control. They are three potential stock positions (procurement, manufacturing and delivery). These points can represent flow synchronisation positions or may be used to incorporate the external demand information in the production planning. In the latter case, we use the decoupling point concept to model the three main demand response strategies: Make To Stock, Assemble To Order and Make To Order.
- A planning and control process: this models the policies and rules used to manage the production operations. The well-known reorder replenishment point (ROP), kanban and material requirement planning (MRP), can be used.

In order to insure the coherence of the generic model instanciation, some rules have to be respected. This is done with a configuration tool which had been developed with excel worksheets. This solution is used to insure consistency and the easy parameterisation of the simulator.
The model is also enriched by the use of coordination mechanisms. The aim is to model logistical information treatment. So, forecasting techniques, demand and produc-

tion information sharing can be incorporated in the supply chain (Essaid et al, 2007).

Figure 1 illustrates the supply chain conceptual model.

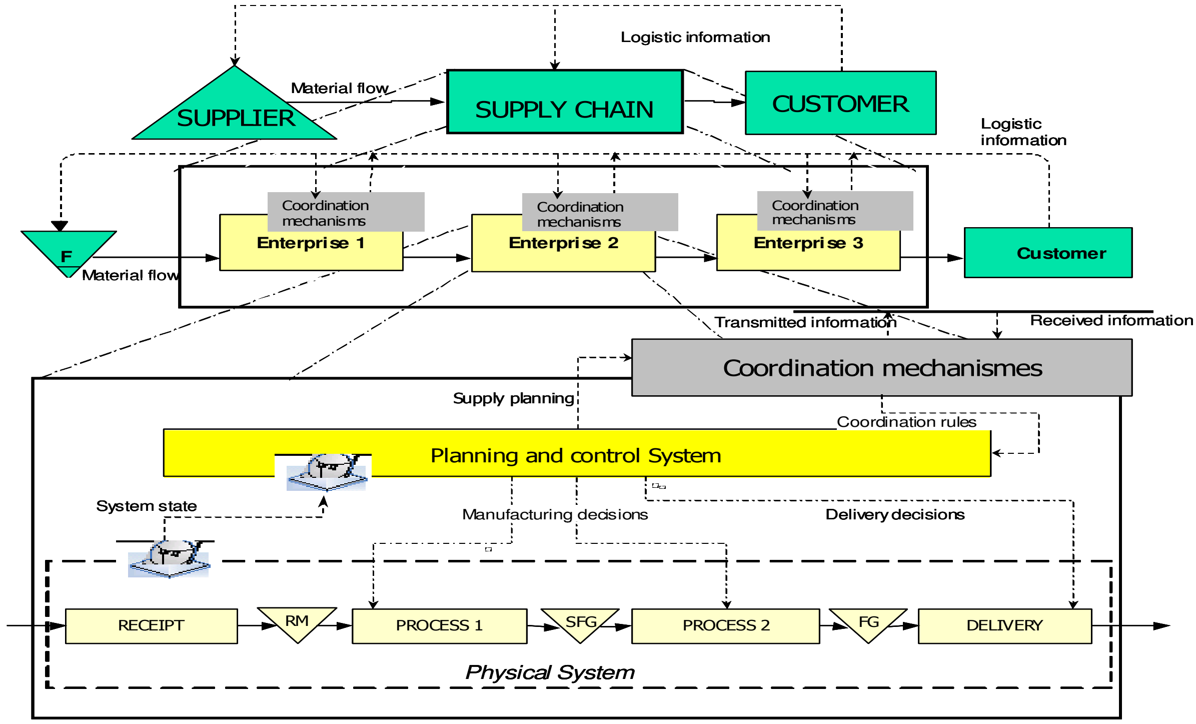

figure1. Supply chain conceptual model

The processes composing the model are described in figure 2 using UML class diagram (Unified Model Language).

