1 Introduction

Technology is fast becoming one of the main drivers of change in business. While some bring about incremental improvements, others are disruptive and change the rules of the game.

One such technology that has generated large interest from especially the discrete manufacturing industry is that of holonic systems. Formulated in 1967 by Hungarian philosopher Koestler (1968) the holonic system, consisting of numerous networked holons, imitates social and biological organisms in its ability to synergistically combine both autonomous and cooperative behaviour in efficiently pursuing dynamic system goals. As such it exhibits unprecedented levels of agility, flexibility and responsiveness - all as an innate and pervasive capability.

Sectors within the discrete manufacturing industry currently face business drivers of increasing complexity and continual change under decreasing cost. This is manifested in reduced product life cycles, reduced time to market, volatile product volumes and variant mix, abundance of product features and reduced investment while remaining robust in operation.

These business drivers call for an unparalleled level of agility as the discrete manufacturing industry pursue one of its holy grails: mass customisation. Holonic systems are therefore an obvious and natural area of interest for this industry and indeed accounts for the brunt of research in this area.

The question of the applicability of these systems to the chemical processing industry has been raised but a very limited amount of research has been conducted in this area (Chokshi and MacFarlane, 2002)

Additionally, current research focuses on narrowly defined sectors within the chemical processing industry that overtly face the same business drivers as the discrete manufacturing industry (for example campaign processes). It makes no mention of its general applicability to the basic chemicals sector which faces quite a different set of business drivers.

It is, therefore, the intention of this study to frame the opportunity by assessing the applicability of holonic control systems to the basic chemicals sector, and specifically a commodity petrochemical producer by systematically addressing the following research questions:

1. Are holonic systems only useful in improving process agility or does it represent a predictable evolutionary response to the current dilemmas and the pursuit of ideality in the automation domain?
2. What are the strategic drivers and their associated profit drivers and manufacturing requirements in the petrochemical industry?
3. In what way do holonic control systems enable pursuit of these manufacturing requirements?

In systematically addressing these questions, this study commences with a literature survey that explores the concept of the holonic system. Due to pertinent similarities and an intensely researched nature, the areas of modularity and intelligent agency are included. The literature study then focuses its application in the discrete manufacturing environment with respect to business rationales, architectures and design principles.

Following on this the make-up of the chemical processing industry is studied with respect to the different sectors that exist, their business drivers and anticipated improvement in traditional automation technology. Further, a generic commodity petrochemical producer is also selected as the basis for this investigation.

In order to construct a robust assessment framework the literature study then explored the link between strategy and technology and identified technology roadmaps as a suitable assessment framework.

A detailed analysis aimed at answering the identified research questions is then conducted. Firstly, the theory of inventive problem solving is employed to show that holonic systems are a higher order concept that conceptually solves a number of topical automation requirement contradictions (for example efficiency versus agility) - a key point to establish before even considering its application to the basic chemical sector.

Secondly, its suitability to a commodity petrochemical producer is analysed. Using the formulated technology roadmapping tool the manufacturer is positioned in terms of both its current and foreseen future strategy and associated profit drivers which is then cascaded down to frame the desired operational and then automation requirements.

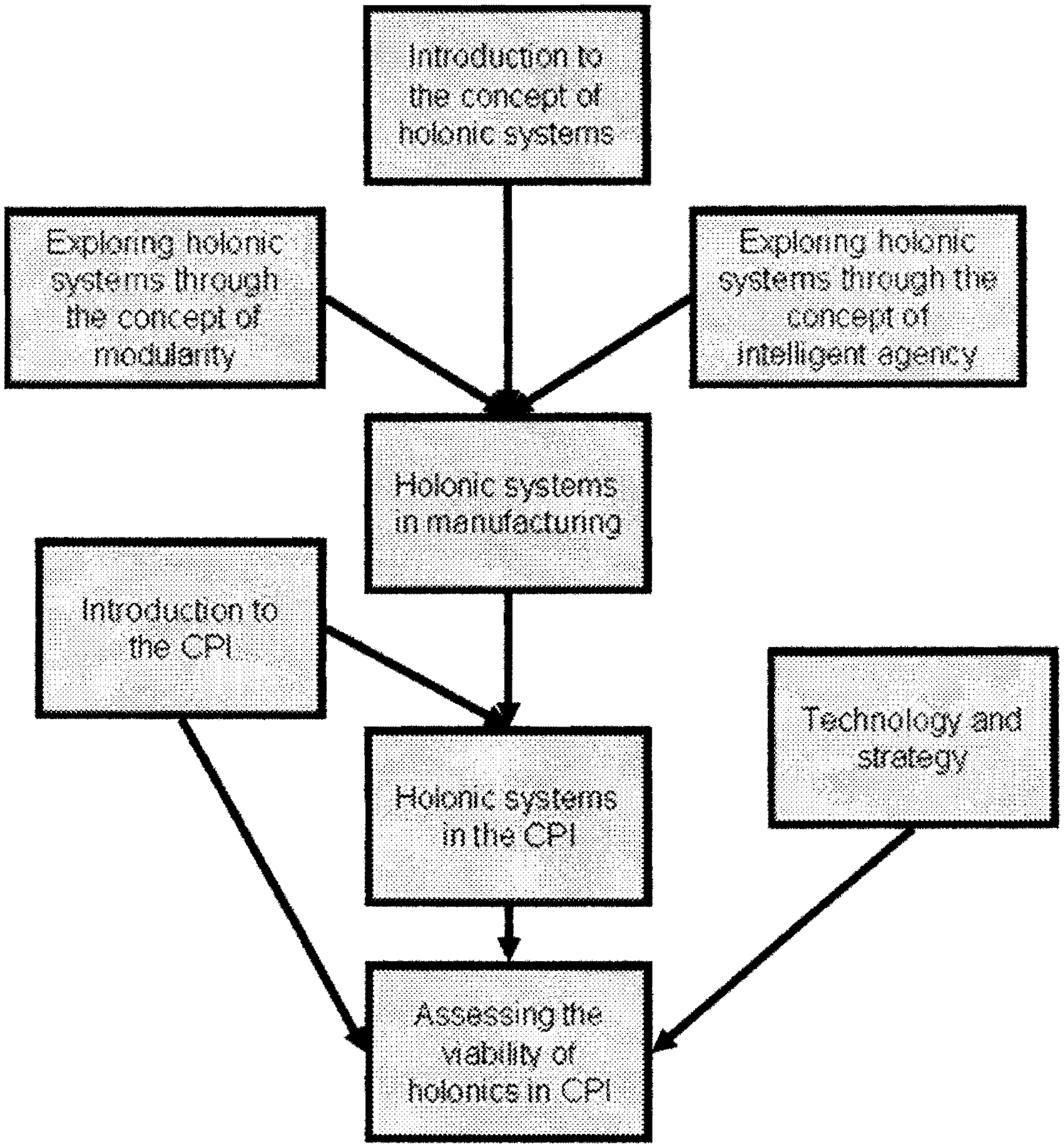
Finally the ability of holonic systems to fulfill these automation requirements are explored and compared to that of current and foreseen future traditional automation capabilities.

These high level automation requirements can potentially be used as focal points for more functional detailed analysis of the application of holonic system to the chemical processing industry.

This work represents a pathfinder project in the relevant research area which implies the integration of a large number of bodies of knowledge (width). The depth of the study was therefore purposely limited to addressing the topic conceptually (i.e. “what?”) rather than also functional-detailed (i.e. “how?”). The study could be utilised as a basis for future functional-detailed exploration.

The flow of the argument in this work is depicted in figure 0.

Figure 0 ***Depiction of the flow of the argument in this work***



2 Literature

2.1 The concept of the holon and the holonic system

2.1.1 Winning trait in the new era: mastering complexity and change with decreasing costs

A rapid increase in production and product complexity seems to be an unavoidable consequence of technological progression. In 1970, of the thirty most valuable product exports of the United States, only 38% were classified as complex products made through complex means. This figure had risen to 56% in 1995 when, additionally, only eleven of the 1970 products were still in the top thirty (Ryman and Cash, 1999). Futurists expect this trend towards ever-increasing complexity to continue unabatedly for the foreseeable future.

The rationale for embracing increased complexity lies in its providing limitless opportunities. This offers freedom from the constraint of scarce resources, one of the ground rules of the mass production era. The price exacted for these benefits is that complexity confounds traditional analytical thinking in the following ways:

- cause and effect relationships are nonlinear, difficult to identify and when identified seldom remain stable over time
- complex systems have highly unique features.

Futurists predict that, in exploiting these opportunities, technology will become the most significant driver for change (Bushko and Raynor, 1997). Opposing this technology-push mechanism is a strong current trend towards market-pull, fuelled by the growing surplus of industrial capacity (Bussmann and McFarlane, 1999). This leads to customers being more demanding and expecting constant product innovations and low cost customisation. Whichever of these opposing mechanisms is dominant at a particular time, increased rates of process and product changes will result.

Simultaneously dealing with complexity and change has stimulated the concurrent development of several similar (but not identical) streams of thought on production processes and product technology. These range from familiar concepts such as object-orientedness and intelligent agents to the lesser-known concept of holonic systems. Essentially, these concepts are employed to pursue the same goal: improving the ability of a complex system to thrive under conditions of uncertainty.

Object-orientedness focuses on the elimination of arbitrary system complexity. This facilitates system changes and hides the complexity from the external observer. Intelligent agency focuses on autonomous information processing. Its aim is the creation of autonomous agents that pursue a common goal in a heterarchical society of agents. Holonic systems, seen by some commentators as a unifying theory (Mathews, 1996), incorporates principles from both these fields as well as adding the unique characteristic of flexible hierarchies. In rapidly developing an understanding of holonic systems, pertinent aspects of these three fields of study will now be discussed

2.1.2 Background to holons and holonic systems

Although they may seem like similar strands of thought adapted to different applications, students of the field believe that holonic theory forms the foundation of a wide class of systems (Mathews, 1996; Ramos and Sousa, s.a.). These include object oriented and intelligent agent systems which are seen as constrained applications of holonic principles.

Object orientation is a hierarchical approach focusing on the organisation of complex systems. Its basic unit is the module (or object). Intelligent agency is a heterarchical approach to creating a robust and adaptable information processing system. Its basic units are agents.

The concepts of the holon and the holonic system was constructed by the Hungarian philosopher Arthur Koestler in 1967 in order to explain the evolution of living organisms and social organisations.

The word *holon* is constructed from the Greek word *holos*, meaning whole, and the suffix *–on*, meaning part of.

Koestler observed that entirely self-supporting, non-interacting entities do not exist and therefore wholeness and partness cannot be ascribed to any system in absolute terms. All systems are intermediate structures in a hierarchy classified by orders of complexity. A system therefore concurrently exhibits characteristics common to wholes and characteristics common to parts. Its partness is manifested by its co-operation with other parts in the achievement of some high level goal, while its wholeness is manifested in its pursuing of its own sub-goals in an autonomous manner (Winkler and Mey, 1994).

In 1969, Herbert Simon extended the implication of Koestler's work by observing that complex systems will evolve from simple systems more rapidly if they are constructed from stable intermediates than if they are not.

An example of this is that the formation of a complex molecule through synthesis from simple reactant molecules is much more likely if the reactant molecules form stable intermediates first.

In this sense, a whole / part intermediate is referred to as a *holon*, the basic building block of a holonic system. Holons are assimilated into flexible hierarchies, termed *holarchies*. A holon is therefore not locked into a rigid hierarchy, but may simultaneously belong to several holarchies and may join or separate from holarchies as the need arises. Holarchies are formed in response to setting a global objective. A change in this objective, or disturbance threatening the realisation of this objective provokes a commensurate change in the holarchy.

The level of system flexibility afforded by this characteristic was recognised for its commercial potential, particularly by researchers in the field of manufacturing. As a consequence, the lore of holonic systems has mostly been cast in the vernacular and along the concerns of the manufacturing environment.

Issues that are of contemporary research interest and that would assist in the development of a vision for the utilisation of holonic systems in chemical processing is discussed in paragraph 2.2.1. These include the architectural composition of holonic systems, holon behaviour, as well as the design of holonic systems. Past, current and expected future research focuses in holonic systems are given in Figure A3 in the appendix.

Table 1 compares the key characteristics of holonic theory, intelligent agency and object-orientation.

Table 1 ***A comparison of critical aspects of object-orientation, intelligent agency and holonic systems***

Aspect	Object-orientation	Intelligent agency	Holonic systems
Basic unit	Object	Agent	Holon
Structure of relationship between basic units	Hierarchy with autonomy enforced by encapsulation	Heterarchy with cooperation ensured through algorithms	Holarchies, based on concurrently autonomonous and cooperative basic units, which arrange themselves in flexible hierarchies in response to the system objectives
Focus	The elimination of arbitrary complexity	Robust and autonomous information processing	Reconfigurability
Relative number of commercial applications	Abundant applications in computer programming	Some applications in computer programming and robotics	Few applications in manufacturing environment

2.1.3 Exploring holonic systems through the concept of modularity

"Many students of the art hold out more hope for object-oriented programming than for any of the other technical fads of the day" (Brooks, 1987)

2.1.3.1 Definition

For purposes of this discussion, the constructs of modularity and object-orientation are used interchangeably.

Modularity is an approach aimed at the efficient organisation of complex systems, such as products and processes. Modular systems are organic, consisting of a number of highly individualistic nested modules coherently pursuing a set of system objectives.

Object-orientation is based on three concepts:

- encapsulation and data hiding
- abstract data types
- polymorphism

These concepts are briefly discussed below.

2.1.3.2 Encapsulation and data hiding

Modularisation is achieved by segregating information into *visible* design rules and *hidden* design parameters (Baldwin, 1997)

The visible design rules specify three attributes of the modular system:

- an architecture, that specifies what modules the system consists of, together with the role of each module
- interfaces, that specify the way in which modules interact with its environment
- standards, that specify the criteria for assessing the performance of a module against design rules

Visible information is universally accessible.

The hidden design parameters are encapsulated into a module. These parameters are hidden from observers external to the specific module. It can therefore not be referenced externally. Consequently, these parameters do not affect the system design beyond the local module.

By hiding the state and behavioural procedures from an external observer, the principle of encapsulation ensures that individual modules are inherently autonomous. However, this autonomy is not absolute since modules are obliged to cooperate with other modules as well as the main routine according to the norms embodied in its innate features (Mathews, 1996).

2.1.3.3 Abstract data types and polymorphism

Abstract data types (ADTs) are user-defined modules (Henderson-Sellers, 1992). The definition covers all aspects of visible information, such as functionality, interfacing and standards. As such, it provides an abstract way of collectively referring to data and functionality encapsulated to form a module.

This approach enables classification and taxonomical differentiation becomes possible. Consequently, classes of objects are identified based on their exhibiting similar traits.

Classification enables the emergence of polymorphism. This principle relates objects of several different classes through some common base class. Polymorphism enables distributed control.

2.1.3.4 Module interactions

Three types of interactions are typically recognised (Henderson-Sellers, 1992). They are:

- aggregation, which is the so-called has_a or consists_of relationship in which one module consists of a collection of submodules (eg. vehicle has_a (wheels, doors,...))
- association, which denotes the direct use of one object by another
- specialisation (also referred to as inheritance), implies a taxonomical hierarchy and denotes an is_a relationship (eg. vehicle is_a sedan)

These relationships imply hierarchical interactions.

2.1.3.5 Rationales for modularity

“A solution to growing complexity...” (Baldwin, 1997)

System complexity is classified as either essential or arbitrary. The former refers to the complexity innate to the system. It is therefore unavoidable. This is the type of complexity dealt with in physics in the pursuit of discovering sets of unifying principles. Einstein argued in favour of the existence of these principles since “God is not capricious or arbitrary”.

On the other hand, accidental complexity is the result of mismatches in paradigms, methodologies and tools used to design the system when applied by the various system designers (Riel, 1996). Encapsulation and data hiding is aimed directly at reducing the extent of arbitrary complexity.

In addition to reducing the level of arbitrary complexity, encapsulation also provides the significant benefit of matching the level of complexity that is revealed to the information requirements of the external observer. Although the modules may be complex themselves, the organisational structure is simple. This aspect allows simplified operation of an innately complex system.

“Logically and physically separating the functional units makes it easier it easier to alter one [module] without affecting the rest of the system” (Milner and McFarlane, 1998)

Modularity significantly facilitates change. Its major advantage is in allowing changing the implementation without affecting the interface. The repercussions of module changes are therefore localised. This attribute simplifies reconfiguration.

Moreover, systems designed consonant with object oriented principles are endowed with a unique ability for allowing effortless change. The essential reason being that object orientation forces a bottom-up design approach.

Conversely to the bottom-up approach, the top-down design approach starts off by specifying a unique system goal. Progressive design steps are then directed at providing an increasingly detailed description of a system geared towards pursuing this unique goal in the most efficient manner. These system attributes act as significant barriers to change, locking the system into its pursuit of the initial goal.

In contrast to this, object oriented design is initiated by specifying the system architecture (which modules to use). The architecture is geared towards fulfilling a general responsibility rather than a specific function. This forces the designer to explicitly design the module in a vaguely defined situation. The resulting system is therefore uniquely flexible and responsive. (Van Brussel et al., 1999)

2.1.4 Exploring the holonic system through the concept of intelligent agents

"The difference between an object and an agent is that an agent is more active." Van Brussel et al. (1999)

2.1.4.1 Definition of the concept of agency

Wooldridge and Jennings (1994) defined artificial intelligence as the specialised field within computer science which aims to construct agents that display characteristics of intelligent behaviour.

