INTEGRATION IN ADVANCED MANUFACTURING: A SYSTEMS AND CONTROL PERSPECTIVE

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ABSTRACT - *The problem of system integration in the context of an Industrial Enterprise is a multidimensional problem with fundamental dimensions those of: (i) Overall process operations, (ii) Overall System Design/Redesign, and (iii) Information, Data and Software. Each of the above three areas is of multidisciplinary nature and it is frequently considered by the respective groups as representing the entirety of the problem. The aim of this paper is to consider the general problem of integration from all its fundamental aspects, focus on two of the key paradigms, that is Global Operations and Overall Design and then show that systems and Control concepts and problems play a central role in the development of an overall integration methodology and associated techniques. The subject of modelling emerges with a central role in the effort to develop integration and new families of systems emerge in the corresponding areas. Amongst the important families of systems that are crucial for system integration are the Multilevel hybrid systems (Hierarchy of Operations), Structure Evolving systems (in the total Design), and Object Dynamic Systems (Data problems). The significance of the above families in the integration process and their link with generalised control problems are discussed. The paper provides an overview of the subject area and focuses on the development of the general conceptual framework for integration. It also provides an agenda for Systems and Control Theory around the theme of Evolving or Evolutionary Systems which are the new areas emerging in integrating the overall design.*

Keywords: Systems Integration, Control Strategies, Organization, Systems Modeling.

1. INTRODUCTION

The current desire for greater flexibility, higher efficiency, cost reduction and shorter cycle times together with concern for the environment, quality and safety, demands an integrated approach encompassing all types of activity from high level strategy to plant operation. Business level strategies cannot be accepted as feasible unless their realisation on the different operational layers is first considered; similarly, operational strategies are not acceptable unless their implementability on a given system, process is evaluated. The increased requirements for efficient, safe and environmentally friendly operations process plants can be met provided that they have been considered already at the early stages of plant design. Furthermore, modern plants are composed of units with smaller size and medium capacities, but with extensive use of recycles and increased degree of energy integration, which make the plant operation more sensitive to disturbances and possible lead to inherently unstable behaviour. Therefore, to design plants that are safe, easy to operate and cost-efficient, a new approach is required that will transcend the traditional separation and sequencing among the activities of process design, such as chemical process engineering (or other process nature dependent discipline), process optimisation and economic appraisal, instrumentation engineering, and control analysis and design. Designing plants which can perform well throughout their life cycle is difficult. Issues of redesign of existing systems frequently arise when the original operational assumptions are not valid anymore. Integrating operations and design is a formidable scientific and technological challenge. The close integration of business, operational and design issues has not been considered so far in any systematic way and this has been the source of difficulties in implementing effectively business level strategies on industrial processes. The setting up of operations and design activities are supported by databases and software systems, which however are usually dedicated to the particular activity. Integration of software systems and data structures is an important issue which heavily depends on adopting common standards. However, there are issues in data modelling which have a distinct significance due to the integration requirements.

The current practice of treating every issue independently, without taking into account the existing interactions, and relying on testing for the evaluation of alternatives, is time consuming, expensive and rarely leads to good results. The need for an integrated approach that breaks the traditional boundaries between technical and managerial disciplines, also between operational and design issues, as well as between software and data supporting individual activities is becoming very strong. Global enterprises have to be able to respond to sudden changes in market demands and this implies that they have to be able to propagate high level decisions throughout the organisation down to the lowest level and in turn be able to perceive and react to changes at the lowest level. The responsiveness of the plant to such requirements implies that operational requirements have to be interpretable to design terms and these should be considered at the design stage; otherwise, the problem of plant redesign has to be considered, which by no means is a simple matter. The natural hierarchical organisation of operations and tasks defines a multimodel environment where understanding the role of interfaces becomes a critical issue. Hybrid systems are naturally linked to the problem of understanding behaviours based on multimodel interconnected processes, whereas global control and measurement issues arise due to the hierarchical form of organisation.

