# Q'@GILE SYSTEM: QUANTUM AGILE MANUFACTURING SYSTEM FOR ENGINE MACHINING

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***Abstract***. *We propose the Q'@gile manufacturing system concept for the machining activities of the prime parts of internal combustion engines. Q'@gile system is forged with scalability and agility which enables volume fluctuation of single parts and mixed production of engine part variants, without compromising financial investment constraints. The system encompass a replicated number of Q'@gile cells to implement a quanta of production capacity, each cell being able to manufacture a complete set of machining operations over a single engine part. A simulation model was built which compares Dedicated Transfer Lines against Q'@gile systems. Initial simulations have shown that an 8-cell system would achieve equivalent DTL performance. A systematic design of future scenarios for powertrain types and volumes requirements was also conducted. This shown greater profitability risks in the near future for traditional engine machining and assembly plants, especially for 3-cylinder and V6 engine plants which use DTLs in a climate of successive engine volume changes, rapid engine innovation and global competition. The Q'@gile system concept addresses such business constraints and evolves naturally to change in a non disruptive way.*

***Keywords***. *Automotive industry, engine machining, agile manufacturing, Q'@gile system.*

## 1. INTRODUCTION

Intensive competition and global R&D in automotive propulsion technology led to fuel efficient and low emission vehicles. This in turn has reduced engine in-production life-time. The high initial investment required for new engine machining facilities and the costly and time consuming systems engineering activities (required from the design stage to production ready) involved in adopting new facilities or retooling of existing facilities (that occur within the economic lifespan of engine production machines), constitute significant constraints on achieving efficient engine manufacture. Moreover, anticipated technological advances in vehicle propulsion arising from promising fuel cells and diesel and hybrid powertrains, can be expected to provide means by which car engine manufacturers can increase capture of market share. This means that an increasing pressure will be placed on engine manufacturing systems to accommodate unexpected change during their lifetime.

Automotive companies consider car engine manufacturing activities a core business. The companies have a set of engine plants which machine prime engine parts and make the final assembly of the engines. Nowadays, most engine manufacturers machine three main parts, namely: engine blocks, cylinder heads and crankshafts. The remaining components are outsourced. The three parts are typically machined using inflexible but in-production, efficient dedicated machines that were designed to carry out specific metal removing operations on a particular engine make and model. The system composition of this type of machinery, termed a Dedicated Transfer Line, lacks flexibility but has sufficient capability to accomplish the aims it was designed for, namely: high volume, single engine part production.

The automotive field is seeking rather different directions, in a move for greater agility to support product diversity. Car engine manufacturers are responding to such challenges by: 1) forming alliances with respect to engine R&D and high volume engine manufacture; 2) rationalising the design of particular engine families to enable the production of several engine variants with the same engine machining facilities; 3) adopting agile machinery with capabilities to enable rapid engine changeover or mixed engine type production.

## 2. OBJECTIVES

The objectives of this project are:

$O_1$ - Develop and propose a new engine machining approach which addresses limitations of industrial practice (in terms of both engine volume fluctuations and diversity of engine variants), and has potential to overcome those limitations in an economic way and thereby match current and emerging business need.

$O_2$ - Develop a simulation model which has analytic capabilities and user interface facilities that readily enable comparisons to be drawn between traditional engine machining approaches and the proposed engine machining approach.

## 3. REVIEW OF AGILE MANUFACTURING CONCEPT AND INDUSTRIAL PRACTICE

A couple of decades ago Yoram Koren [1] observed that the “the age of mass production is gone and the era of flexible production is being started” and characterized the concept of the “factory of the future”, in response to change in consumer preferences in modern society characterized by shorter product life cycles . Those characteristics included:

- Rapid introduction of new products
- Quick modifications to products with similar function
- Manufacturing of small quantities at competitive production costs
- Consistent quality control
- Ability to produce a variety of products
- Ability to produce a basic product with customer-requested special modification

Mikell Groover [2] confirmed Koren forecasts: “*shorter product life cycle*”, “*increased emphasis on quality and reliability*”, “*more customised products*” and “*greater use of Computer Integrated Manufacturing*”.