Having been developed for numerous applications, definitions of agents proliferate. Based on a literature survey, Franklin and Graesser (1996) proposed the following consolidated definition:

"An autonomous agent is a system situated within and part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to affect what it senses in the future."

Agents are implemented as either hardware or, as is more often the case, software-based computer systems.

Agents have distinctive characteristics. Grouping of these characteristics into classes of behaviour further illuminates the concept of an agent. These classes are given in table 2 (Franklin et al., 1996; Wooldridge et al., 1994; Huang et al.1994).

Table 2 Definitive characteristics of intelligent agents

Characteristic	Aliases	Meaning
Autonomous		the ability to exercise control over its own actions
Cooperative	Communicative, social ability, coherence	the ability to interact with other agents
Reactive	sensing and acting	the ability to perceive their environment and to respond to changes in its environment in a timely manner
pro-active	goal-oriented, agile	the ability to take initiative through goal-directed behaviour
Adaptive	learning	the ability to infer and implement changes in its behaviour based on experience
Selective		the ability to select stimuli from a noisy spectrum which deserves attention
Flexible		Actions are not scripted
Robustness		the ability to maintain performance given imperfections and limitations of various kinds, e.g. inaccurate sensors, incorrect models

Depending on their application, different characteristics (see table 2) are emphasised in different agents. Autonomy and cooperation are characteristics strongly accentuated in holonic systems and warrant further investigation.

2.1.4.2 Autonomy and co-operation

An agent is deemed autonomous if it has the ability to exercise control over its own actions. As such, autonomy is perhaps the most highly emphasised characteristic of agents in general. This is not surprising since multiagent computer systems are inherently heterarchical.

Heterarchical systems ban all forms of hierarchy. Every agent has full authority over its own actions. Heterarchical systems are extremely agile, being able to respond to a wide range of disturbances as well as proactively influencing its environment to further its own agenda.

However, when there is no explicit form of overall control, purely heterarchical systems are unpredictable and may become unstable (Van Brussel et al., 1999). In addition, purely heterarchical systems are difficult to optimise globally.

In alleviating some of these difficulties, many agents have been endowed with the ability to co-operate with other agents. Computer system agents are seen as being co-operative when it interacts with other agents. The level of interaction ranges from local cooperation to global coherence.

The so-called *contract net* is a popular cooperation algorithm. This algorithm is based on interagent negotiation. The negotiation mechanism consists of a negotiation protocol and negotiation strategy. The aim of the mechanism is to decompose a global problem into local problems while promoting interaction and coherently integrating local solutions (Heikkilä et al., 1996).

In terms of this algorithm, the different roles that a particular agent could fulfill are one or more of the following:

- proposer, which proposes a specific activity
- planner, which plans a specific activity
- requester, which broadcasts requests for activities
- executor, which structures event execution
- monitor, compares the current system state to the ideal state and flags constraint violations
- controller, which handles events internally

The following data structures and messages are used:

- functional model
- resource model
- object model
- requests
- proposals
- contracts
- orders
- plans
- signals

2.1.4.3 Agent architectures

Different approaches have been adopted in constructing a computer system that exhibits these characteristics. The classical approach is aimed at developing so-called *deliberative agents* which make logical decisions based on pattern recognition and symbolic manipulation. The agent utilises an explicitly represented, symbolic world model. Although seeming attractive from a theoretical point of view, this approach has proved extremely challenging to implement.

An alternative approach embraces a completely different paradigm by rejecting the use of a central world model as well as any form of symbolic reasoning. These *reactive agents* obtain knowledge of the world through direct perception, rather than by memory or reasoning. Although easier to implement practically, these agents are still limited in the range of tasks that can be performed.

In response to these two extremes, a hybrid approach, aimed at creating multilayer agents, was formulated. The modelling layer provides a model for the agent's environment and tasks. The reactive layer responds to routine tasks or tasks not previously planned or modelled. The deliberative layer is employed to manage tasks requiring higher reasoning. A control layer resolves interlayer conflicts.

Examples of multilayer agents are shown in figures 1 and 2.

Figure 1 ***Diagrammatic representation of a multilayered agent based on the TouringMachine architecture.***

Source: Ferguson (1994)

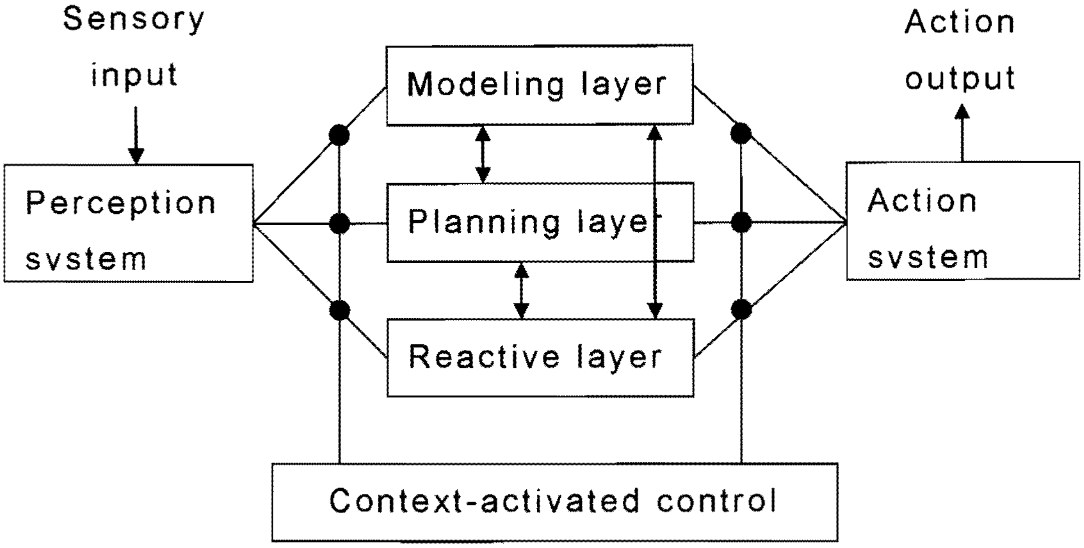
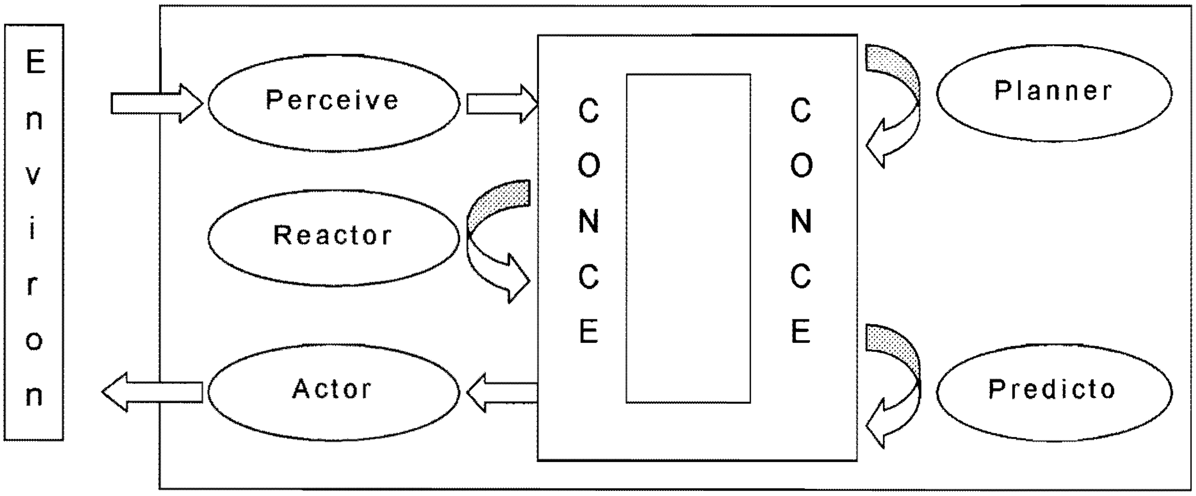


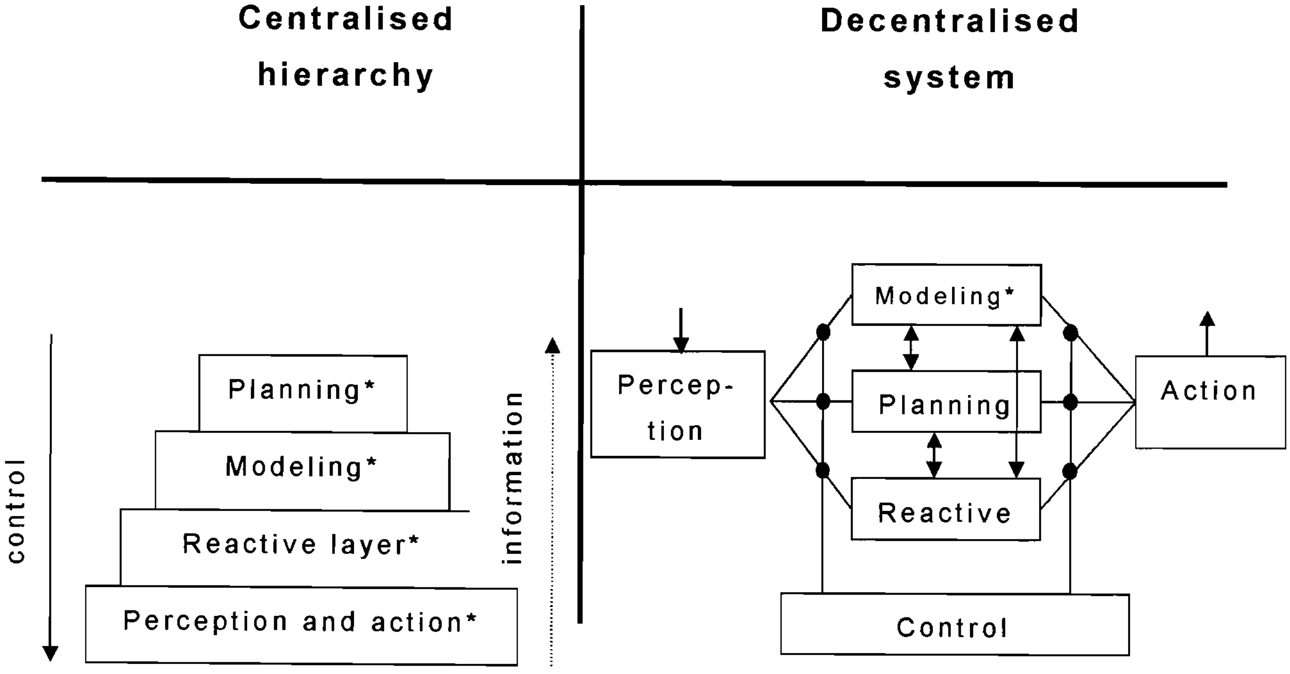
Figure 2 ***Diagrammatic representation of a multilayered agent based on the WILL architecture***

Source: Moffat and Frijda (1994)



These layers represent different levels of knowledge abstraction. It is important to note that the layers are not related through a functional hierarchy, nor do layers carry representations of the total system. Hence the different levels of knowledge abstraction are localised and encapsulated within the same local entity. Multiagent systems are therefore truly decentralised. To highlight the differences, figure 3 portrays a centralised hierarchical representation of the TouringMachine architecture.

Figure 3 ***A comparison between a decentralised and centralised organisation of the TouringMachine agent.***



* Layers are system wide

* Layers are localised

2.2 Holonic manufacturing

2.2.1 Focus areas

2.2.1.1 Architecture

Although having been extensively discussed in literature, no standard architecture has yet been developed for holonic systems. However, Van Brussel et al. (1999) have developed a highly referenced generic approach at specifying the holonic architecture.

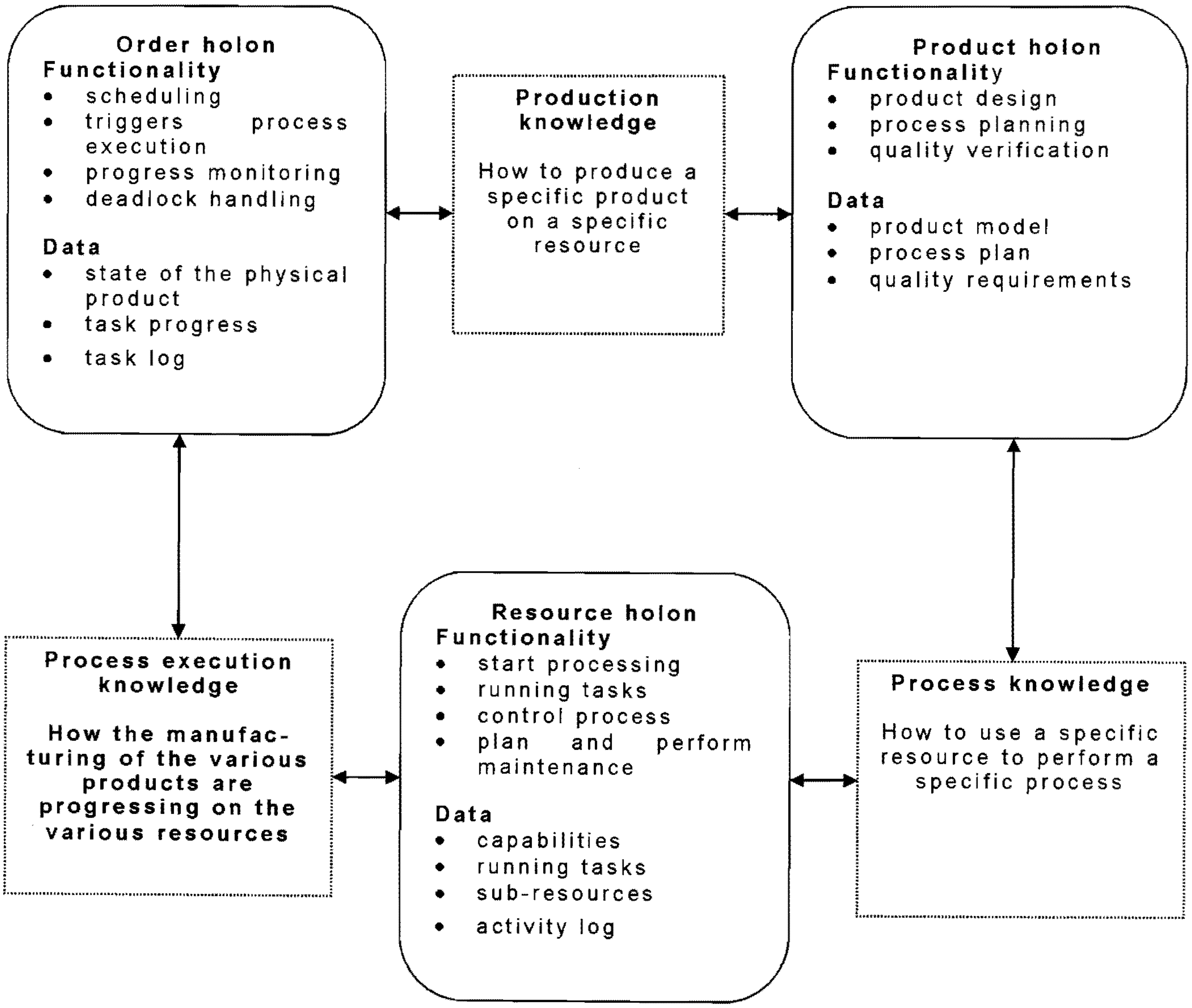
This approach draws strongly on the principles of object orientedness in specifying encapsulated objects (basic holons) that are composed of data and functionality. Three basic holon types are defined:

- *order holon*, which represents a manufacturing task and is responsible for its correct and timely execution
- *product holon*, which contains the knowledge of the product and the methods required to produce it
- *resource holon*, which represents a physical resource that extends functionality to the other holons

The exchange of information between a particular pair of holons captures a specific type of knowledge on the manufacturing system. These, together with the data and functionality encapsulated in the basic holons are given in Figure 4.

Figure 4 ***Diagrammatical representation of the data and functionality encapsulated in the basic holons together with the manufacturing system knowledge arising from their communication***

Source: Van Brussel et al. (1999)



In theory, manufacturing systems could be constructed from these basic holons only. However, the level of intelligence required of the basic holon when functioning completely unsupervised, is prohibitive. Additionally, state of the art distributed optimisation techniques cannot guarantee the same performance as traditional centralised approaches (Van Brussel et al., 1999). Until these issues can be resolved satisfactorily, Van Brussel et al. (1999) suggested the introduction of a *staff holon* which functions at a supervisory level. Its purpose is the provision of information to the basic holon which enables the basic holon to make correct decisions.

The interaction between the different holons gives rise to the existence of holarchies. These flexible hierarchical relationships are based on the principles of aggregation and specialisation as attributed to object oriented systems (see section 2.1.3.4). The holarchies required to form a holonic manufacturing system are given in table 3.