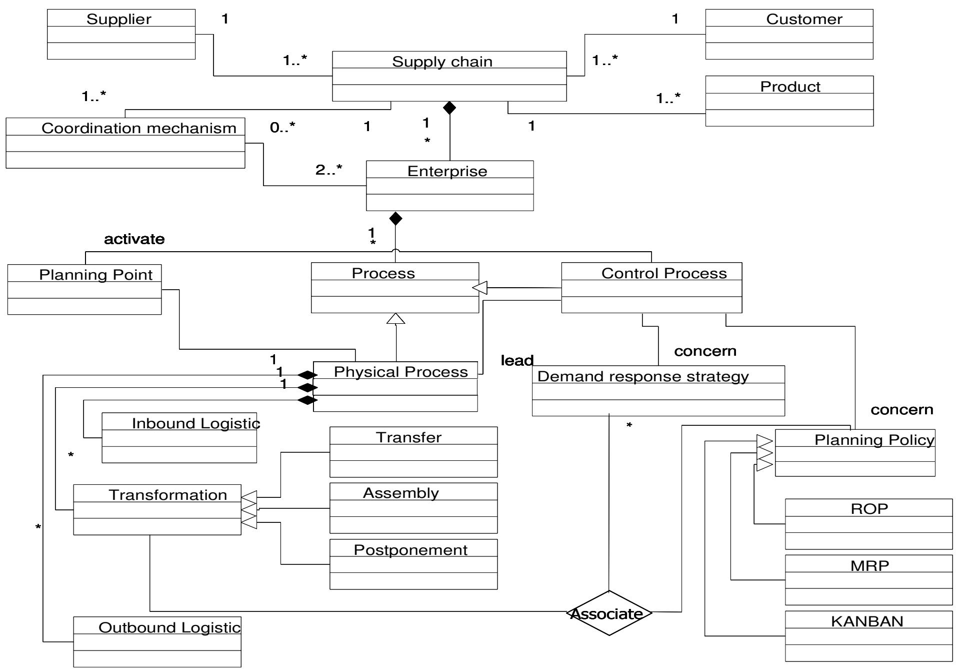

Figure2. Supply chain UML class diagram

The model can operate with two product flows. The first step for the supply chain configuration consists of creating the products macro-nomenclature. Depending on the process type at each manufacturer of the supply chain, numbered products are automatically generated by the spreadsheet. In the second step, the demand response strategy and the planning and control policy are chosen.
The next step of the configuration tool is to choose the enterprise efficiency classes. We will see in the next section how this is done by using efficiency metric.
Finally, the parameters of the model are calculated and introduced into the simulator.

4. Overall Equipment Effectiveness

4.1. Overall Equipment Effectiveness definition

Overall Equipment Effectiveness (OEE) is an excellent methodology for evaluating and improving the efficiency of manufacturing processes. Increasingly since the early 1990s, OEE has emerged as a leading method for accurately measuring the actual plant productivity. Although, initially, OEE was regularly associated with Total Productive Maintenance (TPM) programs, it is now being considered as a powerful means of evaluating key productivity indicators (Understanding the OEE Calculation, OEE Toolkit v5.1).
By definition, OEE is the product of Availability, Performance and Quality category percentages:
OEE = Availability * Performance * Quality

Where:

Availability is a measure of downtime, *Performance is* a measure of losses of speed, and *Quality* is a measure of defect.

The production time in a plant is composed of several phases, the definitions are as follows:

- Total Available Time: all of the time that the plant is open and could be used for production.

- Planned Production Time: total available time minus the planned shutdown time. Planned shutdown could include employee breaks, holidays and scheduled maintenance.

- Operating Time: the difference between planned production time and downtime. Downtime events include equipment breakdown, unscheduled maintenance, setup time and changeover.

- Net Operating Time: the difference between the operating time and time lost to speed reduction. Speed reduction events include operating equipment at below rated speed (increased cycle time), frequent short-lived stoppages not requiring maintenance and certain operator errors.