A report dated 1998 by Cox and Alm [3] stated that historical data buying patterns in USA, from the early 70s to late 90s, showed a growing in product variety within several industries. Markets have seemed closer and closer the customer’s individual taste, this also confirming Koren foresight. Customisation phenomenon however seem to have just started, being fuelled by advances in technology and human knowledge that enable the management of complexity that arises needing to design, build and manage manufacturing systems that can deliver the flexibility and production rates needed, at acceptable cost and quality. Modern technologies are shifting the business paradigm from producer-centred productivity to consumer-centred customisation.

According to Kidd [4] the concept of Agile Manufacturing is still emerging. The concept *Agility* is defined by François Vernadat [5] as: “the ability to closely align enterprise systems to changing business needs in order to achieve competitive advantage”. Agile systems combine efficient and responsive operations, Hoek [6], enabling high quality products to be manufactured in an efficient way, thus enabling competitive prices and being responsive to customers.

In the context of the automotive industry, and more specifically in the field of engine manufacturing the prevalent approach has been mass production, through the use of dedicated transfer Lines (DTL), modular transfer lines, flexible transfer lines and, more recently, *Agile systems*. These approaches show a growing level of flexibility in terms of engine variants and a higher level of responsiveness.

The major limitations of transfer lines approaches are essentially linked with:

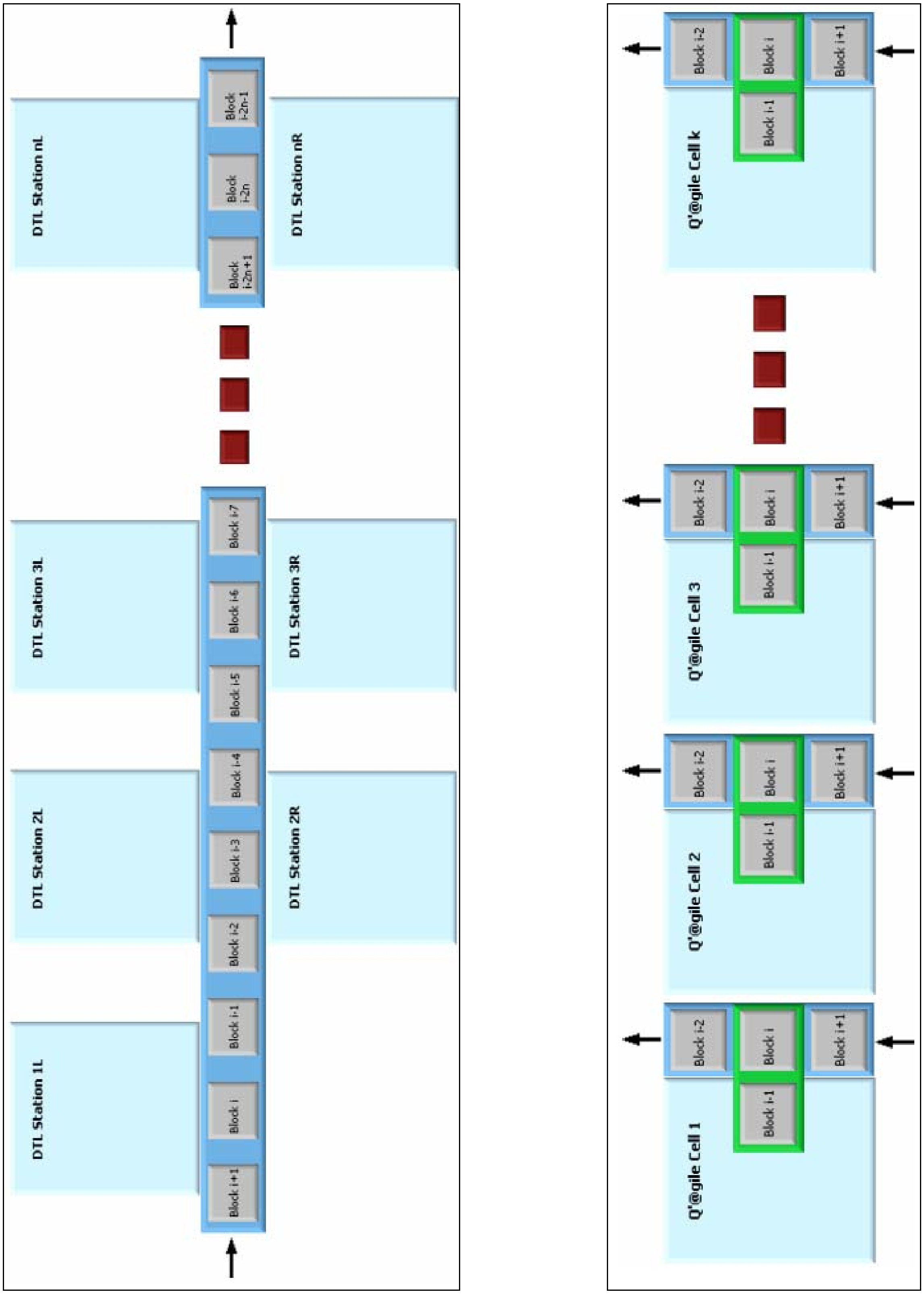
1) System dependability on single machines, e.g. a single machine breakdown requires a whole system halt;
2) Lack of system flexibility to readily adapt to new product variants in an economic way;
3) Production capacity is fixed.