Table 3 *The holarchies required to form a manufacturing system*

Holarchy	Type of basic holons
Order aggregation holarchy Order specialisation holarchy	Order holons
Product aggregation holarchy Product specialisation holarchy	Product holons
Resource aggregation holarchy Resource specialisation holarchy	Resource holons
Resource allocation holarchy	Resource and order holons
Process planning and execution holarchy	Staff holons, resource holons, product holons

In the style of object orientation, the approach described above treats the holon as a black box that conforms to a set of specifications. The internal structure and behaviour of the holon is dealt with using concepts from intelligent agency.

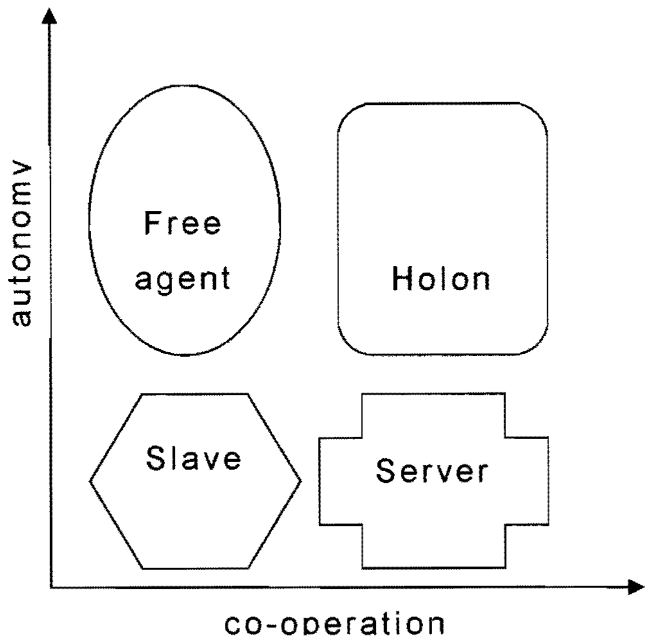
2.2.1.2 Behaviour: autonomy and cooperation

Whereas the architectural design of holonic systems is based on the principles of object orientation, the internal design of holons is based on the principles of intelligent agency. According to Bussmann (1998), these principles are encapsulated in:

- algorithms pertaining to the physical behaviour of the holon
- decision rules that determine holon behaviour
- communication and cooperation techniques that facilitate appropriate levels of cooperation
- organisation techniques that assess and implement organisational alternatives
- decision rules that allow the holon to cooperate with other holons

As they are directly related to the basic observations on which holonic theory is based, the holon attributes of autonomy and cooperation are strongly emphasised. In fact, its ability to display these two opposing behavioural traits is definitive, as portrayed in figure 5.

Figure 5 ***Combinations of autonomous and cooperative behaviour***



In holonic literature, autonomy is seen as the capability of an entity to control the execution of its own plans and strategies (Van Leeuwen and Norrie, 1997). Some practical interpretations of autonomous behaviour are:

- distributed control
- local decision making
- local task execution
- local monitoring and detection
- autodiagnosis functionality
- autorepair functionality
- dynamic strategies

Cooperation is defined as the process whereby a set of separate entities develop mutually acceptable plans which are then executed (Van Leeuwen and Norrie, 1997). Practically, this is interpreted as:

- a communication mechanism to achieve coherent decisions
- globally optimised performance
- consistent and stable control

The contract net protocol, as described in section 2.1.4.2 is often used to attain cooperation.

This behaviour is enabled by internal holon structures analogous to those ascribed to the agents that were discussed in section 2.1.4.3

2.2.1.3 Holonic system design

A top-down design approach results in systems that are developed for peak performance in a specific context. These design solutions are typically very fragile and do not survive disturbances (Bongaerts et al., 1995)

Conversely, holonic systems design is a strictly bottom-up process. Van Brussel et al. (1999) have suggested the following design methodology:

1. *Identification of the manufacturing holons*

   During this phase all manufacturing holons are identified according to the classification given in figure 4. These holons are assigned a general responsibility, rather than a precise function. This ensures that the holon, having been designed to perform in a vaguely defined situation, is reusable.

2. *Detailed design and implementation of the manufacturing holons*

   Detailed holon design should support reusability of the holon in many different holarchic structures.

3. *Installation and configuration of the manufacturing holons*

   The developed holons are installed. A fully holonic system should be self-configuring.

4. *Operation of the manufacturing systems*

   The design process culminates in the operation of the manufacturing system.

2.2.2 Holonic systems in manufacturing

2.2.2.1 Business rationales

The effectiveness of a manufacturing system is measured by its ability to continuously support business goals that change over time.

The nature of these business goals is strongly dependent on the specific locus of a company in the total supply chain between the extremes of basic raw material input and final product output. The manufacturing industry is typically located between primary / secondary processing and retailers. This proximity to the market place is characterised by the heterogeneity of products and competitive strategies that focus on product differentiation at cost parity.

In this manner, Bussmann et al. (1999) have assessed the suitability of holonic control in manufacturing by comparing it to generic control system requirements that satisfy current and anticipated future manufacturing business drivers. The discussion below summarises their findings.

Bussmann et al. (1999), Heikkila (1996), McFarlane (1995) and Van Brussel et al (1999) point out the following current and foreseen future drivers in the manufacturing industry:

- reduced product life cycles leading to faster changing products,
- reduced time to market leading to faster introduction of products,
- volatile product volume and variant mix,
- abundance of product features and variants which lead to more complex products and processes
- reduced investment while remaining robust

Aligned with the dominant competitive strategy of product differentiation at cost parity, all of these drivers focus on product variability based on market capture. In this sense the market is an external disturbance to the manufacturing process.

Bussmann et al., 1999 summarise these drivers as increasing complexity and continual change under decreasing cost and make the following observations:

- Arbitrary complexity must be eliminated through standardisation. The remaining (essential) complexity can be optimally structured by employing an intuitive manufacturing system that exhibits transparent and well defined behaviour.

- Continual product changes require the re-use of existing manufacturing equipment, either through flexibility of function or reconfigurability.
- Changes in throughput require scalability while changes in mix require selectivity.
- The prerequisite of decreasing cost and the subsequent implication of scarce resources could yield the manufacturing system more vulnerable to both internal and external disturbances. Increasing robustness will therefore be required and can be achieved through either structural (buffers and time slack) or dynamic system flexibility (adapting to failure by using spare capacity).

Translating these business requirements into generic control system requirements, the authors specify the control system attributes given in table 4.

Table 4 ***Generic control system attributes (Busmann et al. (1999))***

Attribute	Rationale
A decentralised, product / resource based architecture	Fully centralised control is too complex and difficult to change. The control itself can become the bottleneck. Decentralisation should be product or resource based where the product or resource contains all the required control capabilities (regulatory control, multivariable control and real time optimisation). This enables the system to be changed and scaled up more easily and reduces complexity.
Interactions should be abstract, generalised and flexible	This maximises scalability by reducing the dependency between resources. As such, no assumptions are made about the internal structure or behaviour of other components while dynamically deciding with whom and how to interact.
The control system should be both proactive and reactive	Reactivity enables disturbance rejection. All resources participate in the (decentralised) planning process and therefore need to be proactive.
The control should be self organising	Optimal rejection of disturbances should not only be achieved through local resource response, but also through reorganisation of the manufacturing system.

Furthermore, McFarlane and Matson (1999) specify two distinct attributes that facilitate the mastering of change and uncertainty.

The first, responsiveness, is defined by Goldman et al. (1995) as "the ability of a company to operate profitably in a competitive environment of continually, and unpredictably, changing customer opportunities". As such, it constitutes a reactive component in addressing change and uncertainty.

The second aspect, agility, is defined by Goldman (1995) as the ability of an organism to pro-actively affect the environment in which it operates through varied activities. This constitutes a pro-active attitude towards managing change and uncertainty.

These two mechanisms of response and initiative are deemed of critical importance for the business success of manufacturers currently and in the future.

The mapping of business drivers to business requirements to control system requirements, created by Bussmann et al. (1999), is given in figure 6.

Figure 6 ***Mapping business drivers to requirements (Busmann et al. (1999))***

	standardisation	minimal system structure	intuitive structure	trasnparent behaviour	flexibility	reconfigurability	scalability	robustness
complexity	x	x	x	x				
responsiveness					x	x	x	x
decentralised architecture			x			x	x	x
product / resouce based architecture		x	x			x	x	x
abstract / generalised interactions	x			x	x	x		
flexible interactions				x	x	x	x	x
reactive ability				x	x			x
proactive ability				x	x	x	x	
self-organisation		x	x			x	x	

2.2.2.2 Computer integrated manufacturing

Rapid advances in information technology and systems have enabled the ability to integrate a wide range of design, planning and production systems. In the manufacturing environment, integration has often been pursued in a centralised manner in the form of Computer Integrated Manufacturing (CIM).

CIM is a rigid, centralised, hierarchical system that consists of levels of increasingly complex functions, the aggregate of which is sufficient to obtain global optimisation. Centralised systems are very successful in pursuing operational efficiency under restrictively defined conditions.

However, Bussmann (1998) notes particular shortcomings of CIM. Being honed for a particular set of conditions, the inflexible hierarchy is fragile and performance declines rapidly outside the defined (normal) operational envelope. Additionally, reconfiguration and extensions to the current system (maintenance) requires more effort than in the case of decentralised systems. Components in CIM are coupled - each part strongly depends on the rest of the system, while the whole system is dependent on component. This impedes change and scalability.

Centralised systems appear more complex to the external user than their decentralised (and modular) counterparts. It is therefore more difficult to fully integrate humans into the system. Equally, centralised data structures are more difficult to access which makes diagnosis more difficult.

2.3 The chemical processing industry

Running total sales of $1,5 trillion p.a. (1999 dollars), the chemical processing industry is a key driver for technological development, economic growth, as well as environmental protection. In providing products that affect quality of life, it is an important determinant in the material well-being of people (Swift, 1999)

The industry consists of the following sectors:

- basic chemicals (commodities), for example
    - oil and gas
    - petrochemicals
    - polymers
- speciality chemicals, for example
    - adhesives
    - catalysts
    - fine chemicals
- life sciences, for example
    - pharmaceuticals
    - agrochemicals
- consumer products

The chemical processing industry is a key supplier to other sectors such as manufacturing (for example automotive, aerospace, textiles and clothing, electronics), mining, and agriculture.

The relationship between these sectors, the percentage of annual sales attributable to each sector, as well as the different routes-to-market is given in figure 7.

A summary of the salient features of each sector (excluding consumer products) is given in table 5.

Figure 7 *The relationship between the different sectors in the chemical processing industry, the percentage of total industry sales attributable to each sector, as well as the different routes-to-market. Source: Swift (1999)*

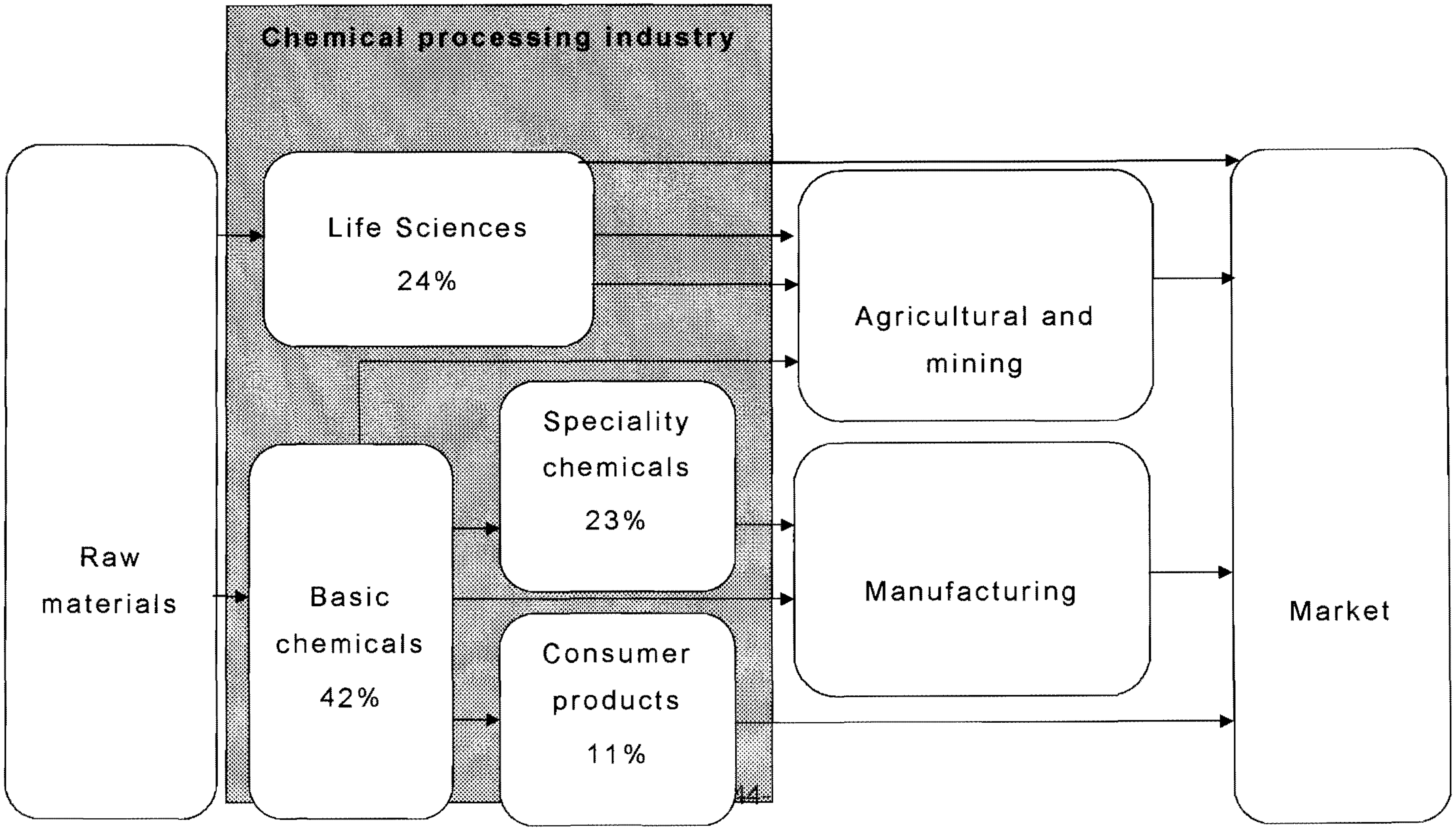


Table 7 ***Summary of the salient features of the different sectors in the chemical processing industries*** Compiled from Swift (1999)

	Basic chemicals	**Fine chemicals**	**Life sciences**
Examples	Petrochemicals, ammonia, methanol, polymers	Adhesives, fine chemicals, catalysts	Pharmaceuticals, agricultural
Business maturity	Highly mature	Good growth potential	Rapid growth
Expected real growth (1998 – 2010)	1.25%	3.25%	4.75%
R&D spending as percentage of sales	4-5%	5-8%	10-25%
Competitive drive	Cost, no product differentiation, prices driven by capacity utilisation leading to high cyclicality and low profit margins, pursue process efficiency, economies of scale are important	Product differentiation or cost; prices are set by value-and-use not cost; higher profit margins than basic chemicals; strong customer and technical servicing component	Product differentiation as main competitive driver; prices set by both cost and value-and-use; much higher profit margin than basic chemicals; strong intellectual property component
Process technology	Continuous and dedicated	Ranging from continuous and dedicated to batch and general	Batch and general purpose equipment
Barriers to entry	High amount of capital required	Technology	Protection of intellectual property

2.3.1 Trends and drivers in the chemical processing industry

CAPE-21 (Computer Aided Process Engineering in the 21st Century) is a program for exploring promoting the computer aided process engineering supported by industry and academia. In an August 2001 report the following business drivers are identified (CAPE-21, 2001):

- Increasingly volatile and competitive markets
    - shorter product life cycles
    - greater product differentiation
    - more agile and flexible performance of multi-product processes
    - more flexible and responsive manufacturing networks
- Margin compression and intensifying competition
    - High efficiency
    - Flexible and responsive to market dynamics
    - Safe and clean
    - More reliable and resilient
    - Consistently produce top quality products

Green (1997) also mentions cyclicality as a pervasive driver. In the short term, the well-established principle of cyclicality in the prices of commodities is expected to continue unabated. Green (1997) describes the causal process. A period of global economic upturn is experienced and process industries become increasingly cash rich. Within the context of continuous improvement, financial prosperity is canalised into expansion or efficiency improvement projects. Both these project types increase production capacity. Utilising increased capacity leads to a shift in the supply-demand balance in the direction of decreased product margins. Inevitably, a period of global economic downturn is experienced with a further slump in commodity prices. Commodity producers respond to this slump in prices through either of two mechanisms, both aimed at reducing the utilised capacity

- Consolidation through mergers and acquisitions. This is aimed at employing the principle of economies of scale by reducing and spreading costs over more units of output. It represents a classical cost leadership strategy.
- Commodity cycles do not occur congruently. Buying into those commodity markets that show a price upturn, whilst selling off or consolidating those that show a price downturn, typifies the response of some companies (Rycroft and Cash, 1999)

Many commodity markets currently suffer from overcapacity, such as :

- Peroxides (Brown, 1999)
- Polyolefins (Richards, 1999)
- Nafta (Tullo, 1998)

2.3.2 Technological shifts

The major technological shift expected to occur is that of the diffusion of biosciences into the processing of basic chemicals. Traditional equipment will be replaced by equipment now functioning in the domain of life sciences only (Swift, 1999)

Pertaining to intelligent processing systems, an extensive literature survey carried out by Stephanopolous and Han (1995) identified the following current and expected future areas of focus:

- diagnosis of process operations
- developing a unifying frame work for fault diagnosis
- modular estimation and diagnosis (Mjaavatten and Foss, 1997)
- decoupling the impact of faults
- constructing models for diagnosis
- developing diagnostic procedures
- monitoring and analysis of process trends
- formal representation of process trends
- data validation and rectification
- recognition of temporal patterns
- extraction of unique features
- intelligent control
- nonlinear control
- expert (knowledge based) control
- adaptive control
- fuzzy control
- neural control
- planning and scheduling through
    - logic based scheduling
    - rule based scheduling
    - scheduling through goal directed search
    - artificial intelligence and operations research methods for scheduling

- modelling, simulation and reasoning languages
- knowledge based engineering design
- expert systems in design
- design modelling
- innovative model based design

In order to evaluate current consensus on the future development of process control technology specifically, the output from the Chemical Industry Vision 2020 partnership is analysed. The Chemical Industry Vision2020 Technology Partnership (Vision 2020) is an industry-led partnership/process among public and private sector stakeholders in the chemical and allied industries. Stakeholders identify common problems and leverage technical expertise and financial resources to develop the critical enabling technologies of the future. Through collaborative efforts among industry, national laboratories, and academia, the Vision 2020 Partnership fosters step-change technology innovation, which may be beyond the risk threshold of individual companies.