- Productive Time: the difference between the net operating time and the time lost to quality issues. Quality losses include rejected and reworked products.

Table 1 illustrates OEE factors calculation

OEE Category	How it is Calculated
Downtime Losses	***Availability*** is the ratio of Operating Time to Planned Production Time (Operating Time is Planned Production Time less Downtime Loss). *Availability* of 100% means the process has been running with no stops. ***Availability = Operating Time / Planned Production Time***
Speed Losses	***Performance*** is the ratio of Theoretical/Ideal Speed to Actual Speed. *Performance* of 100%means the process has been consistently running at its theoretical maximum speed. ***Performance = Parts Produced / (Ideal Speed * Operating Time)***
Quality Losses	***Quality*** is the ratio of Good Parts to Total Parts. *Quality* of 100% means there have been no reject or rework parts. ***Quality = Good Parts / Parts Produced***

Table1. OEE Calculations

4.2. Simulation experiment based OEE

OEE can be used to characterize an enterprise efficiency profile via the capability of its production process. Practically, firms cooperating in a supply chain may be dissimilar from a process capability point of view. Thus, the connectivity of the material flow may be imperfect. This is called process capability discount.
The second source of the *connectivity failure*, the idea that two companies can not adequately connect, is the difference of the planning and control systems used by the partners. We call this control process discount.

Figure 3 illustrates these two sources of flow discount.

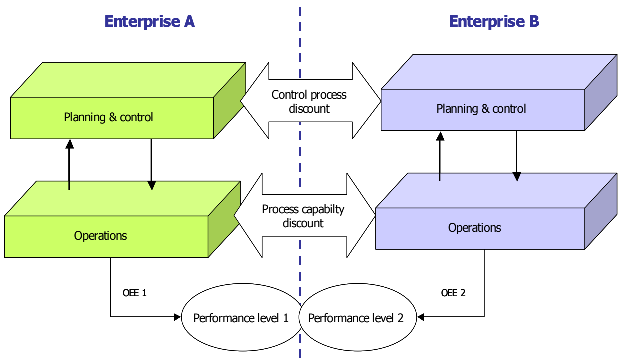

figure 3. Connectivity failure sources

In our work, we consider four efficiency levels by using the framework developed by (Miltenburg, 1995). The author distinguishes four levels of manufacturing maturity: infant, industry average, adult and world class. Forwards, we use the notations A, B, C and D to refer to these four classes of enterprises.

Table 1 shows the OEE factors values of the four enterprise's classes which are used in the simulation experiment.

Enterprise class	**A**	**B**	**C**	**D**
Lose %		*5%*	*10%*	*20%*
OEE	85%	73%	62%	44%
Availability	90%	86%	81%	72%
Performance	95%	90%	86%	76%
Quality	99,90%	95%	90%	80%

Table 2 . OEE values by enterprise class

Note that we have fixed the percentage of performance loses to insure the validity of OEE factors values. This is done by using statistical values observed in case studies concerning manufacturing efficiency in some industrial domains. So, observed variables such as average setup time, scrap ratio, average breakdown time are used as target values to fix the OEE factors for the four classes of enterprises.
In discrete manufacturing production, average OEE is about 60%, this corresponds to average OEE of the aforementioned four classes. The values given in table 2 are used as average target values. Some variations around the mean values are allowed when simulating.

Figure 4 summarizes our approach. In the scheme, OEE enterprise classes A and B are integrated to form the supply chain. The simulation model instanciation is done by using the values of variables calculated from OEE classes. Each enterprise class corresponds to an efficiency level. The OEE is decomposed into its factors: availability, performance and quality. Then the following variables are calculated:

- Unavailability: is decomposed into three categories, which are: breakdown, setup and idle times. These variables are then used to calculate the following ones: Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), unit order setup, changeover and idle times.
- the scrap ratio
- the run time: mean run and standard deviation run times