Manufacturing systems are defined on physical processes which have to be such that they can respond well to the multitude of operational requirements. Design, or redesign of the engineering system is thus intimately related to operations and this raises the important issue of integrating design and operations. The problem of design itself is a multitask, multidisciplinary problem which also provides an area where integration is a fundamental problem. This is due to the sequential (cascade) nature of the design problem, where every stage has its own tasks and criteria. The characteristic of such a process is the evolution of the system formation as we go through the different stages and integration here means understanding and being able to affect such an evolutionary process. Two distinct forms of evolutionary processes are associated with design: the first is evolution of structure due to the cascade nature of the process, whereas the second is time evolution due to the early or late stage of the overall design process. Each one of them describes different aspects of the integration in design. Understanding such processes is also important in handling issues of systems redesign, which emerge when the process has to be modified to meet new requirements.

Supporting overall operations and design requires appropriate data, information structures and software tools. The natural linking of the operations and design aspects implies that the corresponding data and software systems must also reflect such interconnections. Linking data and software systems expresses the third aspect of integration which is the one mostly considered so far. This area largely depends on adopting common standards; despite its great significance, it will be considered only briefly, and we will focus on those aspects which have a clear systems dimension. Of special interest is the problem of describing transformations in data systems, which introduces another type of evolving, or evolutionary systems to those arising in design, and have significant impact on integration. The area of Object Oriented dynamical systems or Temporal object based systems [14] is an important new field that emerges here.

The aim of the paper is to consider the system and control aspects of integrating operations and design of industrial processes (with the emphasis here on the first), identify the general families of problems that arise, and describe the associated modelling issues. The objective is to identify the generic issues, rather than discuss specific problems in detail. The paradigm that will be used is that of continuous processes (as far as the engineering system). The main contribution of the paper is that it provides a unifying Systems, Modelling and Control framework within which the problem of Systems Integration in manufacturing system may be considered. This is achieved by introducing a number of generic clusters of problems which are prerequisites for the development of an integration methodology and technology. Such families of problems define the backbone of the integration methodological framework and include the examination of issues such as:
(i) Functional Model Derivation and Interfacing,
(ii) Model Embedding of Function Models,
(iii) Global Controllability of the Operational Process hierarchy (Realisability of high level strategies),
(iv) Global Observability of the Overall Operations (Model based Diagnostics),
(v) Operations–Design Interfacing,
(vi) Model Structure Evolution in Design,
(vii) Early-Late Design Variable Complexity Modelling and prediction of System Properties, and
(viii) Evolutionary Systems and Data Structures.
Such clusters contain a plethora of specific problems, most of which are new and define new areas for research.

The paper is based on concept of integration presented in an elementary form by [24] and it is organised as follows: In section (2), we describe the problem under consideration and raise some general issues. In section (3), we consider the problem of integration of Process Operations and in section (4), we introduce the basics of the problem of integrated design. In section (5), integration issues related to data are considered. The paper provides a description of issues and problems and thus it remains on a non-technical level.

2. PROBLEM STATEMENT AND GENERAL ISSUES

Complex Systems is a generic term used to describe some of the major challenges in Science and its applications, Engineering, Business, Society, Environment, etc. The term refers to problems which may be of large or small scale, centralised or distributed, have a composite nature (in terms of simpler sub problems), high degree of interaction between subsystems, manifest a multi-facet behaviour (in terms of particular aspects), have possibly an internal organisation and require a multidisciplinary approach for their study. It is thus clear that complexity has many different dimensions and gaining understanding for each of these dimensions is critical in developing approaches for complex systems. The nature of complexity implies that there is need for division of the overall problem into sub problems which may be more easily handled by teams of specialists.