Process control is seen as a key enabling technology in the chemical industry. However, its future application is believed to be strongly integrated with the fields of chemical measurement and information systems.

The drivers for continued development of process control technologies are:

- cost reduction via increased efficiency
- speed to market requirements
- the improvement of product quality

- safety and environmental concerns,
- the support of new process and product innovation

Areas identified for future development are:

- nonlinear model predictive control
- performance monitoring
- estimation and inferential control
- identification and adaptive control
- molecular characterization and separations
- process sensors

A summary of the roadmap is given in table 8.

Table 8 **Summary of the Vision 2020** ***roadmap for the development of process control and chemical measurement applications***

Requirements	Development focus	Implementation focus
Nonlinear model predictive control		
A decision model to determine the most appropriate technique to employ in model based control. The development of practical nonlinear model-based control techniques that quantifiably improves plant performance and can be supported in an industrial environment.	Improved modelling paradigms that exploit process data all forms of prior knowledge. Tailor solutions to control optimisation through algorithm engineering. Control relevant characterization tools for process nonlinearity. Long term sustenance of advanced controllers in industry.	Collaboration between scientists and engineers in the measurement and control field. Stronger integration between control and optimisation fraternities. Curricular changes.
Estimation and inferential control		
The measurement and utilization in control of critical variables currently difficult to measure.	A framework for hybrid modelling (data driven vs. knowledge driven). Tools for determining optimal	Industrial problems.

Requirements	Development focus	Implementation focus
Improving the underlying theory of parameter and state estimation. The ability to quantify the adequacy of inferential model. Enabling the utilisation of hybrid modelling approaches.	sensor location Controller design methodology that appropriately incorporates different levels of measurement granularity. Improved state and parameter estimation methodologies. Techniques for large scale modelling.	
	Performance monitoring	
A framework for selecting the best technology. The ability to selective combine empirical and first principles based models. Performance monitors to be expanded to focus on multivariate, multiloop, nonlinear, constrained, large-scale, time-varying systems	Assessment of plant wide variability while fully understanding the interaction between the model and the controller. Wide-scale root cause analyses. Knowledge based control and measurement tools. Alternative tuning methods (stochastic vs. deterministic).	Industrial problem solving. Short courses and workshops. Test-bed centres for integrated advanced control systems. Cooperative research centres between industry and academia.

Requirements	Development focus	Implementation focus
	Locally automated high performance sensors, transmitters and valves. Methods to address robustness. Tools to diagnose faults in real time.	
Identification and adaptive control		
Socio-moral framework of operations requires higher environmental and safety sensitivity. Maximising the capital asset life cycle. Providing process controls to plants that have operating characteristics that change over time.	Develop practical adaptive control theory applicable in industry. Integrate existing first principle process knowledge into adaptive control schemes. Incorporate advanced on-line measurement into identification and adaptive control. A practical unified and generally accepted fundamental approach to	Collaboration between measurement and control communities. Technology transfer mechanisms between industry and academia. Industrial applications. Multidisciplinary education. Vendor participation.

Requirements	Development focus	Implementation focus
Empirical modelling	identification and adaptive control Integrating advances in data mining, data base technology, communications and human factors.	
Molecular characterization and separation		
Moving laboratory detection limits to process analysers. The implementation of multidimensional sensors in process applications. The ability to perform sampling of complex streams and provide critical information for process control. The ability to optimize the placement of sensors and analysers to provide the greatest leverage on the control of the	Developing analysers that move current laboratory capabilities to the process, but are robust and easy to maintain and support. Develop mobile analysers for acquisition of improved fundamental understanding and data gathering. Developing technology for characterization of polymers. Developing improved structure, property and processing modelling capability especially for	Improved employee training. Improved industry and academic interfaces. Establish research focus for the mundane but common problems not often dealt with in dissertations.

Requirements	Development focus	Implementation focus
plant. The ability to extract the maximum information from a measurement system and transforming that into actionable process control information.	macromolecules. Developing improved technology for physical and chemical characterization of solids and slurries. Developing technology that improves the effectiveness of the measurement system in implementing the control strategy. Developing new approaches to sampling and sampling interfaces. Develop low maintenance, self calibrating and self-diagnosing analysers and sensors.	

Sensors		
Develop sensor systems that are cost effective in any scale process. Sensors enable improved responsible care practices. Sensors need to enable the process control system to run harder and closer to constraints.	Developing sensors for multiphase systems. Developing sensors for solids. Developing a systematic approach to developing new sensor materials Developing methods to provide low cost sensing strategies. Developing easier calibration models and calibration transfer among similar sensors. Developing technology to provide smart sensors for all process measurements.	Induce vendors to provide hardware and software that is modular and architecturally open. Provide user friendly sensors to eliminate the need for a measurement specialist. Provide new directions in education. Funding of the development of robust, low maintenance sensors.

2.3.2.1 Globalisation

While Western markets for chemicals are mature, Asian markets promises exceptional growth potential. Leading chemical processing industries are therefore globalising at an increased rate (Swift, 1999)

2.3.2.2 Consolidation

It is expected that consolidation will occur in all segments of the chemical processing industries. Joint ventures are aimed at expanding the technological base of a company, while mergers and acquisitions are aimed at controlling overcapacity. (Swift, 1999)

2.4 Holonic systems in the chemical processing industry

With the bulk of holonic systems research focused on the discrete manufacturing industry, investigation into its applicability to continuous processing industries have mostly been limited to holonic scheduling systems.

In an attempt to begin to consider the wider applicability of holonic systems specifically to the chemical processing industry, Chokshi and McFarlane (2001) have considered the rationales for its deployment in this sector. Their main focus are campaign processes in which the same process equipment is used to produce different products in subsequent processes.

Based on the business drivers identified in the CAPE-21 survey (see section 2.3.1. above) the following process operation requirements are derived:

- increasing production throughput and process efficiency
- responsiveness to both internal and external disturbances
- agile production systems and continuous change management

Both process engineering and process control are singled out as areas requiring significant future development in order to ensure the survival and sustainability of the industry. It is, however, pointed out that existing research and development efforts lead to a number of apparent contradictions:

- increased efficiency could increase complexity (for example pinch technology)
- improved responsiveness could increase rigidity (for example including process buffers helps with rejecting disturbances but increases total residence time in the process leading to slower product response times as well as an increase in capital expenditure.)
- improved flexibility could lead to higher costs (flexible equipment would probably be more expensive)

From this perspective holonic systems inherently presents an elegant platform for both process architecture and control. Specific useful attributes are:

- the ability to structure complexity
- distributed architecture and control
- self-organising and dynamically integrated
- bottom up design approach

2.5 Process control requirements

Stephanopoulos (1984) noted that a chemical plant needs to simultaneously satisfy a number of requirements in the face of external disturbances:

- economic imperatives
- production quantity and quality
- operational constraints
- safety
- environmental regulations

This is translated to the following automation requirements:

- suppressing the impact of external disturbances,
- ensuring the stability of the process
- optimising the performance of the process

In order to achieve these goals, the automation system in turn has to perform the following activities:

- measure and validate
- analyse and forecast
- plan, promise, schedule
- control and optimise

The above provides a generic framework for analysing the attributes of different control systems.

2.6 Strategy

Strategy is often defined as the match an organisation makes between the opportunities and risks created by its external environment and its internal resources and skills (Grant, 1991). In developing a business strategy, two different approaches exist, each of which focuses on one of these two extremes of the business process.

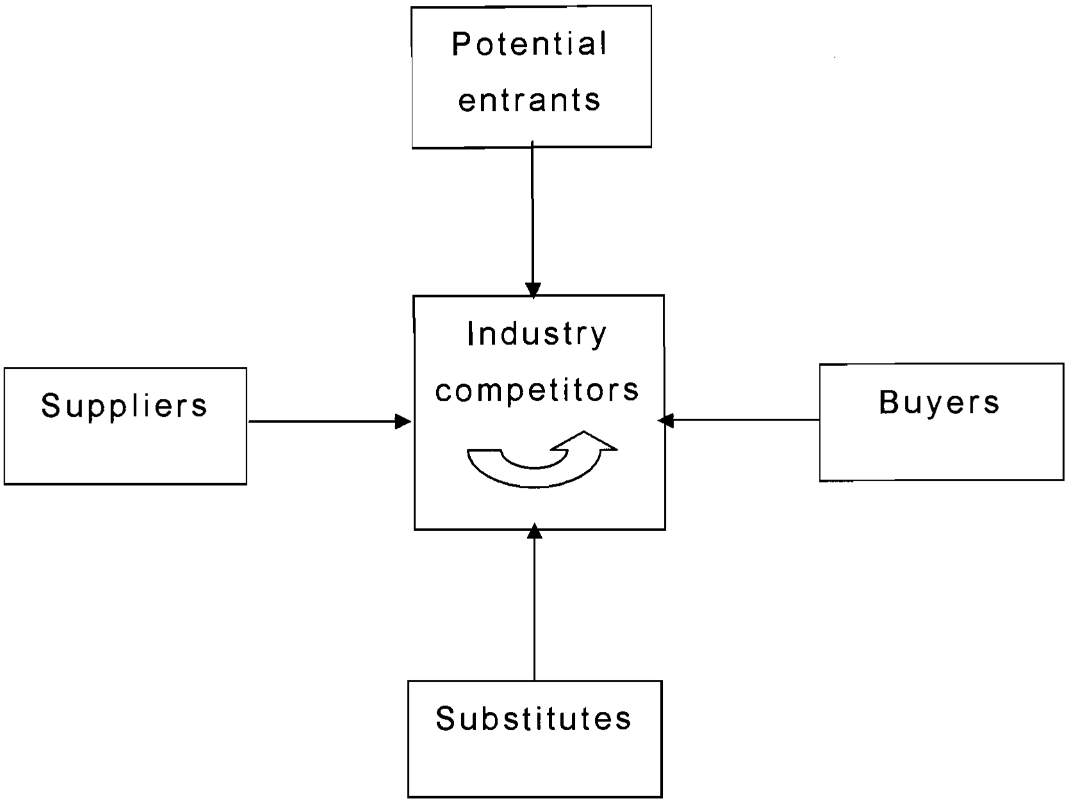
2.6.1 The competitive forces paradigm – opportunities and threats in the external environment

In this approach, the competitive strategy is based on two characteristics of the external environment:

- the attractiveness of the particular industry for long-term profitability together with the factors that determine it,
- the determinants of relative competitive position between incumbent firms within the particular industry

The first central theme is that of industry structure. This approach disconnects industry profitability from product / service attributes, solely focusing on industry structure. This structure is determined by the dynamic balance of the five competitive forces depicted in figure 8. In this view, the firm is imprisoned by the structure. Its only degree of freedom is to attempt to influence this structure in its favour.

Figure 8 ***The five competitive forces which determines the competitive structure of the industry (Porter, 1985)***



Satisfying customer needs, as well as the balance between supply and demand, are deemed important determinants of profitability. However, both these are determined by industry structure. Whereas satisfying customer needs is essential, the industry structure actually determines the distribution of created wealth. Therefore, strategic actions are aimed at satisfying customer needs while attempting to maximise the proportion of created value captured by the firm. Equally, the balance between supply and demand is also determined by the five dynamic forces.

The second central theme is that of the firm's relative competitive position within the industry. Since a favourably positioned firm could remain profitable within an unfavourable industry, positioning could be more important than industry structure. Sustainable competitive advantage is seen as positioning that allows above average profitability over the longer term.

Two main approaches to generic competitive strategies are acknowledged. The first is that of cost-leadership in which a company strives to become the lowest cost producer. However, to remain an above average performer, the cost-leading company must at least achieve differentiation parity with its competitors.

The second main generic strategy is that of product (or service) differentiation in which the company endeavours to offer a product or service which is preferred by customers due to its unique features. Again, differentiators must still achieve cost parity with its competitors.

Within this paradigm, technology is seen as an important resource supporting the chosen generic business strategy. It therefore either reduces production costs or improves the ability to differentiate.

Accordingly, its ability to affect industry structure (each individual competitive force) ensures that technological change is one of the principal drivers of competition.

Porter (1985) outlines the following criteria against which the desirability of technological change can be gauged:

- the technology itself lowers cost or enhances differentiation, and is sustainable

- technology change shifts cost or uniqueness drivers in favour of the firm
- pioneering technological change translates to a first-mover advantage besides those advantages already inherent in the technology
- the technological change improves the industry structure

2.6.2 The resource based view – internal resources and skills

Critics of the competitive forces approach highlight the following restrictive assumptions on which the approach is based (Barney, 1991):

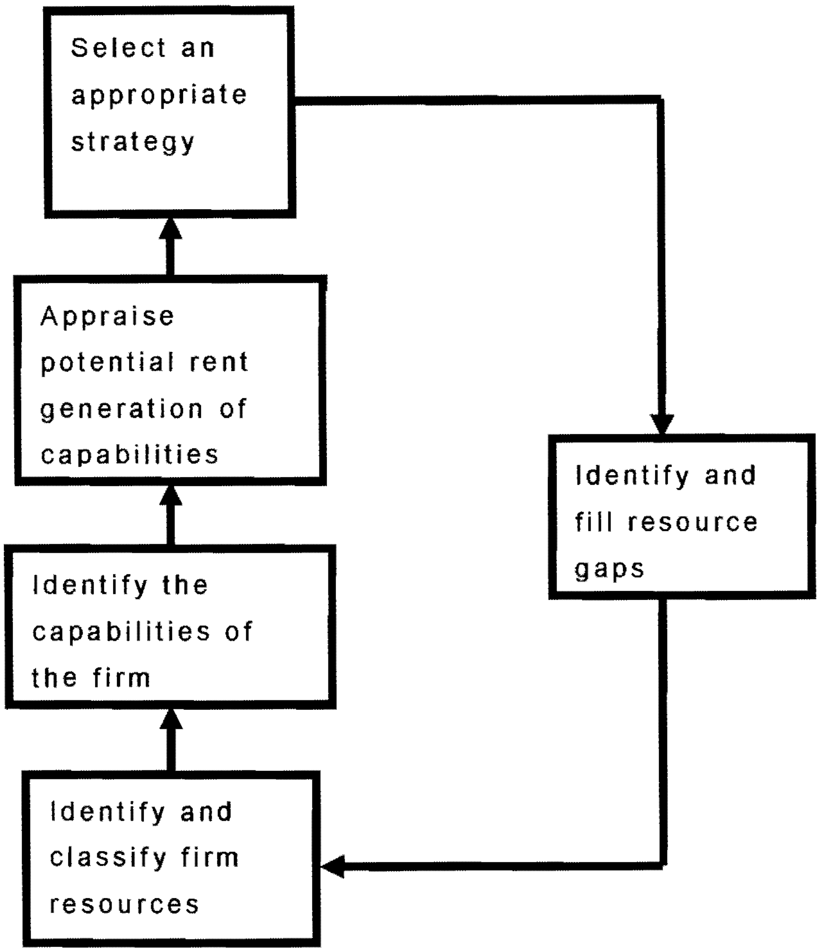
- firms within a particular industry are identical with regard to the strategically relevant resources they control and the strategies they pursue
- should resource heterogeneity develop within an industry it will be short-lived since the strategically relevant resources are highly mobile

Accordingly, the second approach to developing business strategy focuses on the strengths and weaknesses within a company. It is based on assumptions opposite to those mentioned above:

- firms within an industry may be heterogeneous with respect to strategically relevant resources they control
- these resources may not be perfectly mobile.

This introspective approach focuses on the resources within a company, the capabilities supported by these resources and the consequent rent generating potential of these resources (Grant, 1991). This cascade is portrayed in figure 9.