These variables are instantiated per enterprise class and then configured in the simulator. Control parameters such as stock replenishment level, service level, safety stocks…are fixed by choosing the planning policy. For each enterprise, a planning and control policy is chosen and implemented in the simulator. In this experiment we use the same planning policy (ROP for instance) in a MTS production environment.
Simulation run length is 10,000 hours, which is largely sufficient to overcome a transition phase. The external demand is set to a normal distribution with a mean of 50 units per week and a standard deviation of 5 units.
The production run time is set to 0.1 pieces per minute. The planned production time is set to 10 hours.
The simulation outputs statistics are: the average inventory level in the supply chain (including raw material, semi-finished and finished good inventories) and the delivery delay to the end costumer.

5. Simulation results

The purpose of the first simulation experiment was the calibration and the sizing of the supply chain model.
Firstly, each efficiency class was simulated in isolation using a unique external demand. This demand is assumed to be a normal distribution stochastic variable.
The planning policy used is the ROP model, in a MTS environment.
The simulation model validation was conducted by comparing the simulation outputs with the target values given in table 1.
The first aim of the experiment was to compare the capacity needed for each class of enterprise to respond to the external demand without delivery delays.

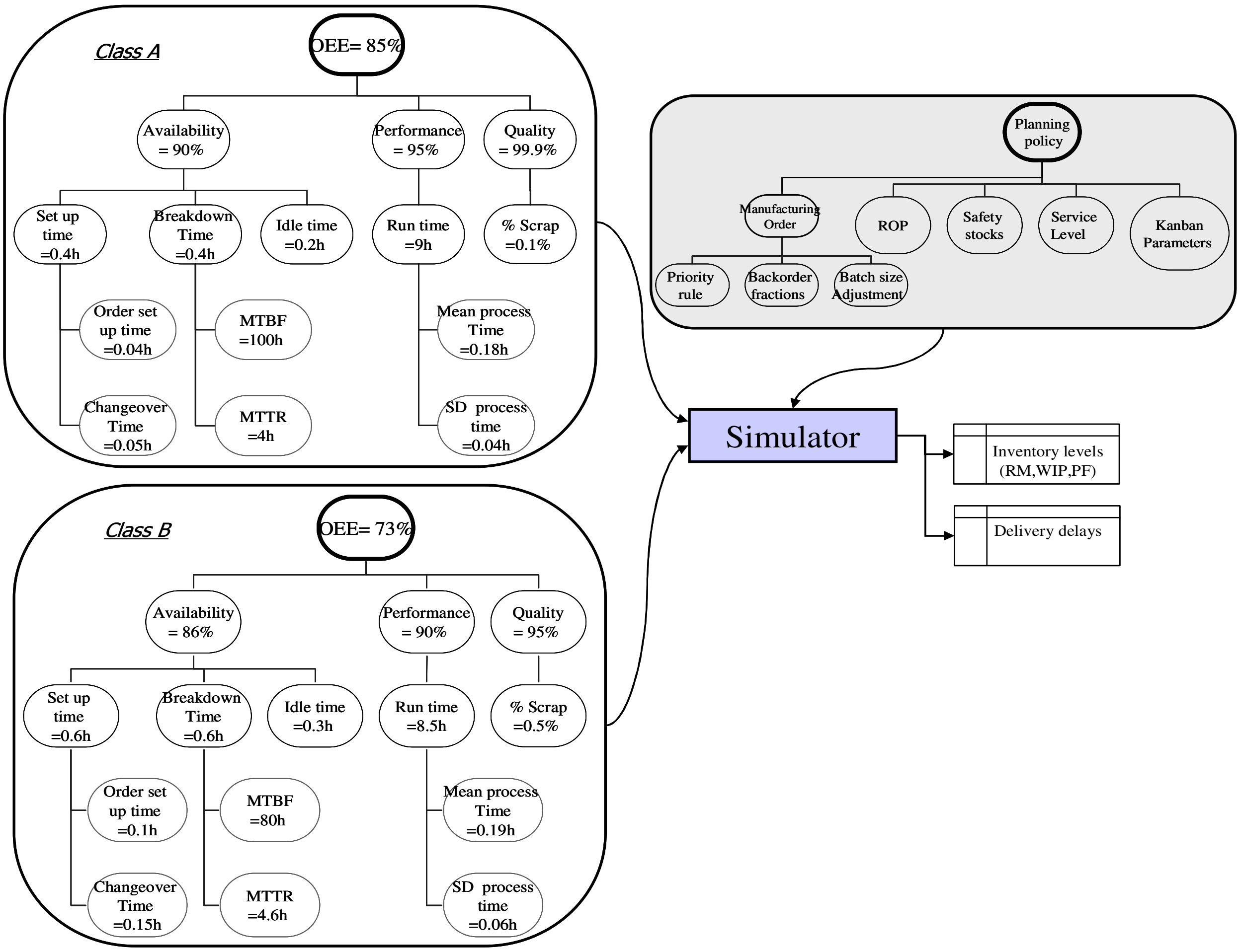

figure 4. Simulation based OEE instanciation

The results for the three classes A, B and C are given in figure 4. The capacity excess percentage for class B and C is (respectively) 50% and 100%. This means that, to achieve a zero delay delivery goal with the same external demand a class B requires 50 % more capacity than class A. This capacity cost/delivery interchange is a crucial point to be considered when enterprises are chosen to incorporate a supply chain production project.