These factors limit the economic applicability of such approaches to products which have a high volume and steady demand over time, along with few variant changes. However, at present, stringent emissions legislation, technological advances and global competition in the engine manufacturing arena are imposing lower and lower engine in-production lifespan, thereby reducing the probability of successful introduction of such systems.

Agile Systems were successfully introduced in the engine machining field recently. These systems are based in CNC machines grouped in cells. Each system has around 8 cells and each cell holds from 1 to 6 CNC machines (for economic reasons however, it is said that the system should have a minimum of 2 machines per cell). There is transport automation to link the cells and gantry robots inside each cell to place the engine part in the machine and to remove it from the machine. Inside each cell all the machines perform the same machining operations. Several replicated machines are needed on each cell so that the cell cycle time is kept at a low level. The system is considered by Price [7] to have higher uptimes than DTLs and that the higher initial investment required is offset by a lower global expenditure during the overall lifespan of the system.

## 4. Q’@GILE SYSTEM CONCEPT

The Q’@gile concept is a new approach to prime engine part production which has an inherent capability to address current problems of lack of engine manufacturing agility and an installed base of excess capacity. Q’@gile is designed to provide manufacturers with freedom to modify their production capacity, via systemic processes of plant instalment, dismantlement or reallocation, at a defined *Quantum* level. In theory the proposed solution promises improved agility in terms of being able to make fast and cost effective responses to market changes, that might for example arise from significant competitors initiatives (such as those arising from advances in the internal combustion engine and alternative vehicle propulsion technologies). Q’@gile can also reduce risks associated with large investments in engine production capacity, in two main aspects: a) smaller and phased investments are required to adjust a scalable capacity to market demand; b) by decreasing time based uncertainty factors through a major shortening of the look-ahead time period for plant capacity decision making. Figure 1 b) depicts a representation of an engine block Q’@gile system, where the number of cells can vary from 1 to K, therefore adjusting capacity to part demand. The production capacity can be adjusted from a minimum of 1 x Quantum to a maximum of K x Quantum parts. Q’@gile system is contrasted with DTL in Figure 1.



a) b)

**Figure 1.** Representation of engine blocks manufacturing systems: a) Dedicated transfer line with a fixed number of stations; b) ***Q'@gile*** system holding a variable number of cells.