Figure 9 ***The resource-based approach to strategy analysis (Source: Grant, 1991)***



Competitive advantage is achieved by implementing a value creating strategy based on the capabilities (and hence resources) of the firm. This advantage is deemed sustainable once all efforts to reproduce it have ceased.

Barney (1991) identifies resources as all assets, organisational processes, firm attributes, information and knowledge that are controlled by the firm and that enable the firm to conceive and implement strategies to improve effectiveness and efficiency. This includes all forms of technology that the firm controls. Accordingly, this approach is particularly relevant to technology strategy.

Grant (1991) notes that resources and capabilities are important sources of direction within a firm that outlines its identity and purpose. In fact, resources and capabilities form a more durable and stable basis for strategy than one that depends on the needs that the business seek to satisfy. Grant (1991) also indicates that resources are the basis of corporate profitability. Previously, profitability was largely seen as a function of the particular industry structure. However, technological change, international competition and diversification have ensured that profitability has become a function of competitive advantage. This places direct focus on the resources and capabilities as sources of competitive advantage (see figure 9).

A more specialised form of the resource based approach was introduced by Prahalad and Gamel (1990). It focuses specifically on firm competencies as the root of competitive advantage. Nurturing a portfolio of competencies, rather than a portfolio of businesses, facilitates improved responsiveness as well as the ability to deliver unique products / services.

Teece et al. (1991) built on this approach by stressing the importance of dynamic capabilities. It focuses on the ability to combine competences and resources that allows responding to changing environments.

2.7 Technology and strategy

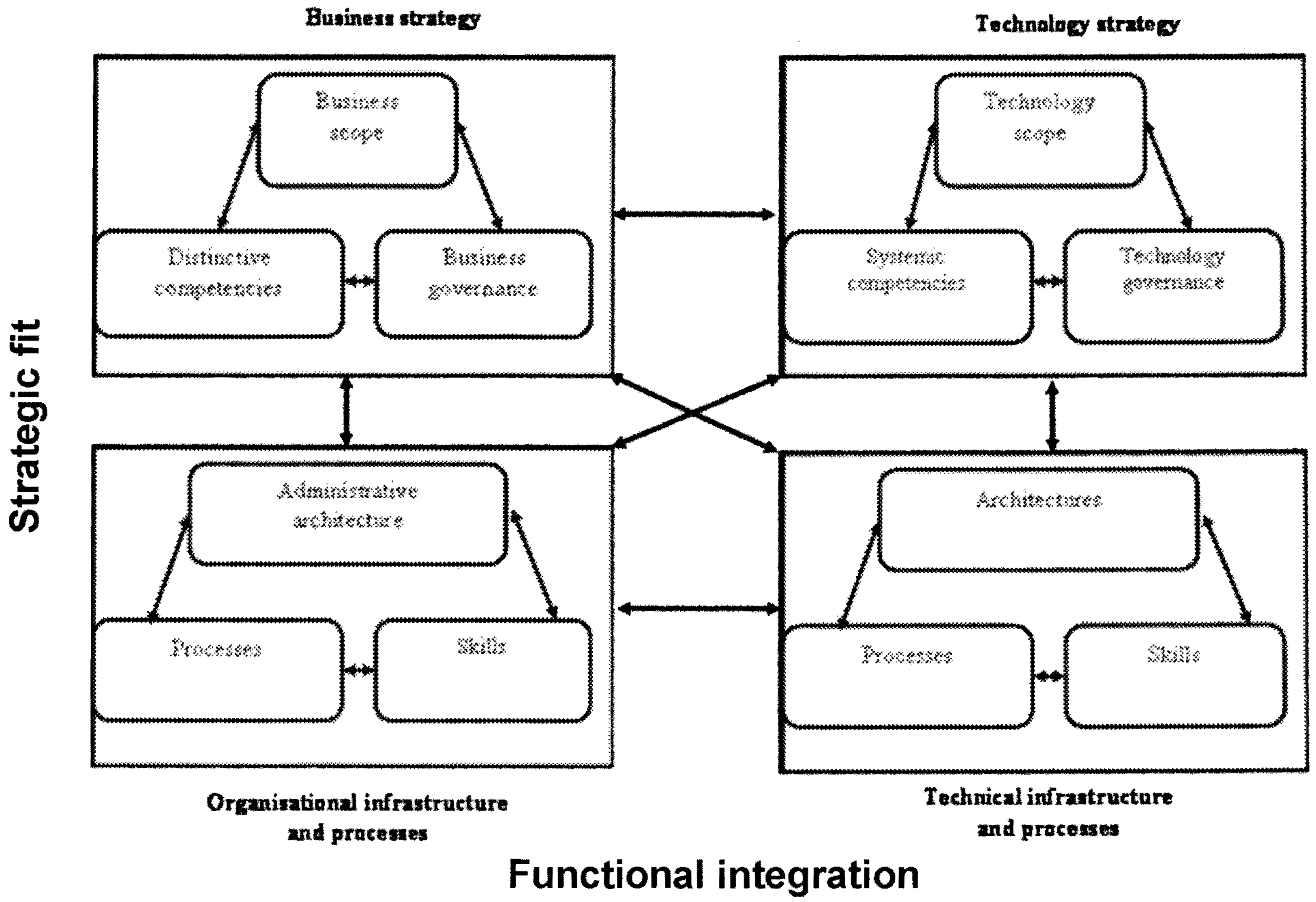
Technology is fast becoming one of the most significant drivers for change. It is accepted as axiomatic that the long-term success of a company is inextricably intertwined with its ability to optimally apply technology over the long term (Stacey and Ashton, 1990).

On the one hand, it is imperative to maximise the utility of its existing technologies, while, on the other hand, companies are faced with a profusion of potentially viable technological options. Some of these might prove to bud into disruptive technologies, threatening the competitive position of companies inexperienced in their application (for example the demise of the Swiss watch industry after failing to adopt quartz crystal based time-keeping).

In order to explore the link between technology and strategy, Henderson, Venkatraman and Oldach (1996) created a strategic alignment model. The model is based on two imperatives: strategic fit and functional integration.

The strategic fit axis aligns the external positioning of the firm with its internal arrangement. The functional integration axis aligns decisions and practises in the technological domain with those in the business domain. This model is depicted in figure 10.

Figure 10 *Strategic alignment model (Source: Henderson et al (1996))*



Based on this model, Henderson et al. identified four dominant alignment perspectives:

- strategy execution (business strategy determines organisational infrastructure which in turn determines the technical infrastructure)
- technology potential (business strategy determines the technology strategy which in turn determines the technical architecture)
- competitive potential (Technology strategy drives the business strategy which in turn determines the organisational infrastructure)
- service level (technology strategy determines the technical architecture which in turn drives the organisational architecture)

Henderson et al. are careful to point out that the different alignment perspectives represent potential response patterns and therefore all four perspectives warrant consideration.

It is within this framework of strategic fit and functional integration that a number of technology management functions, such as technology planning and assessing the viability of new technology, occur.

Technology assessment and planning form an integral part of the continuous (and iterative) technology strategy formulation process. Focusing on the technology-business interface, it explores future outcomes given current and expected future conditions. It then facilitates decisions on proactively affecting the technology-business trajectory with the goal of improving the firm's future competitive position (Garcia and Bray, 1997)

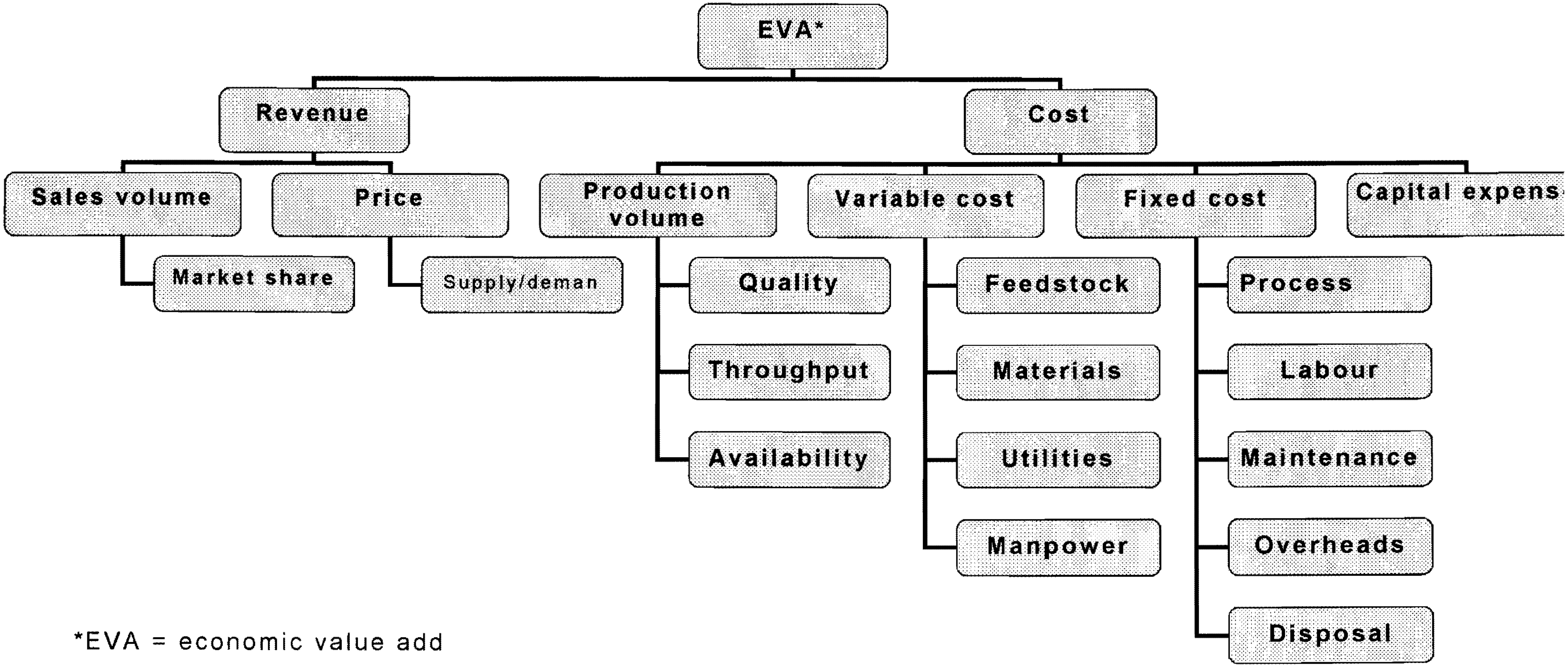
A number of technology management tools have been developed to assist in this process. Two tools in particular, DuPont analyses and technology roadmapping, are of particular interest in constructing a framework for assessing the viability of holonic systems to the chemical processing industry and are discussed below.

2.8 DuPont analysis

The DuPont analysis, created by the chemical company of the same name, relates primary financial statement elements to the business drivers affecting each. Business drivers can subsequently be mapped to the requirements for any aspect of the business, for example automation.

A DuPont chart for a generic chemical company is given in figure 11 (PA Consulting Group (1997))

Figure 11 *Generic DuPont chart relating key business drivers to primary financial statement elements*



*EVA = economic value add

2.9 *Technology roadmapping*

A technology roadmap is an integrative, graphical portrayal of the trajectory of the technology-business interface in a particular business unit, company, group of companies or other economic entity. (Lowe, 1995; Garcia and Bray, 1997). It represents the initial technology-business state, desired end state as well as delineating the intermediate stages between these two (Gordon, 1995). Describing these intermediate stages enables a disciplined progression towards a common goal and procures enough focus to ensure timely availability of resources (Albright, 1998).

A distinctive feature of the roadmapping process is its high proclivity towards customisation and consequent lack of stereotypes. Therefore, no standard model will be discussed but attention will be focused on prominent and characteristic attributes.

Of central importance to roadmapping is the fundamental motive for engaging in the process. The European Industrial Research Management Association (EIRMA) Working Group on Roadmapping notes that markets and technology are two main business drivers. It was found that the relative importance a company attached to either of these drivers is reflected in the roadmap as follows:

- close proximity to the market place instigates a focus on market needs; roadmaps in these sectors tend to be needs driven (i.e. the roadmap is used to determine the technologies required to satisfy market needs)
- companies further from the market place are more inclined to focus on the available technologies; roadmaps in these

sectors tend to be needs searching (i.e. they relate the available technologies to potentially achievable targets)

Some authors explicitly reject the needs searching mode of use (Garcia and Bray, 1997) but their claims are suspect due to their strong identification with an industry located in the first mentioned category.

The characteristic elements that a roadmap consists of (EIRMA Working Group) are:

- time, since a technology roadmap describes the current, desired future and intermediate stages; anticipation and foresight is an important aspect associated with roadmaps
- deliverables, which are often desired performance targets for products of processes
- technologies, which are used to obtain the stated deliverables; these elements are often supported by a hierarchy of subroadmaps depicting how these elements are obtained and developed
- skills and science, which are needed to develop or sustain the required technologies
- resources, including financial, human, intellectual and physical assets

These elements, as well as the relationship between them, are investigated using appropriate techniques and tools. These could include scenario planning, foresight, benchmarking and value chain analysis. The roadmap then integrates these elements into a coherent graphical portrayal of the technology-business interface (Lowe, 1995). Consequently, each element in the roadmap is situated at the top of a cascade of information. The roadmap is therefore hierarchical in matching the level of detail required to the interest level of the observer.

Ensuring availability of the technology requirements needed to enable progression along the desired trajectory is often dealt with within the context of the technology process (Thompson, 1998). With a needs driven roadmap, business needs are linked to required technological capabilities. Depending on the current state of these capabilities within the organisation, the process steps of identification, selection, acquisition, exploitation and protection are built into the chosen trajectory. Each of these elements will be substantiated through those tools and techniques commonly used in their efficient execution.

Although technology roadmaps are chronologically ordered, they are hardly ever linear. Thompson (1998) advises that it should be a cyclical process which links to other cyclical business processes, additionally exploring both feedback and feed forward loops.

These attributes all contribute to ensure that the following benefits are derived from a roadmap (Garcia and Bray, 1997; Albright, 1998):

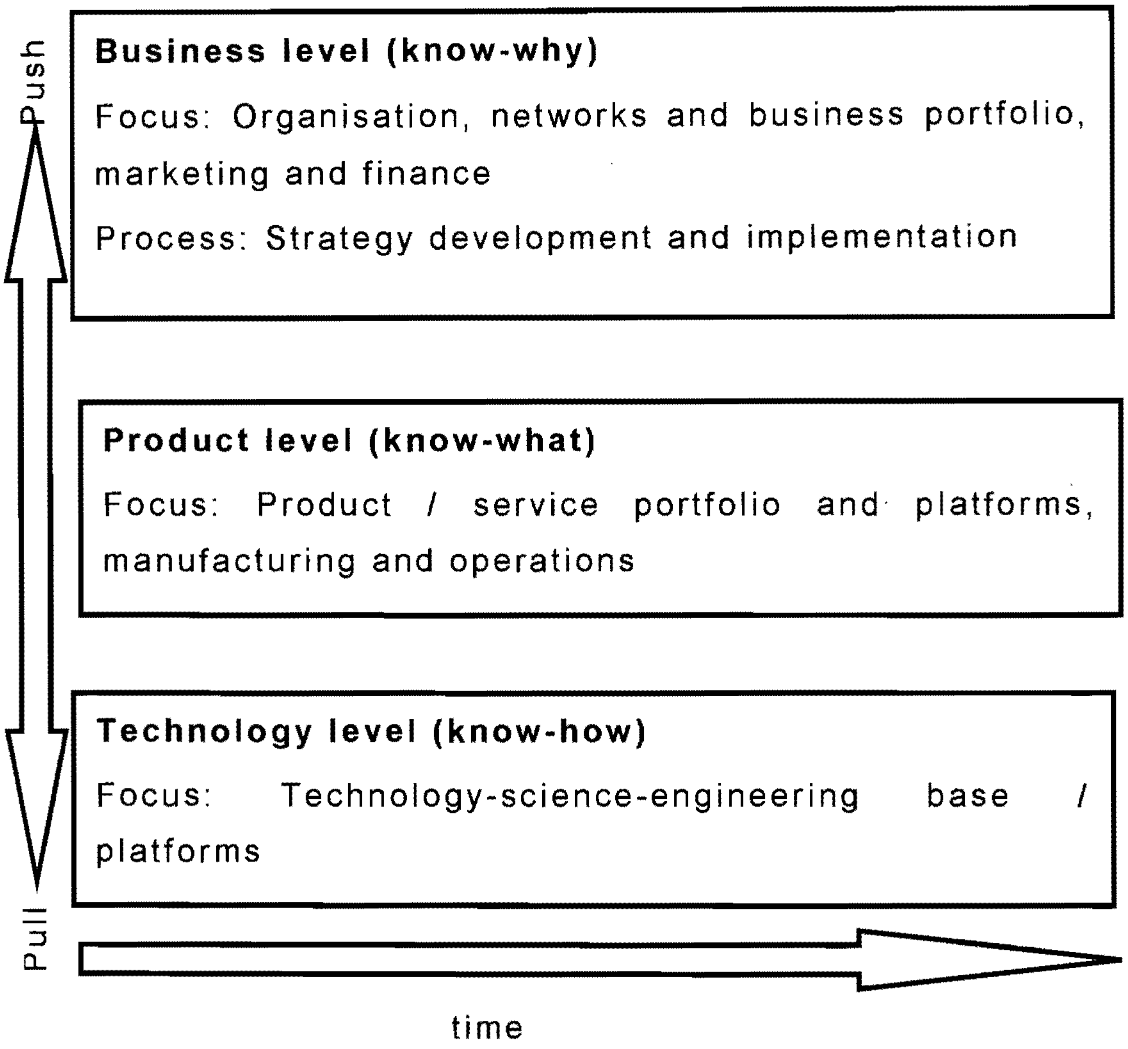
- it ensures a disciplined progression towards a commonly agreed goal
- it procures enough focus to ensure timely availability of required resources
- it clearly identifies areas of technological insufficiency in a company, given the business needs
- it is an exceptionally useful communication tool which could be used at all levels of the business, including

functional departments, research and development, as well as marketing

- the process of constructing the roadmap could be a valuable learning experience for a business
- it is a helpful tool in developing technology foresight

A number of different approaches to roadmapping are discussed in detail in Appendix A. As a tool to assess the applicability of holonic systems to the chemical processing industry the specific roadmapping approach selected is that of the EIRMA working group in conjunction with the fast-start technology roadmapping processes (conceptually depicted in figure 12) (Phaal et al, 1999)

Figure 12 Fast-start technology roadmapping process (Phaal et al, 1999)



Business level (know-why)

Focus: Organisation, networks and business portfolio, marketing and finance

Process: Strategy development and implementation

Product level (know-what)

Focus: Product / service portfolio and platforms, manufacturing and operations

Technology level (know-how)

Focus: Technology-science-engineering base / platforms

These multilayered roadmaps visually demonstrate alignment between strategy and technology. The specific format chosen is adapted from figure 12 as four tiered and explores the alignment between strategy, profit drivers, operational requirements and automation requirements.