Such solutions are usually worked out by teams of experts with little knowledge on the issues of the other areas; furthermore, there is no global co-ordination and understanding of the interactions of the alternative aspects of complexity and this makes the development of acceptable global solutions a major challenge. Systems Integration emerges as the general task that can co-ordinate the activities in the particular sub problem areas to produce solutions which are meaningful and optimal (in some sense) for the whole. The development of a systemic approach for complex problems is the essence of integration. This requires ability to specialise the set of global objectives to the level of the subsystem, methods to work out solutions which are locally and globally feasible and in a sense optimal, as well as understanding of interactions between the subsystems and alternative aspects of the overall problem. Systems integration is a multi-task, multidisciplinary problem which is central in handling the major challenges in technology, economy, society, and environment.

The problem of system integration in manufacturing systems is examined here and it is considered [10] nowadays as a major technological challenge; this, however, is perceived by different people in different areas from entirely different viewpoints. The dominant trend is to treat the problem as a software problem and neglect the multidisciplinary nature of the task and the very many different aspects of the problem, apart from software and data. The paradigm of discrete manufacturing, which is characterised by the presence of buffers between operational and dynamic performance of unit processes, has also influenced the developments in integration and created the general impression that technical and operational issues may be treated independently. The practical significance of integration has created some urgency in working out solutions to difficult problems and this has led to the development of interdisciplinary teams empowered with the task to create such solutions. Bringing together people from different areas is clearly necessary, but not sufficient in producing solutions with acceptable performance.

The key issue here is the lack of methodology that bridges disciplines and provides a framework for studying problems in the interface of particular tasks. Recent developments in the area of hybrid systems, new developments in the area of organisation and overall architectures contribute in the emergence of elements of such a methodology. There are, however, many more aspects in the effort to develop a framework of integration which are currently missing. This paper deals with the needs for development of a systems based, holistic approach to the problem of integration that addresses the emerging generic systems, modelling, control and measurement problems in a systematic way.

The overall problem of systems integration in manufacturing systems may be represented by the following diagram

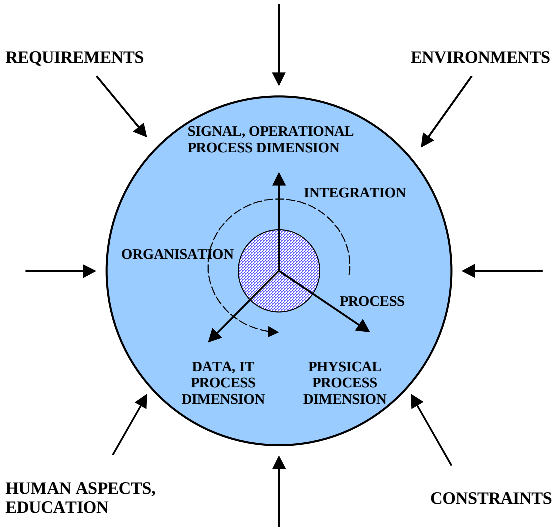

Figure (1): Basic System Shell of Manufacturing Integration

where activities are grouped in the three main dimensions each one of them having their own integration aspects. These are:

(i) Physical Process Dimension
(ii) Signals, Operations Dimension
(iii) Data, IT, Software Dimension

and there is a number of side activities which are relevant to all above. The Physical Process Dimension deals with issues of design-redesign of the Engineering Process and here the issues are those related to integrated design. The Signals, Operations Dimension is concerned with the study of the different operations, functions based on the Physical Process and it is thus closely related to operations for production. In this area, signals, information extracted from the process are the fundamentals and the problem of integration is concerned with understanding the connectivities between the alternative operations, functionalities and having some means to regulate the overall behaviour. Both design and operations generate and rely on data and deploy software tools. Compatibility and consistency of the corresponding data structures and software tools expresses the problem of integration in this area and relies heavily on adopting common standards. The development of integration requires support from a number of other areas such as formation of multidisciplinary teams, relevant educational programs, etc.