### 4.1 Q'@gile cells

The central element of a Q'@gile cell is a high-speed general purpose CNC machining centre. Suitable transport automation, plus a working table with several servo driven axes, is required to complement use of this machining centre element. The minimum setup for production start, i.e. be able to produce cylinder heads or engine blocks, equates to a single Q'@gile cell per engine part. Thus a quantum level of production capacity that can be deployed when adopting the Q'@gile engine production approach is set by a single Q'@gile cell. Installing (or removing) capacity by a quanta is accomplished by installing (or removing) an integer number of Q'@gile cells. This approach contrasts markedly with the traditional DTL approach which requires a full engine production system to be installed prior to the start of any production run. In the case of Agile Systems the minimum set-up would be one machine per cell (this equates to 8 machines, under a 8-cell system), plus the full transport automation system and all gantry robots, for each prime engine part .

Thus any given Q'@gile system will comprise an integer number of replicated cells and it therefore follows that the process of system design, systems engineering and test will largely be linked with the activities in a single cell design, engineering and test. Since general purpose CNC machine technology is well established, in principle quantum changes to Q'@gile production capacity should be accomplished in significantly compressed time frames relative to the deployment of DTLs.

Hence this study proposes use of Q'@agile cells for engine block machining, where each cell should be composed of:

1. A high speed general purpose CNC machining centre with a minimum of 3 axes (XYZ), a tool magazine and an automatic tool changing device.
2. A working table device with several axes, which incorporates:
   2.1 a double pallet exchange device which rotates in steps of 180 degrees taking the engine part from a pre and post machining position to the machining area, and vice-versa; plus a W-axis which moves interchangeably to and from the machining position.
   2.2 a device with 2 axes holding the pallet which incorporates fixtures and a pallet clamping device. The B-Axis, which rotates the block, thereby enabling access to 4 faces (for an inline-type engine block) or 5 faces (for a V-type engine block), and the A-axis, which tilts at least 90 degrees enabling access to the remaining part face. As an alternative to this tilting movement (A-axis), tilt of the head of the CNC machine could be enabled (by up to at least 90 degrees), thereby providing a 4th axis of movement.
3. Transport automation (e.g. a gantry robot and a roller conveyor) with capabilities to take engine blocks to and from the cell and to deliver the blocks into pre and post machining position and to enable their removal following machining operations at that cell.

It is also proposed that a Q'@agile cell for cylinder heads machining be similar to a Q'@agile cell for engine block machining. However cylinder heads specifics may require a slightly different CNC machining centre, transport automation and working table multi-axis device. This is due to differences in the material type, physical dimensions and weight of the part, type of metal removing operations and machining positions that are needed in respect to cylinder head parts.

### 4.2 Q'@gile cells installation, removal and reallocation

Q'@gile cells should be: (1) added to an existing engine production facility (to increase the available production capacity by integer quantum steps), (2) removed from an existing production facility (to decrease capacity by quantum steps) or (3) transported and installed at some other engine plant around the globe so as to balance engine production more equitably with respect to geographical locations where parts are assembled into complete engines. The time period and engineering effort involved in installing or removing cells should be as small as possible. Here it is proposed that such operations should take a time period of up to 3 months maximum, where that time period extends from the time a decision is made to install or remove a cell to the time that the modified Q'@gile system can start producing. However, due to the nature of general purpose CNC machining centres, and the replicative nature of Q'@gile cells within production systems, it is envisaged that even shorter periods of time may be feasible. The infrastructure facilities needed, such as a power and coolant drainage system, should be carefully planned in order to allow the installation and removal of cells without significantly disrupting engine production or at least to minimise any disruptions.

In comparison to DTL production systems, Q'@gile systems will normally require lower initial capital expenditure prior to production start. In theory, capacity additions (and deletions) should be phased in as demand develops. In a typical manufacturing scenario where a primary engine manufacturer decides to produce the three main engine parts (block, heads and crankshafts) and subcontract the manufacture of the other engine parts, initial expenditure could typically be centred on three Q'@gile cells only: this being determined as being the theoretical minimum configuration to get engine production started. This minimum of three is set because one Q'@agile cell is required to machine each main part. This contrasts with three full DTL production lines, one for machining each main engine part. As an example, suppose that actual demand for a particular engine type over a 10 year period varies as shown in Table 1.