3 Application

3.1 Holonic systems in a stream of consistent evolution

"The secret of success is consistency of purpose" – Benjamin Disraeli

This section (3.1.) addresses the first research question.

Question: Are holonic systems only useful in improving process agility or does it represent a predictable evolutionary response to the current dilemmas and the pursuit of ideality in the automation domain?

Methodology: The theory of inventive problem solving is used to derive an abstract solution (the predictable evolutionary response) to some key contradictions currently found in the manufacturing industry from a process control point of view. It is shown that the attributes of the proposed abstract solution is similar to the attributes of a holonic system.

3.1.1 Theory of inventive problem solving

In the early 1950s the Russian scientist and engineer Genrich Altshuller evaluated around 400 000 patents in the hope of identifying recurring patterns of innovation that could be used to guide future innovation by eliminating typical trial and error methodologies.

His research led him to conclude the following:

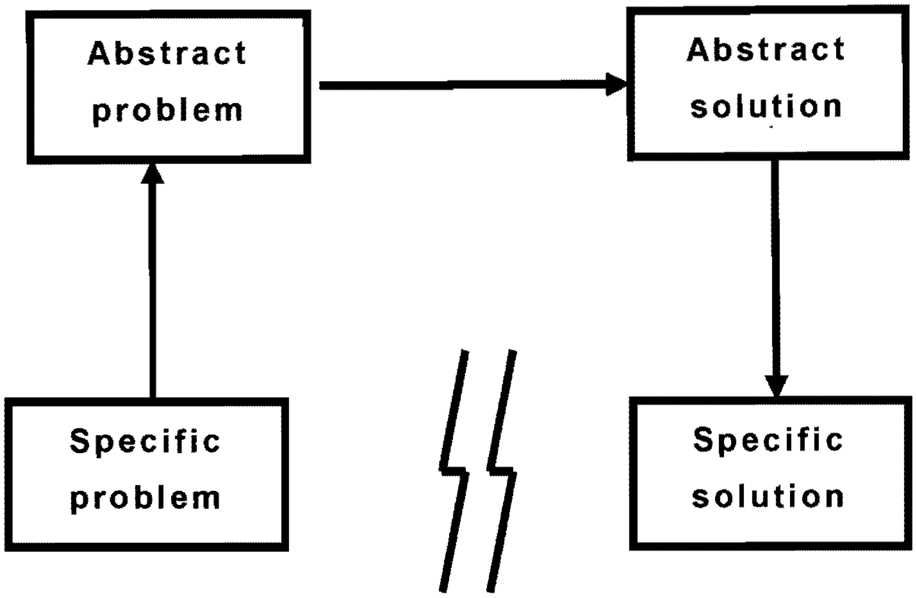
- all innovations emerge from the application of a very small number of inventive principles and strategies.
- technology evolution trends are highly predictable.
- the strongest solutions transform the unwanted or harmful elements of a system into useful resources.
- the strongest solutions actively seek out and destroy the conflicts and trade-offs most design practices assume to be fundamental.

Based on these observations the following two principles were established:

- all systems have uniform evolution in the direction of increased ideality (principle of ideality).
- any inventive problem represents a conflict between new requirements and attributes of the old system (principle of resolvable contradictions).

The TRIZ process consists of identifying a specific innovation problem, translating it into an abstract problem statement for which a number of potential abstract solutions are suggested which in turn can then be translated into specific solutions. This process is depicted in figure 13.

Figure 13 *The TRIZ problem solving process*

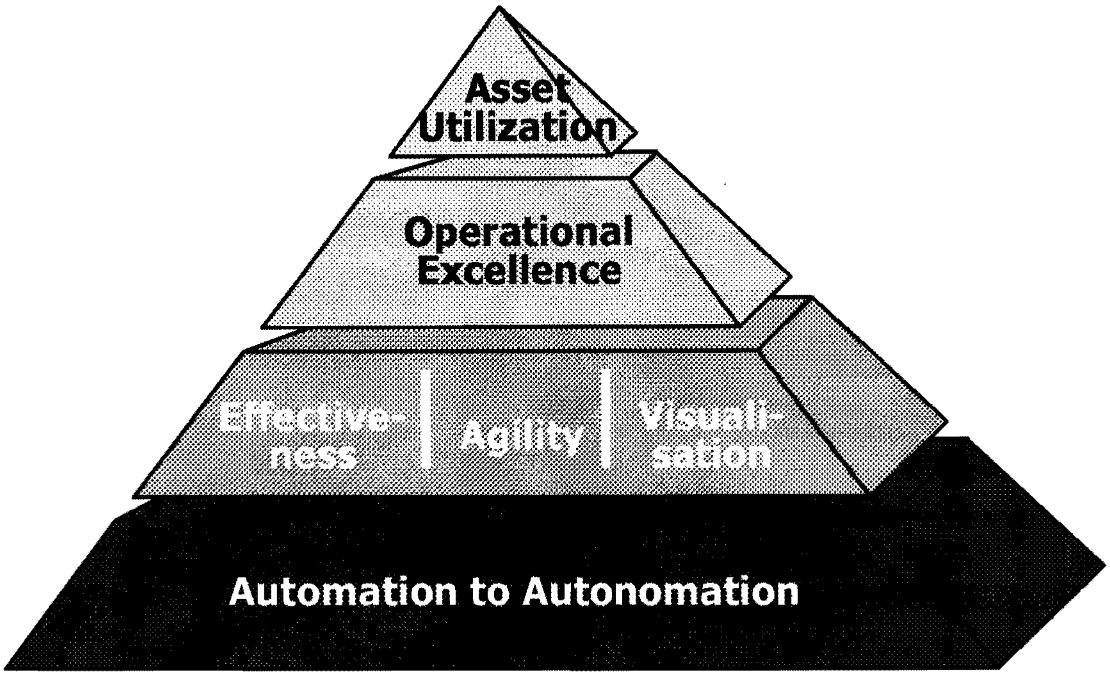


As a unifying framework for predicting the direction of future innovation, the TRIZ methodology will be applied below to show that the fundamental tenets of holonic systems theory represent a predictable evolutionary response to the current dilemmas and the pursuit of ideality in the automation domain.

3.1.2 Solving contradictions and satisfying ideality

Hill (2002) presented the Automation Research Council (ARC) vision of operational excellence as consisting of three main requirements: effectiveness (used interchangeably with efficiency), agility and visualisation. This is represented in figure 14.

Figure 14 *Effectiveness, agility and visualisation as the keys to operational excellence (ARC, 2002)*



Hill (2002) does not provide definitions for the three requirements but based on the literature study in section 2 the following definitions will be assumed:

- effectiveness: used interchangeably with efficiency, the ability to do the right things right, the pursuit and attainment of the global optimum;
- agility: the ability to proactively influence the environment, rejecting disturbances, being flexible and responsive
- visualisation: presenting information, knowledge and wisdom from previously mute data.

Concurrently achieving all three requirements within the constraints of existing automation systems would seem to pose a number of contradictions. A contradiction occurs when improving one system attribute leads to an apparent inescapable deterioration in another. For instance, a flexible (agile) system designed to pursue any of several objectives may be less efficient than a fixed system designed to always pursue a specific objective.

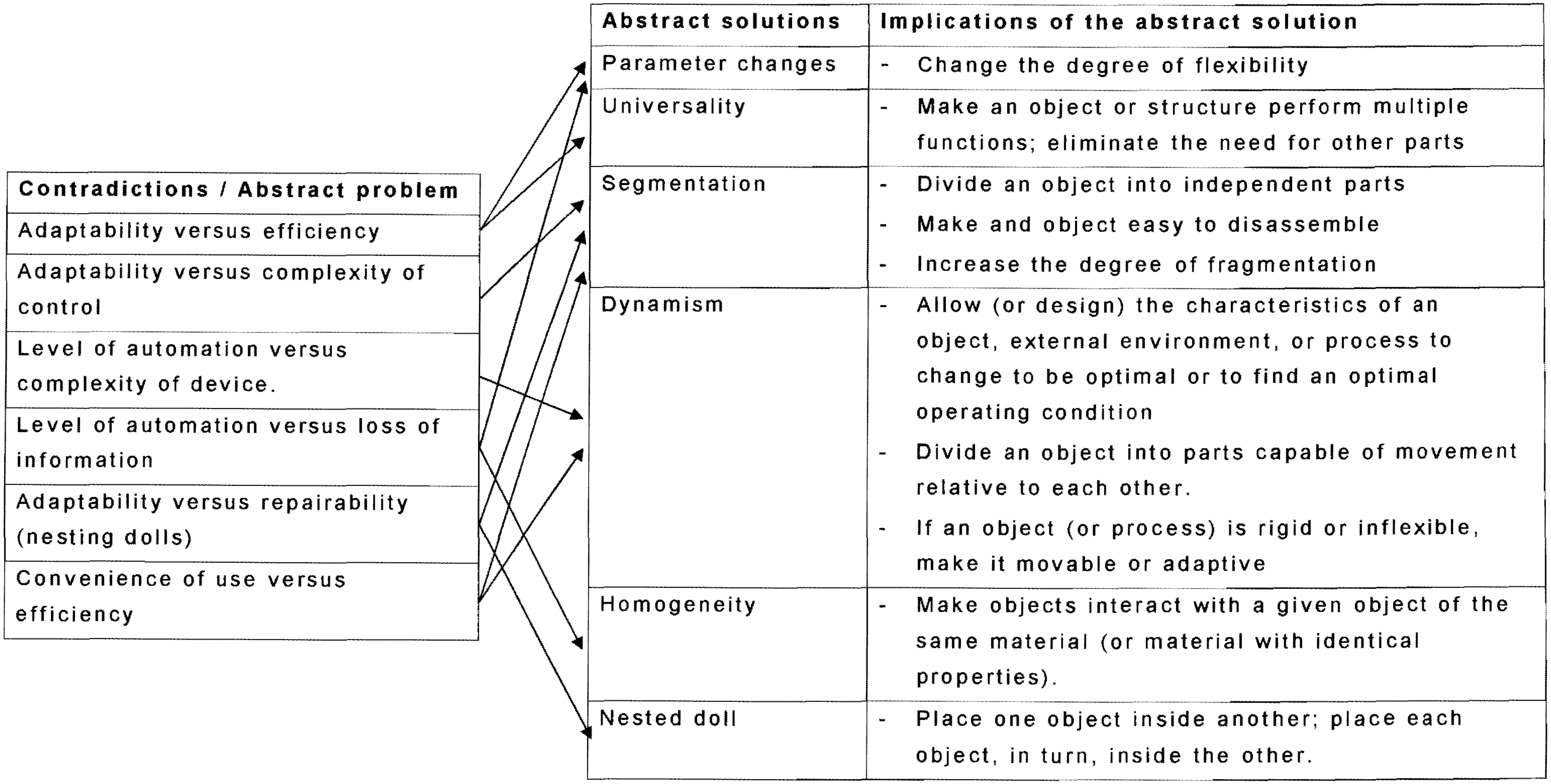
A further number of these contradictions within the context of centralised, hierarchical, integrated systems versus decentralised, heterarchical, segregated systems have also been identified implicitly in the literature study in section 2 and is analysed in table 9.

Table 9 *Existing contradictions in automation* **innovation.**

Symptoms	**Contradictions**
A flexible system designed to pursue any of several objectives may be less efficient than a fixed system designed to always pursue a specific objective	Adaptability versus efficiency
Increasing the flexibility of an system makes it more complex to control	Adaptability versus complexity of control
Increasing the level of automation would lead to an increase in the complexity of the automation system.	Level of automation versus complexity of device.
Increasing the level of automation in manufacturing may lead to reduced human participation as the system becomes less transparent	Level of automation versus loss of information
Improving the adaptability of a system could reduce its repairability.	Adaptability versus repairability (nesting dolls)
Making a system more convenient to use could reduce its overall performance.	Convenience of use versus efficiency

The contradictions in table 9 are stated as abstract problems. By employing the TRIZ methodology these abstract problems are related to abstract solutions (given in table 10) and in turn to characteristics in holonic systems that are specific manifestations of these abstract solutions (given in table 11).

Table 10 *Mapping of abstract problems to abstract solutions.*



Contradictions / Abstract problem
Adaptability versus efficiency
Adaptability versus complexity of control
Level of automation versus complexity of device.
Level of automation versus loss of information
Adaptability versus repairability (nesting dolls)
Convenience of use versus efficiency

Abstract solutions	**Implications of the abstract solution**
Parameter changes	- Change the degree of flexibility
Universality	- Make an object or structure perform multiple functions; eliminate the need for other parts
Segmentation	- Divide an object into independent parts - Make and object easy to disassemble - Increase the degree of fragmentation
Dynamism	- Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition - Divide an object into parts capable of movement relative to each other. - If an object (or process) is rigid or inflexible, make it movable or adaptive
Homogeneity	- Make objects interact with a given object of the same material (or material with identical properties).
Nested doll	- Place one object inside another; place each object, in turn, inside the other.

Table 11 ***Comparison between the suggested abstract solutions and characteristics of holonic systems.***

Specific abstract solution attributes	**Concurrent holonic systems characteristic**
Change the degree of flexibility	Flexibility is a key attributes holonic systems
Make an object or structure perform multiple functions; eliminate the need for other parts	Holons are adaptive with general, rather than specific duties.
Divide an object into independent parts	Holons are autonomous.
Make and object easy to disassemble	Holons can function independently and the effect of change is localised.
Increase the degree of fragmentation	Holonic systems are a fractal structure with infinite degree of fragmentation.
Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition	Holonic systems are adaptive and self-organising.
Divide an object into parts capable of movement relative to each other.	A strong reference to holarchies (or flexible hierarchies)
If an object (or process) is rigid or inflexible, make it movable or adaptive	Hierarchies are inflexible an rigid as the parent-child relationship is fixed whereas holarchies are flexible and adaptive.
Make objects interact with a given object of the same material (or object with identical properties).	Holonic systems are homogenous in form despite functional specialisation.
Place one object inside another; place each object, in turn, inside the other.	Perhaps the strongest reference to the wholeness / partness nature of holonic systems.

This conclusively answers the first research question. The obvious similarity between the derived abstract solution and holonic systems proves that, more than simply being an answer to the requirement for increased agility, holonic systems represent a predictable evolutionary response to the general dilemmas (contradictions) in manufacturing control. This immediately makes it of interest to the commodity chemical manufacturer.

King (2002) performed a similar analysis on the so-called ultimate ideal autonomous object as a meta-paradigm for concepts such as autonomic computing (Horn, 2001). The following are characteristics of autonomic computing:

- self-identification; self-knowing
- self-optimization
- self-(re)configuration
- self-recovery (from perturbations)
- self-protection (security)
- self-learning (including from errors)
- self-regulating (to open standards)
- self-resource-allocation

These characteristics were explained as an expression of the evolution towards ideality based on an expanded list of TRIZ derived ideality criteria as follows:

- infinite functions or functionalities
- no external resources required, self-sufficient
- no disadvantage or negative side effects
- self-contained system (autonomous, auto-diagnosis, auto-repair)
- self-organisation
- infinite versatility

- instantaneous and versatile learning and knowledge

By relating the requirements for autonomic ideality criteria King (2002) concludes that the highest expression of ideal autonomous objects currently envisioned is holonic systems.