Note also that the inventory level is increasing when OEE is decreasing. This is due to the fact that loses in production cause an increasing stock replenishment orders and longer production lead times, so inventory level is consequently increasing.

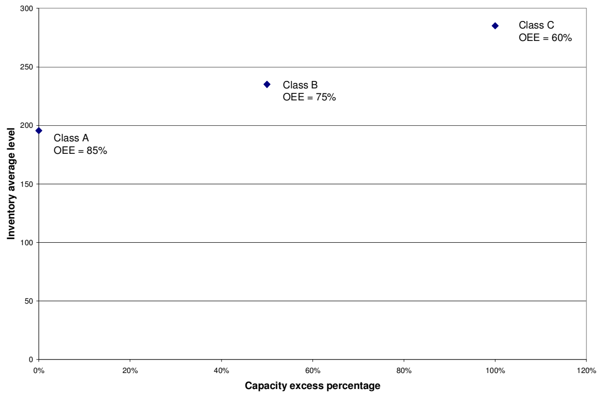

figure 4. Capacity excess and inventory level per OEE value

The second experiment consists in connecting different enterprise classes within a single supply chain.

Table 2 illustrates the results obtained when different combinations of enterprises efficiency profiles are put together in the same supply chain.
Notice that the most efficient combination AAA (all enterprises are world-class) can not achieve a zero delivery delay without any capacity excess. So, a new configuration (coded AAA1 in table 2) is designed by doubling capacities of both processes 1 and 2 in the first tier. In this configuration, the total capacity of the resulting chain is 33% more than AAA configuration. AAA1 configuration can hence perform without delivery delay, but with a significant extra-capacity investment.
An intermediate configuration is also made, where only process 1 (bottleneck) capacity is doubled (AAA2 configuration). This corresponds to 17 % of the total capacity of the supply chain; the delivery delay is then about 255 hours.

The case of the second OEE class configuration (BBB) is more problematic. To achieve a zero delivery delay, capacity excess is needed at each level of the supply chain. By doing this at the first and second tier levels only (BBB1 configuration), the delivery delay attains proximately 770 hours.

The last configuration tested (AAB) is a hybrid configuration where the third tier enterprise is less efficient than the suppliers. Note that this configuration is the worst one in terms of inventory level and delivery delay.

	Inventory level	Delivery delay	Capacity Excess
AAA1	250	0	33%
AAA2	214	255	17%
BBB1	230	772	83%
BBB2	245	0	100%
AAB	285	890	50%

Table 2. Simulation results

Figure 5 summarises the results obtained. It shows the inventory level versus delivery delay for the different supply chain configurations with the percentage of excess capacity utilized.