**Table 1.** Annual engine volumes demand over a 10 year period.

| Year | Annual demand (engines) |
|---|---|
| Year 1 | 70,000 |
| Year 2 | 153,000 |
| Year 3 | 140,000 |
| Year 4 | 145,000 |
| Year 5 | 237,000 |
| Year 6 | 255,000 |
| Year 7 | 210,000 |
| Year 8 | 235,000 |
| Year 9 | 150,000 |
| Year 10 | 145,000 |

Initial forecasting of demand predicted that around 440,000 engines per year would be required in the year 5th and 6th of production. Assume that following revised forecasts that indicate that initial predictions were too optimistic for that particular engine. In such a case, with conventional practice three DTLs would have been installed and production started as planned. In such a scenario the use of DTL production capacity would be fixed at a maximum of 440,000 engines per year and the "global" waste (in terms of installed capacity) would be slightly above 60% (an equivalent capacity waste of 266,000 engines per year) of the installed production capacity.

In a similar set of circumstances, consider the use of a Q'@gile system with a quantum capacity of 20,000 engines per year. To meet the actual demand it is observed that an initial installation of 4 cells (per main engine part) would be required to produce all needed main engine parts during the first year. Following which a further 4 cells would be needed in year 2, minus 1 cell in year 3, and so on, as depicted in Table 2. In such a case, the global waste of installed capacity would be less than 5% (an average capacity waste of 8,000 engines per year) as depicted by figure 2 b).

**Table 2.** Annual demand *vs* production capacity and number of cells to install or release yearly.

| Year | Annual demand (engines) | Annual Q'@gile system capacity (engines) | Number of Q'@gile cells | Install/release |
|---|---|---|---|---|
| Year 1 | 70,000 | 80,000 | 4 | 4 |
| Year 2 | 153,000 | 160,000 | 8 | 4 |
| Year 3 | 140,000 | 140,000 | 7 | -1 |
| Year 4 | 145,000 | 160,000 | 8 | 1 |
| Year 5 | 237,000 | 240,000 | 12 | 4 |
| Year 6 | 255,000 | 260,000 | 13 | 1 |
| Year 7 | 210,000 | 220,000 | 11 | -2 |
| Year 8 | 235,000 | 240,000 | 12 | 1 |
| Year 9 | 150,000 | 160,000 | 8 | -4 |
| Year 10 | 145,000 | 160,000 | 8 | 0 |

Both approaches are illustrated by Figure 2 a) and 2 b). The dark (blue) bars represent yearly engine demand. The light (white) bars represent yearly waste of production capacity. The combined bars (dark plus light bars) show the maximum engine parts production capacity.