3.2 Assessing the suitability of holonic systems to a commodity chemical producer

3.2.1 Research rationale

Contemporary literature hails holonic systems as a solution to the growing demand for flexible and responsive manufacturing. Moreover, this preoccupation with its ability to enable agility has guided, but also limited, the scope for its application to industries that overtly exhibit these drivers. This also holds true for considerations as to its use in the chemical processing industry where it is currently limited to campaign type operations within the speciality chemicals industry. Again, this industry exhibits mainly the same drivers as the discrete manufacturing industry which has so far been the focus of holonic applications (for example, mass customisation, speed to market, new processes and products etc.).

However, the analysis performed in section 3.1 suggests a novel view of holonic systems as a higher order concept that simultaneously solves contradictions currently plaguing the manufacturing industry (e.g. efficiency vs. flexibility) without resorting to trade-offs.

The CAPE-21 survey report (2001) divides the sectors in the chemical processing industry into two main categories:

- mature commodities, where throughput and cost reduction through efficiency are drivers
- fast moving specialities, where speed to market and flexible operations are the drivers.

Consequently, in order to extend the scope for holonic systems application in the chemical processing industry this study deliberately focuses on a mature commodity producer with explicit drivers of cost reduction and throughput.

A large petrochemical manufacturer in South Africa was chosen as a basis for analysis. The information presented in this study, while representative, has been generalised in order to avoid invoking intellectual property limitations which would have placed it outside of the public domain.

3.2.2 Assessment methodology

The suitability of holonic control to the petrochemical industry is determined by the extent to which it enables the pursuit and attainment of strategic goals and consequent business requirements.

The resource based strategy cascade by Grant (1999) is useful as an assessment model. In its needs based mode this model takes the business strategy as the point of departure which then requires particular profit drivers (rent generating potential), which in turn require particular capabilities, which in turn require particular resources (including technology). Based on this model the assessment methodology deployed in this study consists of answering the following questions:

- what are the strategic drivers and their associated profit drivers and manufacturing requirements in the petrochemical industry?
- in what way does holonic control systems enable pursuit of the strategic objectives?

These questions are systematically answered in the following sections.

3.3 Suitability assessment

The suitability is based on the two research questions outlined above in section 3.2.2

3.3.1 Strategic drivers, profit levers and manufacturing requirements

Question: What are the strategic drivers and their associated profit levers and manufacturing requirements in the commodity petrochemical industry?

Methodology: Information readily available in the case study company, interviews with key personnel and the literature survey are used to position the general strategic posture. This is mapped to a DuPont chart in which the profit levers and manufacturing requirements are pointed out.

According to Porter (1985) a firm can adopt either of two strategic postures – cost leadership with parity on differentiation, or product differentiation at cost parity. Based on Swift (1999), the CAPE-21 survey report (2001) and expressly stated by the case study company, the strategic posture is that of cost-leadership. This is generic to the commodity petrochemical industry.

Consequently, the profit levers are variable cost and, for the case study company who are able to sell all products that it produces, sales volume.

From this perspective variable cost is predominantly a function of the cost of feedstock, process material and utilities. Variable cost can therefore reduced by operating more efficiently – which then becomes the first business requirement.

In the situation where all produced goods can be sold, sales volume is a function of throughput which in turn is determined by availability and optimisation to process constraints (maximum throughput).

This corresponds to a make-to-capacity requirement. Importantly, the case study company wants to evolve from this operating requirement to one of make-to-plan and then make-to-order in future.

The above information is used to derive reduced DuPont charts which are given in figures 15 and 16 respectively.

Figure 15 ***Reduced DuPont chart for a cost-leadership make-to-capacity petrochemical industry***

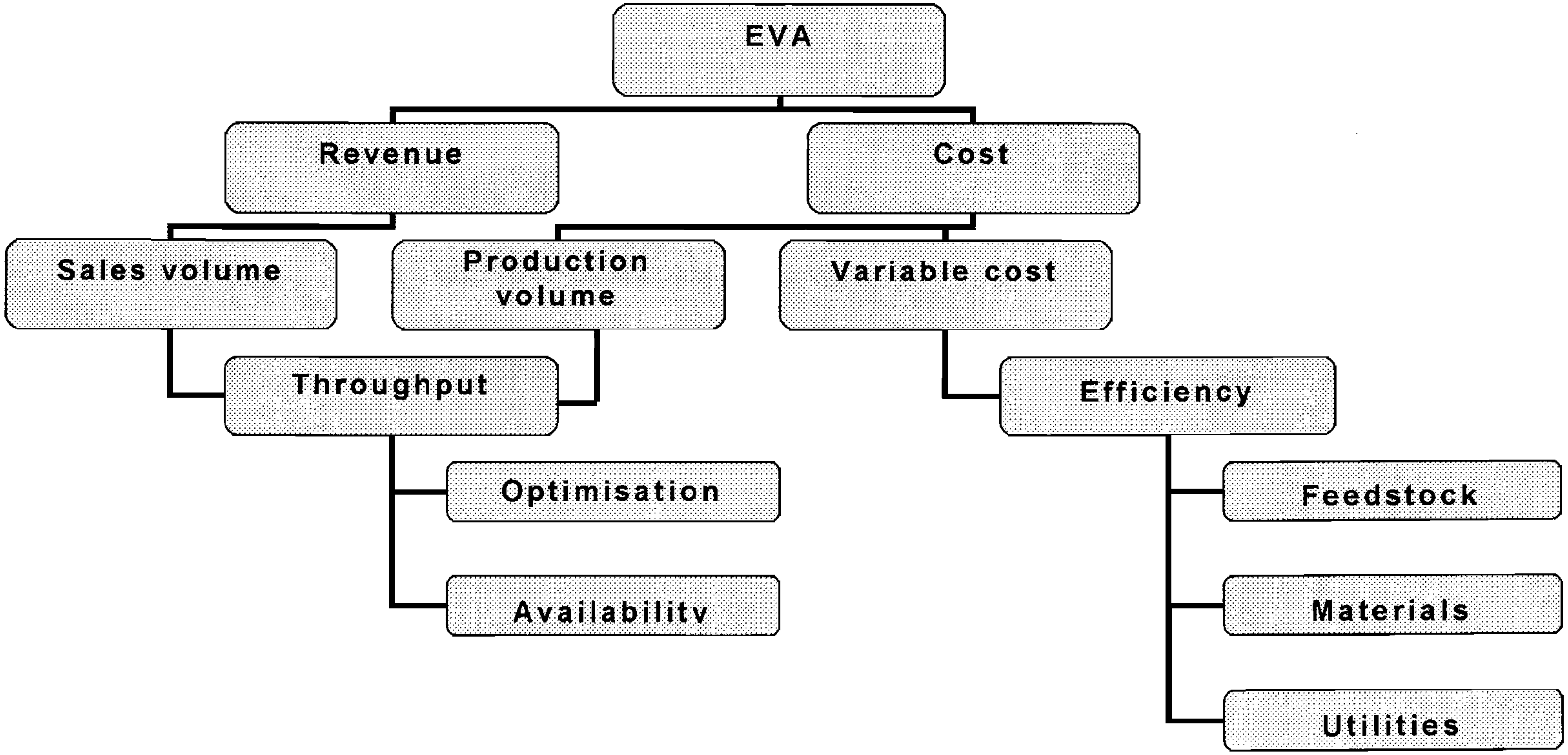
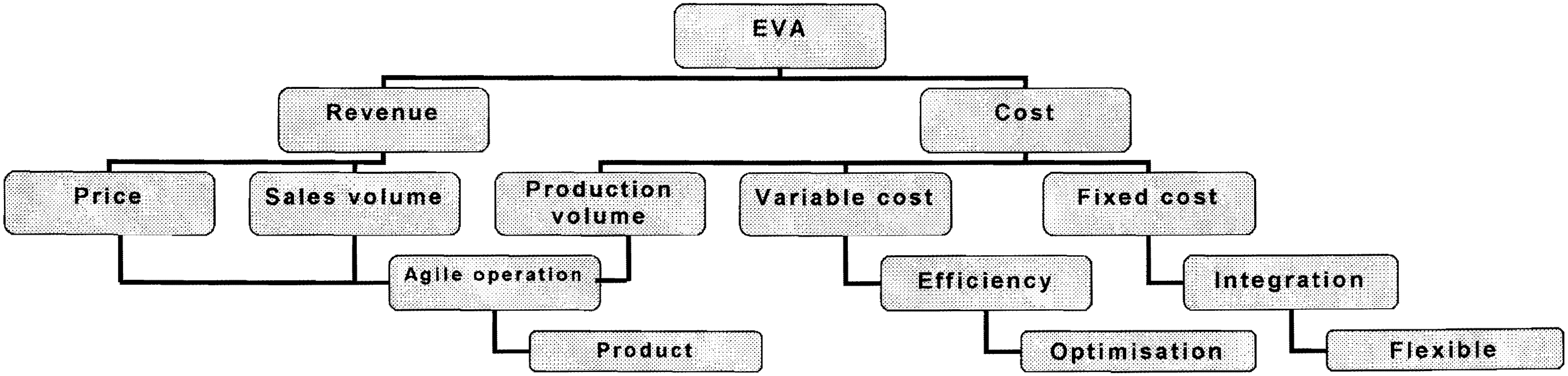


Figure 16 ***Reduced DuPont chart for a cost-leadership make-to-order petrochemical industry***



Figures 15 and 16 provide the answer to the second research question: *"What are the strategic drivers and their associated profit levers and manufacturing requirements in the commodity petrochemical industry"*

3.3.2 Mapping business drivers to holonic systems attributes

Question: In what way would holonic control systems support the pursuit of the strategic objectives?

Methodology: Strategy, business driver and automation requirement data from the case study company (augmented by the literature survey) is mapped to a technology roadmap. Since they represent two different strategic postures taken to its manufacturing extreme, both make-to-capacity and make-to-order tactics are considered. The assessment is based on the literature survey, information readily available in the case study company as well as interviews with key personnel.

A three tier roadmap (the generic form of which has been described in section 2.9) is used: tier one is focused on strategy and tier two on business requirements, while tier three, which is focused on automation requirements, then becomes a useful framework for assessing the viability of a particular control system.

In table 12 the business requirements for both make-to-capacity and make-to-order are mapped to the profit drivers that were identified in section 3.3.1. The profit drivers are subsequently mapped to operational requirements.

These operational requirements are used to derive generic automation requirements respectively for make-to-capacity (table 13) and make-to-order (table 14).

Finally, the attributes of holonic systems, as discussed in the literature survey, is mapped to the generic automation requirements for make-to-capacity (table 15) and make-to-order (table 16) respectively.

Table 12 Conceptual technology roadmap

Strategy	**Make-to-capacity cost leadership**		**Make-to-order cost leadership**		
Profit levers	Efficiency	Throughput	Agile operation	Efficiency	Integration
Operations requirements	**Operations availability** - identify, analyse and react to deviations that could impact on operations availability - supply chain visibility - equipment available and healthy - managed turn-around cycles - feedstock, process material and utilities available and conform to quality requirements - skills availability - total value chain focus; looking for threats	**Process optimisation** - reduce losses - reduce variability that impacts on throughput; dynamic stability - identify and operate closer to dynamic constraints - maximise feedstock, utilities and material yield - dynamic capacity maximisation - identify, analyse and eliminate deviations that impact on optimisation - total value chain focus; looking for opportunities - quality control	Product selection - control process selectivity - flexible product spectrum - identify, understand and manipulate process levers - flexible, managed supply chain - sense and respond to market opportunities - total value chain focus - equipment, process, product and operator integration	Manufacturing optimisation - manage mass, energy and component balances - reduce losses - dynamic capacity maximisation for selected product(s) - identify, analyse and eliminate deviations - total value chain focus; looking for opportunities - quality control	Flexible processing - adaptable processing routes - flexible equipment (in terms of throughput, mix, duty, severity etc.) - understand and manage the impact of change
Automation requirements	See table 13 and 15 below.		See table 14 and 16 below		

Table 13 *Automation requirements for process optimisation and operations availability (make-to-capacity)*

Automation requirements	Operations availability							Process optimisation							
	identify, analyse and react to deviations that could impact on operations availability	supply chain visibility	equipment available and healthy	managed turn-around cycles	feedstock, process material and utilities available and conform to quality requirements	skills availability	total value chain focus; looking for threats	reduce losses	reduce variability that impacts on throughput	identify and operate closer to dynamic constraints	maximise feedstock, utilities and material yield	dynamic capacity maximisation	identify, analyse and eliminate deviations that impact on optimisation	total value chain focus; looking for opportunities	quality control
Dynamic control strategies		X					X	X				X		X	
Optimisation of load distribution and constraint control										X	X	X	X		
Fundamental production accounting	X	X						X					X	X	X
Enable dynamic stability	X		X		X		X						X	X	
Manage process, product, equipment and operator health			X	X	X	X									
Improve understanding of the manufacturing process		X				X								X	

Table 14 *Automation requirements for agile operations, optimisation and flexible processing (make-to-order)*

Automation requirements	Product selection							Manufacturing optimisation						Flexible processing		
	Manage process selectivity	flexible product spectrum	identify, understand and manipulate process levers	flexible, managed supply chain	sense and respond to market opportunities	total value chain focus	equipment, process, product and operator integration	manage mass, energy and component balances	reduce losses	dynamic capacity maximisation for selected product(s)	identify, analyse and eliminate deviations	total value chain focus; looking for opportunities	quality control	adaptable processing routes	flexible equipment (in terms of throughput, mix, duty, severity	understand and manage the impact of change
Manage transients		x	x	x	x		x				x			x	x	x
Manage constraints			x			x		x	x	x		x		x	x	x
Fundamental manufacturing accounting								x	x		x					
Improve understanding of the manufacturing business			x		x	x	x	x			x					x

Table 15 *Fit of holonic systems to make-to-capacity automation requirements*

Holonic systems attribute	Dynamic control strategies	Optimisation of load distribution and constraint control	Fundamental production accounting	Enable dynamic stability	Manage process, product, equipment and operator health	Improves understanding of the manufacturing process
flexible association				x		x
aggregation			x	x		x
specialisation			x	x		x
distributed control				x		
local decision making				x		
local task execution						
local monitoring and detection		x	x	x		x
auto-diagnosis		x	x	x	x	x
auto-repair			x		x	
autonomous	x	x		x		
cooperative	x	x		x		
reactive	x			x		
pro-active	x			x		
adaptive	x			x		
selective	x					
robustness	x			x		
facilitates human interaction			x		x	x

Table 16 *Fit of holonic systems to make-to-order automation requirements*

Holonic systems attribute	Manage transients	Manage constraints	Fundamental manufacturing accounting	Improve understanding of the manufacturing process
flexible association	x	x		x
aggregation	x		x	x
specialisation	x		x	x
distributed control	x			x
local decision making	x			
local task execution	x			
local monitoring and detection	x	x	x	x
auto-diagnosis		x	x	x
auto-repair			x	
autonomous	x	x		
cooperative	x	x		
reactive	x	x		
pro-active	x	x		
adaptive	x	x	x	
selective	x			
robustness	x			
facilitates human interaction	x		x	x

This section provides the basic elements required to answer the third research question, namely *"In what way would holonic control systems support the pursuit of the strategic objectives"*. This is discussed in detail the Discussion (section 4) and Conlusions (section 5).

4 Discussion

4.1 Holonic systems as a milepost within a stream of consistent evolution

The theory of inventive problem solving is aimed at consistent evolution through step wise invention and innovation. It resolves apparent conflicts in the attributes of systems by suggesting a third higher order concept in which the contradiction does not occur.

Applying this technique to the typical contradictions experienced in the chemical processing industry yields an abstract solution that closely resembles holonic theory. This is a strong indication that the holonic concept will be an inevitable result of continuous improvement and innovation.

It also clearly indicates that the preoccupation agility rather than efficiency in holonic systems research is the result of an approach that is constrained by the anticipated business drivers in the discrete manufacturing environment, rather than a constraint of the concept as such.

Combined, this forms a strong argument for initiating research on holonic systems applied in the chemical processing industry.

4.2 The current conceptual viability of holonic systems to a commodity petrochemical producer

4.2.1 Dynamic control strategies

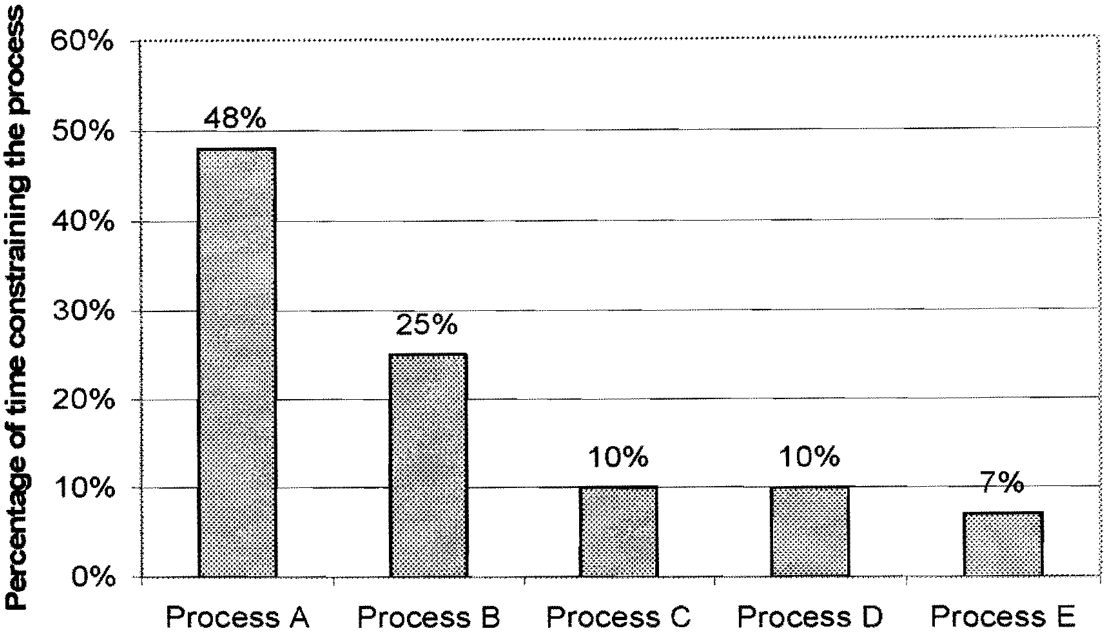
By its very nature, the manufacturing process consists of a number of sequential steps in which a number of inputs are systematically transformed into products and waste. The process performance is constrained to the sustainable maximum performance of the least capable process step.