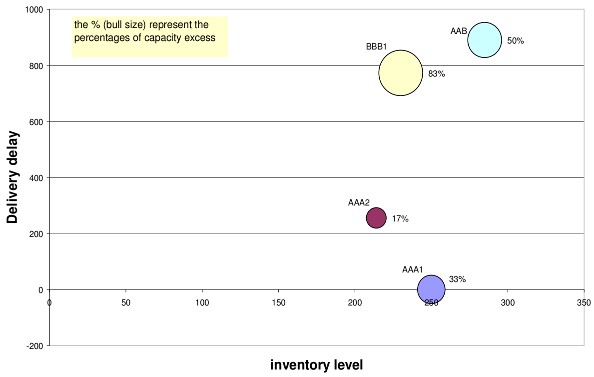

figure 5. Inventory level and delivery delay

Notice that the excess capacity is often added at the downstream of the supply chain. This can be explained by the amplification of the demand at the downstream levels of the supply chain. Indeed, an enterprise with a weak performance level placed in the downstream of the supply chain faces significant demand variability.
So to produce without stock shortages, capacity investment is necessary.

5. Conclusion and future work

In this paper, we have developed a supply chain simulation model to compare the behaviour a manufacturing network when enterprises of different process efficiency are cooperating in a supply chain. The process capability is taken into account by using OEE as an aggregate efficiency metric. The use of local efficiency metric is important in the sense that a poor performance in the whole supply chain can be caused either by the unsatisfactory efficiency of an actor or inadequate connectivity among actors. So, pertinent knowledge of the local efficiency (that of an individual firm) enables the identification of the cause for inefficiency from these two aspects.

Simulation experiments have been conducted in order to measure the impact of different OEE values on the inventory levels for the production system. Then we experimented with different supply chain configurations, formed by dissimilar enterprise efficiency profiles. The results show that a capacity investment is needed to insure a zero delay delivery to the end costumer. This capacity excess is increasing when the enterprise efficiency is decreased or when the supply chain is formed by different efficiency profiles. Furthermore, we have observed the effect of demand variability amplification and the need to have a significant capacity investment in the downstream of the supply chain.

Future work will be focused on:

- the simulation of remaining combinations of efficiency profiles (particularly combinations of companies with a significant difference in efficiency).

- use of appropriate metrics to measure the supply chain failure due to the inadequate connectivity of the actors in the supply chain.
- investigation of other planning policies such as kanban systems.
- application of other demand response strategies (ATO, MTO) to study the effect of demand information availability in the different stages of the production process.
- Implementation of coordination mechanisms to improve the supply chain performance by means of information sharing strategies and planning parameters adjustment.

The simulation model is designed to perform with three tiers supply chains, but the genericity of the model makes it possible to be generalized to more complex supply chains. Adding another tier or grouping serial simple chains within a network are feasible with the simulation tool.

Acknowledgement
The authors wish to thank Chris Yukna for his help in English.

REFERENCES

Al-Zubaidi H and Tyler D (2004). A Simulation Model of Quick Response Replenishment of Seasonal Clothing, *International Journal of Retail & Distribution Management, Vol. 32, No. 6, pp. 320 – 327*

Banks J (1998). Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice. *John Wiley, New York*

Bilczo T, Bugbee L, Fitzhugh J, Gilbert D, Halladin S, Rubert J and Budiman B (2003). Aerospace supply chain dynamics. *International Series in Operations Research and Management Science*

Byrne P-J, Heavy C (2004). Simulation, a framework for analysing SME supply chains. *Proceedings of the 2004 Winter Simulation Conference.* Vol. 2, p. 1167-1175.

Chan W and Rossetti (2003). A Prototype Object-Oriented supply chain simulation framework. *Proceedings of the 2003 Winter Simulation Conference.* p.1612-1620.