Our study is based on the paradigm of continuous processes. This is selected because it contains almost all challenges that emerge in integration; this is due to the strong coupling between the different technical operational stages, as well as enterprise issues on one hand and design – redesign problems on the other. The fact that integration in the process area is of paramount importance for improved profitability in a global market (flexibility in product portfolio and market variability), enhanced safety and satisfaction of frequently conflicting and stricter requirements (environment, other legislation), as well as enhanced quality and reliability makes this paradigm is challenging. A simple illustration of the overall enterprise level activity is given in Figure (2) below.

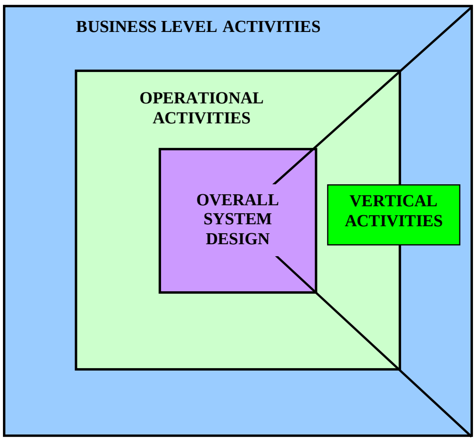

Figure (2): Nesting of Industrial Enterprise level activities

The following main areas are distinguished:

(a) Business Level Activities
(b) Production Related Operations
(c) Overall Systems Design
(d) Vertical Activities

The diagram indicates a natural nesting of problem areas, where design issues provide the core, linked with the formation of the physical process that realises production.

Production level activities take place on a given system, they are mostly organised in a hierarchical manner and they realise the higher level strategies decided at the business level. Vertical activities are issues going through the Business-Operations-Design hierarchy and they have different interpretation at the corresponding level. The problem of integration of Business level, Operation Issues and Design aspects is a multidisciplinary problem which is recognised as one of the major technological challenges. Understanding the relationships between problems on a horizontal (same level), as well as vertical (going through different levels) directions, implies an ability to describe the links between models associated with the particular problems, as well as a capability to translate issues, requirements from one set up to another. Typical problems in each of the areas of the nested diagram are:

(a) Business Level Activities: Here we include issues such as Enterprise strategy, new products and processes, Investments, Improvements etc.

(b) Operational Level Activities: Typical issues here, relate to production are Logistics, Desired Operations, Process Optimisation, Process Control and Supervision.

(c) Overall System Design: Issues included here are Process Synthesis, Global Process Instrumentation, Control Systems Design, Systems Redesign, Real Time Issues and implementation.

(d) Vertical Activities: General nature activities such as Maintenance, Reliability, Quality assurance, Software system support etc. are issues which naturally touch all different layers and may thus be referred to as vertical activities.

An agenda for long term research is to develop a systemic approach that aims at**:**

(i) Providing a conceptual framework that explains the interrelationships between the different aspects - problems of the integrated Technical Operations hierarchy,
(ii) Select the appropriate modelling tools that describe the particular problems and provide

qualitative and quantitative means enabling the understanding of hierarchical nesting and system properties emerging at different levels,
(iii) Study control, optimisation and state assessment problems in the integrated overall operations set up; this involves top-down control and bottom-up diagnostics-prognostics issues,
(iv) Understand the link between operational requirements and process design criteria, develop criteria, modelling concepts and methodologies that explain the evolution of physical system structure through the different stages of the cascade design process,
(vi) Formulate methodology, procedures which may guide design along paths, which guarantee the formulation of systems with desirable characteristics,
(vii) Develop methodologies for redesigning existing systems to meet new operational requirements,
(viii) Explore the system aspects of data merging and transformations which may provide useful tools that may support the operational and design aspects of integration.

3. THE OPERATIONAL HIERARCHY AND THE INTEGRATION PROBLEM

3.1 Description of the Operational Hierarchy

The operation of production of the types frequently found in the Process Industries relies on the functionalities, which are illustrated in Figure (3). Such general activities may be grouped according to certain criteria described below (see also [3]):

(a) Enterprise Organisation Layers
(b) Monitoring functions (i.e. measurement, assessment) providing information to upper layers.
(c) Control functions setting goals to lower layers.