Goldratt (2000) have developed a so called *theory of constraints* that recognises and alleviates this predicament by identifying and exploiting the available excess capacity as buffers that in turn ensures that the process constraint is never idle.

Traditional control strategies acknowledge this need and are aimed at constructing a system that is honed to perfection for optimising the performance of the main process constraint. These systems are designed top-down and mostly consist of fixed, centralised control hierarchies that are ineffectual at dealing with operating challenges outside of its explicit design objectives.

In reality a commodity petrochemical plant consists of a number of alternating processing constraints as depicted in figure 17 (data biased). Note that 52% of the time the main process constraint is not active.

Figure 17 ***Process constraints***



The self-organising, adaptive and cooperative nature of holonic systems ensures that the control system would dynamically restructure to optimise process performance under changing active constraints.

Also, traditionally control systems are designed with fixed relationships between the controlled and manipulated variables (for example cascade and multivariable control). Often these relationships are limited to remain within a single process or unit. Variables from outside the unit process that impact on the performance of the controlled variables are simply treated as irrevocable disturbances. This is often fallacious and leads to a suboptimal structuring of process variance.

The benefit of the holonic control system would be in its ability to identify and adapt to form the optimal process control holarchy for current operating conditions. An example would be in controlling a reactor. The typical traditional control strategy is to manipulate the temperature, pressure and retention time in order to control product yield and selectivity. However, reactant composition which is, say, controllable by manipulating the temperature of a reformer might be the dominant determining input variable.

In the case of the holonic control system the reactor control holarchy will, after a negotiation (and validation) process, simply subsume reactant composition into its control structure through aggregation. This could also be achieved through traditional centralised control strategies. The difference lies in the ability of the process control holarchy to dynamically and continuously form and dissolve control acquaintances to best suit current operating conditions.

4.2.2 Optimisation of load distribution and constraint control

In order to improve the robustness and resilience of the sequential process a characteristic of chemical processing is that many processing steps have been fragmented into a number of parallel process units that are identical in design.

Due to differences in quality of process materials (such as catalysts), small modifications or even simply wear-and-tear, these processes, over time, exhibit different performance profiles. In some cases a unit parallel process will consistently outperform its peers, in others cases performance ebbs and flows with the continual cycle of regeneration and degradation of process material.

Firstly, this means that parallel processes at numerically equal loads are not necessarily equal distances from their respective constraints (do not have the same amount of excess capacity). Therefore, these processes should not physically be loaded equally, but rather based on equal distances from their respective constraints which improves efficiency.

Secondly, it also means that marginal performance (increment in performance for an increment in load) differs. Therefore, should more (less) reactants become available the parallel unit process with the higher (lower) marginal performance should be loaded more (less).

Fixed, centralised control systems have to be expressly designed to offer this functionality. In contrast, the flexible, cooperative, self-diagnostic attributes of holonic systems ensures that this functionality is innate and pervasive.

4.2.3 Fundamental production accounting

Process measurement plays an integral part in manufacturing execution. Measurements are subject to both random and systematic error which introduces a component of uncertainty, and hence inefficiency, in the process. Production accounting is a set of activities based on the law of conservation of mass and energy and is aimed at providing reconciled plant data.

In the absence of an accepted architecture for holonic systems in the chemical processing industry, it is believed that mass, energy and component holons will be used (amongst others). Due to their innate attributes of aggregation and auto-diagnosis, it is believed that the holarchy will attempt to resolve any mass, energy and component imbalances perceived.

The anticipated seamless integration between the holonic manufacturing system and the human participants, together with the available information on mass, energy and component balances could lead to a highly effective visualisation environment.

4.2.4 Enable dynamic stability

A common fallacy about commodity chemical processing is that the express pursuit of stability implies a high degree of static and steady state processes. In this vernacular, stability does not refer to its strict control theory definition of a bounded output response to a unitary input step change, but rather a reduction in standard deviation of business critical variables. This enables operation closer to the process constraint.

The reduction in variability of the controlled variables is, through the process gains, mapped to an increase in standard deviation of the manipulated variables.

In a similar way this concept of shifted variability from the business sensitive layer (for example product quality) to the less sensitive or even insensitive layer (for example valve movement) can be extended to the process in general. Essentially the underlying process flexibility (for example different product routes, buffers, redundancy) and process inputs (for example selective catalysts) are used to ensure the stability of the process outcomes (throughput and quality). A standby pump that immediately activates when its counterpart fails is a current example of such a setup.

Although this strategy is used extensively at the moment, it would be innate to a holonic control system (mainly through self-organisation, cooperation and auto-diagnosis) with the difference that the concept could be further extended systemically up to an interunit (global) level.

4.2.5 Manage process, product, equipment and operator health

Similar to figure 4 (section 2.2.1.1), it is believed that an holonic system in the chemical processing industry will consist of resource and product holons as well as plan holons (instead of orders). Production knowledge is captured between the product and plan holon; process execution knowledge is captured between the plan and resource holon; process knowledge is captured between the product and resource holon.

This architecture contains all the knowledge on the characteristics of the product, performance characteristics of the process and integrity, reliability, availability and utilisation profile of resources, as well as the interrelationship between product, process and resource health. For example, pushing a process to extreme performance could be unsustainable as it will increase the rate of deterioration in the integrity of equipment.

This, combined with the innate holonic attributes of auto-diagnosis, local monitoring and decision taking, being proactive, as well as improving value chain visualisation (in this case on manufacturing health) presents a promising platform for managing the health of products, processes and equipment.

In its collective it would also be able to flag inappropriate operator input.

4.2.6 Improves understanding of the manufacturing process

Being structured in an object oriented manner affords holonic systems the benefit of structured complexity in which the level of exposed complexity can be matched to the interest of the observer. In this sense it caters for from local detail to global overview interests.

Furthermore, its object oriented nature ensures localisation of the impact of changes. This facilitates change which is an inherent part of maintenance or growth.

In literature, a holon's ability to seamlessly interface with humans is defining. Matching its general social society structure, the human becomes a natural integrated extension of the holonic system. Also, the interaction between holons with respect to detailed cooperation and autonomy would provide a very rich source of information on the manufacturing process to humans which will be understandable even on an intuitive level.

4.3 The conceptual viability of holonic systems to the commodity chemical producer of the future

4.3.1 Manage transients

The commodity chemical producer of the future will be more responsive to market demands through an improved ability to selection and produce different products. In the extreme case commodities will be produced in campaigns in flexible equipment and processes. This will alleviate some of the cyclicality in the commodities market.

As a result, future plants will experience deeper (with respect to mass, energy and component balances) and wider (with respect to the number of processes involved) transients.

In this way it resembles mass-customised discrete manufacturing to a larger extent and thus the brunt of holonic system research becomes relevant.

Under these conditions, Chokshi (2001) summarised the benefit of holonic systems as:

- the ability to structure complexity
- distributed architecture and control
- self-organising and dynamically integrated
- bottom up design approach (the ability to sequentially pursue more than one set of business goals are inherently designed into the system)

4.3.2 Manage constraints

To the future chemical commodity producer the incentive for utilising holonic systems with respect to constraint management is similar to that described in section 4.2.2 but is extended to cover the whole manufacturing chain.

4.3.3 Fundamental manufacturing accounting

Similar to that discussed on 4.2.3. but extended to cover the whole manufacturing value chain (including suppliers and customers). In this domain the holonic system is extended to cover both manufacturing execution and enterprise resource planning. An example would be the automatic generation of orders by the customer based on its inventory of product, the subsequent (potential) restructuring on the side of the manufacturer to produce the required product as well as the subsequent order of the required raw materials to the supplier.

4.3.4 Improve understanding of the manufacturing business

Similar to the discussion in 4.2.6. In the case of a make-to-order manufacturer the understanding of the manufacturing process is essential. As in 4.2.4, this concept is extended to cover the manufacturing execution and enterprise resource planning.

5 Summary and conclusions

Contemporary insight into the worth and implication of the holonic systems as a concept is predominantly based on its interpretation as a construct in the discrete manufacturing industry and, consequently, its business drivers.

As such, this preoccupation with the apparently defining ability of holonic systems to enable agility has guided, but also limited, the scope for its application to industries that overtly exhibit these drivers. Importantly, this also suggests that the fixation on agility rather than holistic efficiency in holonic systems research is the result of an approach that is constrained by the anticipated business drivers in the discrete manufacturing environment, rather than a constraint of the concept as such.

This notion is substantiated by the theory of inventive problem solving (TRIZ) that specifies an holonic system in solving the apparent contradictions that previously saw holonic theory confined to the arsenal of agility enablers only.

This realisation is important as it significantly increases the scope for the potential application of holonic systems, none more so than in particular sectors of the chemical processing industry.

Therefore, in contrast to the traditional perspective of not considering the application of holonic theory in efficiency driven industries, this study maintains that it is equally applicable and therefore warrants further investigation.

In light of this imperative to improve our understanding of the holonic concept, this study explored both the concepts of modularity and intelligent agency as similar streams of thought.

The unique insight gleaned from modular architectures is that it is geared towards fulfilling a general responsibility rather than a specific function and therefore facilitates change. It enables changing the implementation without affecting the interfaces. As such, it also ensures structured cooperation. This specifically improves our understanding of the way in which holons should be delineated as well as their cooperative nature.

On the other hand, the unique contribution of intelligent agency is that it provides a vision of agents in control of their own actions in pursuit of their own agenda. No hierarchy exists but multiple layers which represent different levels of knowledge abstraction that is localized and encapsulated within the same entity. This specifically improves the understanding of possible internal structures for the holon and their autonomous nature.

In conclusion, object orientation and intelligent agency are important bodies of knowledge that, due to their similarity and intensely researched nature, efficiently facilitate our understanding of the main concepts of holonic theory and its strongly needed further operationalisation.

The knowledge gleaned from the analysis of modularity, intelligent agency and holonic theory per se, enabled this study to then focus on the industrial application of holonic systems.

The bulk of contemporary holonic applications are directed towards the discrete manufacturing industry with the goal of mass customization in order to support a strategic posture of product differentiation at cost parity. While holonic theory present obvious opportunities in enabling this strategy, the predilection with this posture has also to a large degree defined and confined the understanding of the holonic concept.

Despite having been one of the focal points of holonic systems research, no single technical architecture has been adopted as the industry standard. The architecture mostly commonly used consists of order, product and resource holons that between them capture production, process execution and process knowledge.

A standardized architecture would facilitate the further operationalisation of holonic systems and should therefore form an immediate and strong focus point of its application in the chemical processing industry.

While discrete manufacturing is fundamentally concerned with balancing and integrating the flow of physical components, the chemical processing industry is fundamentally concerned with the balancing of mass, energy and chemical component flows. This difference in focus will be reflected in the standards that are eventually adopted in the different industries.

Main business drivers in the discrete manufacturing industry have been identified as:

- reduced product life cycles
- reduced time to market
- volatile product mix
- abundance of product features
- reduced investment

They are summarized as an increase in both complexity and responsiveness and are largely similar to those experienced in the speciality chemical industry. From the point of view of needs-based strategic fit holonic systems are conceptually more effective in supporting these drivers than traditional centralized manufacturing execution systems.

Having analysed the state of the art of holonic systems in discrete manufacturing especially in terms of the business rationale framework this study then focused on the basic composition of the chemical processing industry as well as current and foreseen future traditional control system innovations.

Technology application is subject to strategic posture. Whereas the speciality chemicals, life sciences and consumer products sectors adopt a similar posture to the discrete manufacturing industry, namely product differentiation at cost parity, the basic chemicals sector is currently based on cost leadership with little or no product differentiation.

For this reason, the very limited research that has been conducted into the viability of holonic systems to the chemical processing industry have focused on speciality chemicals and campaign based operations where the strategic posture is the same as in the manufacturing industry.

Therefore, this study purposely focused on the basic chemicals sector, and specifically a commodity petrochemical producer, in order to prove the applicability of holonic systems to a wider strategic base.

In order to accomplish this, a substantiated framework was required to facilitate the assessment. Two different approaches to strategy were considered. In the first (five forces model) strategy is seen as a purposeful positioning within an industry based on external threats and opportunities and is summarised in either of two strategic postures: product differentiation or cost leadership.

In the second (resource based view) strategy is based on the strengths and weaknesses within an organisation which in turn is based on the resources it has to its avail and is summarised as being either needs-based or needs-searching.

The link between strategy (both external and internal focus) and technology (as a resource) is based on strategic fit and functional integration. Different alignment perspectives were identified but one used throughout research in the manufacturing industry is the strategy execution perspective (business strategy determines organizational infrastructure which in turn determines the technical infrastructure).

Within this perspective technology roadmapping was selected as an assessment framework, the unique contribution of which lies in its ability to visually explore the alignment between strategy, business and resources over time. From the different roadmapping techniques studied a consolidated approach and tool was developed to specifically use as an assessment framework.

This framework was then applied to a commodity petrochemical producer. Firstly, its strategic posture was identified as one of cost leadership (hence the reason for focusing on this sector). Importantly, it was also noted that while the company is currently producing to capacity, in future in wants to migrate to produce-to-plan and finally produce-to-order which would put its business drivers much more in line with the typical discrete manufacturing industry. Therefore, the company ideally needs to invest in technology that supports the current but also future manufacturing approach.

Under the current make-to-capacity cost leadership strategic posture, the profit drivers have been identified as efficiency and throughput with associated operation requirements as process optimisation and operations availability. This translated to the following automation requirements:

- dynamic control strategies
- optimisation of load distribution and constraint control
- fundamental production accounting
- enable dynamic stability

- manage process, product, equipment and operator health
- improve understanding of the manufacturing process

From this analysis, and in answering the third research question, the benefits in adopting holonic over traditional control systems are:

- an holonic control system is more effective in dealing with the continual change in manufacturing bottlenecks leading to higher overall throughput,
- from a global process view, it is also more effective at structuring overall process variability by fundamentally assuming the most optimal control structure consisting of controlled and manipulated variables,
- the imperative to optimize loading on parallel units is innate and will always occur, as opposed to traditional control systems where it has to be specifically designed for every application
- mass, energy and component production accounting is innate with auto-diagnosis and repair behaviour to resolve imbalances,
- it is better suited to fully utilize the available production flexibility in maintaining the stability of business sensitive parameters,
- it would render a more effective human-machine interface. Its modular structure hides unnecessary complexity from the user and localizes the impact of changes. Matching its general social society structure, the human becomes a natural integrated extension of the holonic system. Also, the interaction between holons with respect to detailed cooperation and autonomy would provide a very rich source of information on the manufacturing process to

humans which will be understandable even on an intuitive level

These clear opportunities present a convincing case for utilising holonic automation even in current basic chemical manufacturers.

Under the anticipated future make-to-order cost leadership strategic posture, the profit drivers have been identified as agile operation, efficiency and integration with associated operation requirements as product selection, manufacturing optimisation and flexible processing. This translated to the following automation requirements:

- manage transients
- manage constraints
- fundamental manufacturing accounting
- improves understanding of the manufacturing process.

The business drivers and trends in the commodity producer of the future is more aligned with that of the mass customized discrete manufacturer. Benefits similar to that obtained by the make-to-capacity manufacturer are to be gleaned with the exception that transients will be deeper and wider and the inclusion of the enterprise resource layer into the holonic manufacturing structure. These changes could potentially leave traditional control systems obsolete – made irrelevant by their inherent inflexibility.

An additional benefit would be that migrating to an holonic automation system in pursuit of current benefits under the make-to-capacity regime, also provides a sustainable solution to potential future make-to-order strategic postures.

In conclusion, it is maintained that this dissertation has sufficiently answered the specific research questions that was outlined at the outset and that it has achieved its objectives.

However, these clear and tangible benefits provide a compelling argument for continuing research but now directed towards the functional detail level – how will this be done?

In taking this work further, one firstly should develop a conceptual holonic architecture for a chemical processing manufacturer which will provide a basis for functional detailed studies. Secondly, the clear conceptual benefits discussed above provide natural focal points for further research.

A third area of research that fell beyond the scope of this dissertation is that of combining holonic automation with true holonic processing equipment and processes.