Chang Y and Makatsoris H (2004). Supply chain modeling using simulation. *International journal of simulation.vol. 2 No.1*

Enns ST and Suwanruji P (2006). Evaluating the effects of capacity constraints and demand patterns on supply chain replenishment strategies. *International Journal of Production Research*. Vol.44, pp.4607 – 4629

Essaid M, Grimaud F et Burlat P (2007). Proposition d'un modèle d'entreprise en vue de son intégration dans un réseau logistique. *Congrès International de Génie Industriel. Trois Rivières, Canada.*

Feigin G.C, Connors D and Crawford I (1996). Shape Up, Ship Out. *OR/MS Today*, *4, p24-30.*

Hellström D and Johnsson M (2002). Using discrete-event simulation in supply chain planning. *The 14th Annual conference for Nordic Researchers in Logistics, NOFOMA*

Hung W.Y, Kucherenko S, Samsatli J et Shah N (2004). A flexible and generic approach to dynamic modelling of supply chain. *Journal of Operational Research Society.* vol. 55, pp. 801-813.

Kim C-S, Tannock J, Byrne M, Farr R, Cao B, Er M (2004). State of the art review: techniques to model the supply chain in an extended enterprise. *Operations Management Division University of Nottingham. VIVACE PROJECT*

Kleijnen J (2005). Supply chain simulation tools and techniques: a survey. *International Journal of Simulation and Process Modelling* . Vol. 1, No.1/2 pp. 82 - 89.

Kumar A, Ow P-S and Prietula M-J (1993). Organizational Simulation and Information Systems Design: An Operations Level Example. *Management Science*, *39(2), pp.218-240*

Labarthe O, Espinasse B, Ferrarini A and Montreuil B (2007). Toward a methodological framework for agent-based modelling and simulation of supply chains in a mass customization context. *Simulation Modelling Practice and Theory* Num15 , pp

Maloni M-J and Benton W-C (1997). Supply Chain Partnerships: Opportunity for Operations Research. *European Journal of Operational Research, 101: pp.419-429*

Miltenburg (1995). Manufacturing Strategy, Productivity *Press Portland, Oregon.*

OEE Toolkit v5.1. Understanding the OEE Calculation http://www.oee.com/

Persson F and Olhager J (2002). Performance Simulation of Supply Chain Designs. *International Journal of Production Economics, Vol. 77, pp. 231 – 245*

Pundoor M, Herrmann R (2006). A hierarchical approach to supply chain simulation modelling using the Supply Chain Operations Reference model. *International Journal of Simulation and Process Modeling.* Vol.2, p.124-132.

Reiner G and Trcka M (2004). Customized supply chain design: problems and alternatives for a production company in the food industry. A simulation based analysis. *International Journal of Production Economics, Vol. 89, pp. 217 – 229*

Swaminathan J-M, Sadeh N-M and Smith S.F (1995). Information Exchange in Supply Chains. *Technical Report*. *CMU-RI-TR-95-36. Carnegie Mellon University, Pittsburgh, PA.*

Swaminathan J-M (1998). Modeling supply chain dynamics: A multi-agent approach. *Decision Sciences*. Vol.29

Terzi S and Cavalieri S (2004). Simulation in the supply chain context: a survey, *Computers in Industry,Vol. 53, pp. 3 – 16*

Towill D-R, Naim N-M and Wikner J (1992). Industrial Dynamics Simulation Models in the Design of Supply Chains. *International Journal of Physical Distribution and Logistics Management 22, pp.3-13*

Tzatestas S and Kapsiotis G (1994). Coordinated Control of Manufacturing Supply Chains Using Multi-level Techniques. *Computer Integrated Manufacturing Systems* 7(3), pp.206-212

Wyland B, Buxton K and Fuqua B (2000). Simulating the Supply Chain, *IEE Solutions, January, pp. 37 – 42*