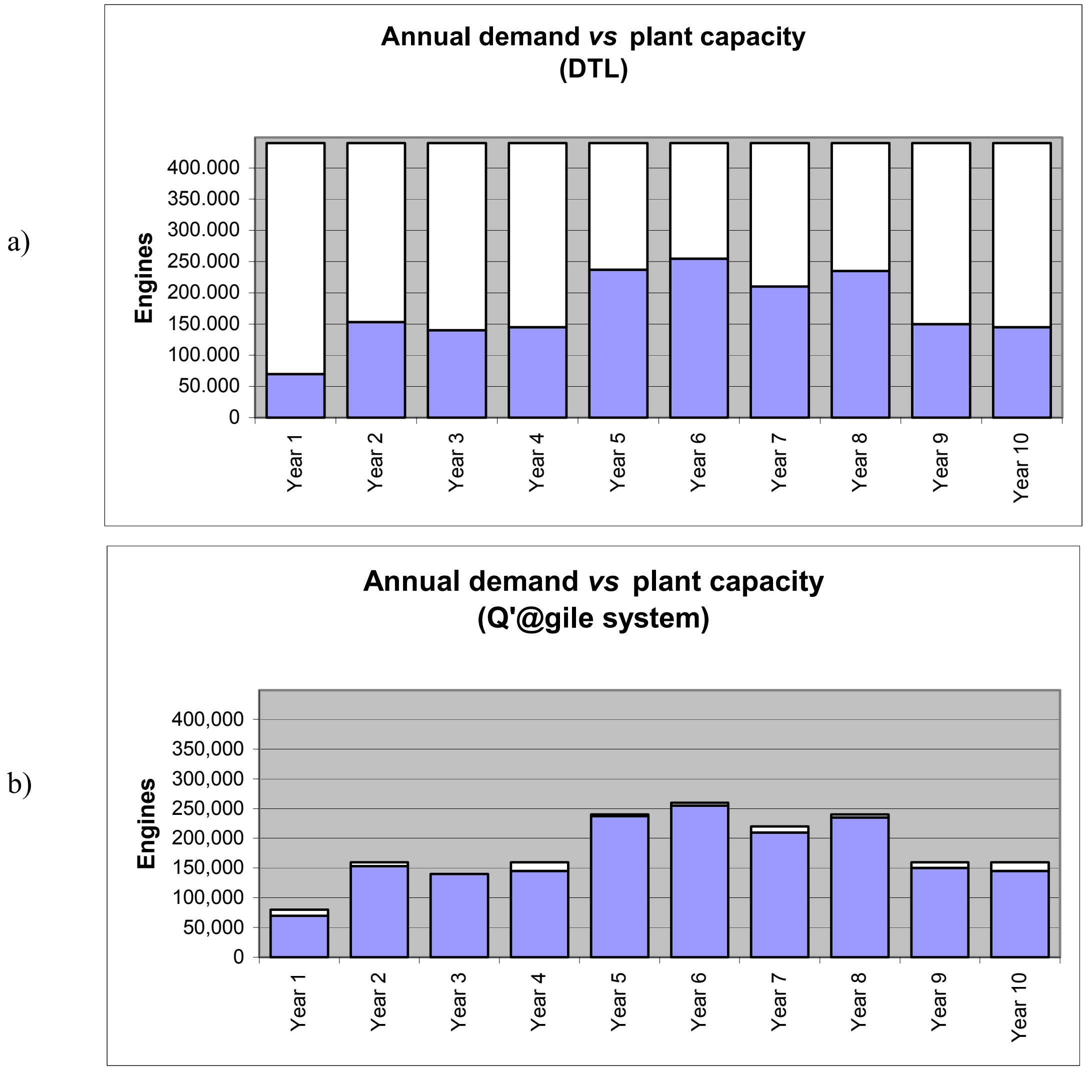


**Figure 2.** Graphical representation of annual demands and engine plant capacities over a 10 year period: a) DTL based engine plant; b) Q'@gile system.

The example scenarios discussed illustrates tremendous potential for Q’@gile systems, in terms of their relative utilisation of installed capacity. The given example is in fact based on a real engine plant, which currently uses transfer lines to machine three main engine parts. The specified capacity is real and the demand for the first three years is also real. The fourth year demand is a company forecast. Demands for the remaining years are author’s forecasts.

Regarding production volume, Q’@gile production systems can incrementally expand as market confidence increases and vehicle orders arise. A quantum in capacity is the integer increment enabled, or “volume grain”. In fact the production capacity is scalable in increments of 1/K of the full system capacity (where K is the maximum number of Q’@gile cells that can be incorporated into the system). In principle, new capacity can be added in increments of 1/K in very short periods of time, possibly without interrupting ongoing machining activities in the remaining production facilities. As discussed previously this inherent ability of Q’@gile systems improves their utilisation and match to market demand patterns. It also reduces production overcapacity and investment risks.

### 4.3 Advantages and limitations of the Q’@gile system

**Expected advantages**

- A scalable production capacity in incremental quanta.
- Progressive investment and lower overall capital expenditure during the lifespan of an engine plant. Protection of the investment by selecting reusable technology.
- Because “standard” Q’@gile cells can be replicated (based on well established CNC technology) system design, engineering, test and commissioning activities can be carried out in a relatively small fraction of the periods taken for traditional approaches.
- Improved overall system uptime and “immunity” to “process coupling” problems should be achieved.
- Q’@gile systems are expected to be highly flexible and responsive to engine part changes and new engine part introduction. Q’@gile systems should allow fully mixed production of engine part variants.
- Q’@gile cells can be relocated around the globe at other engine plants that either: (1) also use Q’@gile systems but require additional capacity; or (2) require an initial production capability for a new engine variant.

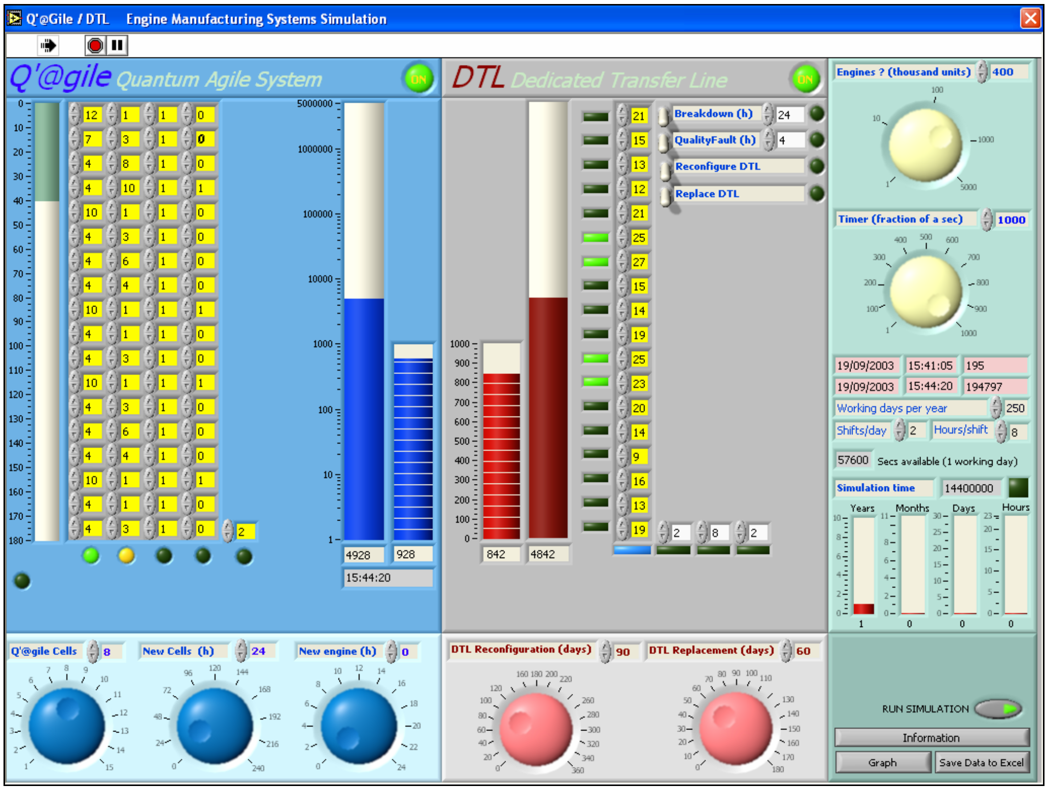
**Expected limitations**

- Higher cycle time;
- The type of technology is more complex
- Additional costs relating the replication of full set of tools and a multi-axis working table and pallet exchanger device per each cell.

## 5. Q’@GILE SYSTEM SIMULATION

A simulation model of engine parts machining has been developed to compare performance of traditional approach (DTL) to Q’@gile systems. This is needed in order to estimate the quantum level of a single cell and the number of Q’@gile cells required for a similar performance under different system behaviours, such as DTL individual stations breakdowns vs individual Q’@gile cells breakdowns; DTL reconfiguration and replacement (for new engine variants) vs Q’@gile cells introduction or removal and new engine variants introduction.

A significant part of the data used to run the simulation model has necessarily been estimated by the author. Particular estimation has been needed with respect to machining operation timings within hypothetical Q’@gile cells. Initial results using the estimated data (which assumes no machine breakdowns, no quality fault stops, no DTL reconfiguration and no DTL substitution) has shown that it would require around eight Q’@gile cells to achieve the same production capacity as that realised by a conventional DTL in machining a 4-cylinder engine block. The data used in the simulation model for a DTL engine block machining has a 39 second cycle time (which is a typical value for 4-cylinders engine block machining). This equates to a theoretical fixed plant capacity of around 347,000 engines per year (using the Harbour Report productivity index which assumes working for 16 hours per day and 235 days per year). In contrast the quantum value for a Q'@gile system was found to be approximately 43,400 engines per year. Hence the adoption of a Q'@gile system would enable the progressive installation of production capacity at quantum steps of 43,400 engines per year, for example as an engine market evolves.



Engines ? (thousand units) 400

Timer (fraction of a sec) 1000

19/09/2003 15:41:05 195

19/09/2003 15:44:20 194797

Working days per year 250

Shifts/day 2

Hours/shift 8

57600 Secs available (1 working day)

Simulation time 14400000

Breakdown (h) 24

QualityFault (h) 4

Q'@gile Cells 8

New Cells (h) 24

New engine (h) 0

DTL Reconfiguration (days) 90

DTL Replacement (days) 60

**Figure 3.** Simulation model under execution: DTL *vs* Q'@gile system with eight cells.

The results would however be quite different if the simulation had taken into account DTL and Q'@gile halt events. Reference uptimes values for DTL (60% to 75%) and Agile Systems (80% to 90%) provided by Price [7] will be used in subsequent model executions. Model execution has already been conducted and a more systematic set of experiments is planned.

The simulation model was developed at Loughborough University using Labview. This tool was chosen given previous work with such tool, along with the easy of construction of friendly HMI.

A systematic design of powertrain types and volumes hypothetical scenarios was also conducted. These scenarios are set between meaningful extremes, which are supported by a mix of information and forecasts extracted from recent studies on a multitude of issues which are directly or indirectly related to the automotive industry, namely: global energy demand, oil resources, fuel prices, vehicle emissions legislation, propulsion technology, sustainable mobility.

A set of 36 future alternative scenarios for powertrain types share is made. The scenario construction assumes four powertrain types in the market during the forecast period: Petrol Engines, Diesel engines, Hybrid engines and Fuel Cells. Major technological breakthroughs and market ready of other powertrain technologies are not subjected to consideration under the forecast period. Each future scenario applies for a period of 15 years (starting in 2005) subdivided in three periods of five years each. The scenarios enable an analysis of the degree of adequacy of DTL vs Q'@gile under I3, I4, V6 share of both diesel and petrol engines.

The concepts, methods and tools can be used by particular automotive companies and engine machinery systems vendors to simulate their particular business (by using their own data) and therefore take rationalised decisions over optimized engine manufacturing approaches.

## 6. RESULTS

The initial model execution has shown that at 100% uptime (for both DTL and Q'@gile), Q'@gile system would require 8 cells to achieve an equivalent DTL manufacturing performance (for an I4 engine). However, in terms of uptimes, it is expected that Q'@gile systems operate in the region of 80% to 95%, while DTLs have uptimes in the order of 60% to 75%, therefore it is expected that even a smaller number of cells is required for an equivalent DTL performance.

Depending on the evolution of demand along each scenario, using DTLs to machine all the engine variants (petrol, diesel, I3, I4 and V6 engines) in different machining facilities is unlikely to be an economic solution over the major scenarios. The same reasoning is not applied to Q'@gile system since it enables fractions of DTL capacity to be installed, and production of a mix of engine parts. DTLs can be used more effectively in I4 engines in both petrol and diesel versions, since these engines have a much higher volume demand than the remaining configurations.

In general, the higher the changes (in terms of volumes and engine variants), the higher the probability of a better investment in a Q'@gile system in contrast to DTL systems.

## 7. CONCLUSIONS

A new manufacturing approach has been proposed in the engine machining field. The system allows capacity to grow or dim as demand evolves. The system compares favourably with DTL systems under volume and engine variant changes. A simulation model has been developed to compare the performance of both DTLs and Q'@gile systems. A 36-future alternative scenarios for powertrain share has been developed based on several relevant automotive issues.

An investment model is required to enable grounded final conclusions to be taken, given the model execution under a systematic set of parameters and alternative powertrain scenarios.

## 8. AKNOWLEDGEMENTS

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