Note that the process unit with its associated Instrumentation (sensors and actuators) are the primary sources of information. However, processing of information (definition of diagnostics) can take place at the higher layer. Control actions of different nature are distributed along the different layers of the hierarchy (control and decision problems). The functions shown in Figure (3) are of the following type [1]:

(a) **Operations Planning**: This refers to activities such as feedstock negotiation and acquisition, customer orders, resource planning etc.

(b) **Production Scheduling:** This is concerned with the optimal timing of different operations runs and involves the combination of feedstock types and specification of the required type/quality of end products from all production locations

(c) **Load Allocation:** This involves the setting of the loads of the processing and utility plants of the overall production unit, such that they satisfy the production scheduling constraints.

The above three activities are known as Logistic type of activities and deal with general issues of production. As such they are also present in other industrial or commercial activities, apart from continuous processes. In the latter case, however, such functions are strongly connected with the technical operations described below:

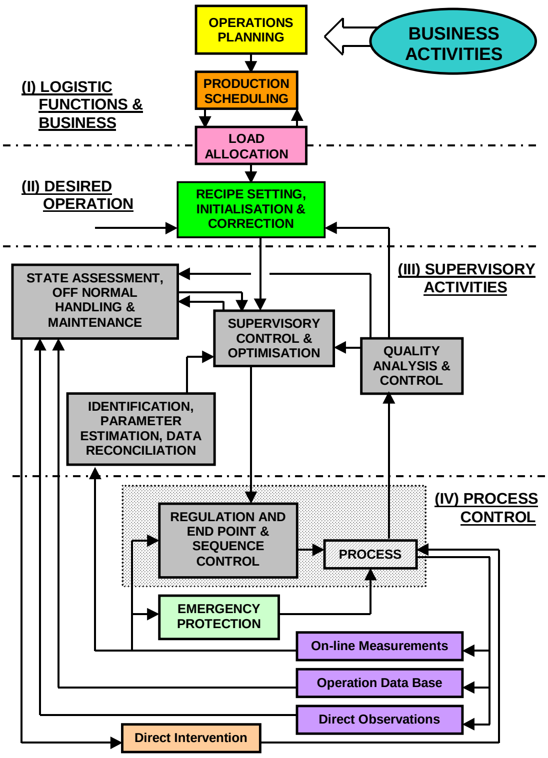

Figure (3): Functions for Operations of Process Plants

(d) **Recipe Setting/Initialisation/Correction:** This is the higher layer of supervisory activities and deals with the co-ordination of the "mode" of operation defined as the set of conditions required for producing the desired products.

The above activity is technical, it is referred to as Desired Operation, and it is a set of technical procedures required to produce the desired product. Although the procedure is determined in a general way (a priori knowledge) there is room for the fine setting of parameters and this involves some higher level control action. The main layer of technical supervisory control functions involves the following group of functions:

(e) **Quality Analysis and Control:** This involves the measurement, estimation of the important quality variables and attributes and then the initiation of corrective actions when product quality deviate from the set standards.

(f) **State Assessment, Off Normal Handling and Maintenance:** This set of activities are linked to the estimation of the actual "state" of the process based on all available information. In case of detection of off-normal process conditions there is a need to implement procedures to remedy the situation. In the case of emergency the Emergency Shut Down Systems provide Emergency protection. The set of all these activities are linked to maintenance and in particular predictive maintenance activities.

(g) **Supervisory control and Optimisation:** Integrating the results from desired operations, quality analysis, state assessment and the general business objectives (coming from the higher business layers of the hierarchy), as well as taking into account the operational constraints (physical) and regulatory constraints (safety, environment etc) to produce an optimal policy, is the aim of the current task. This activity produces as output the optimal set points for the physical operation of the process.

(h) **Identification, Parameter Estimation, Data Reconciliation:** The off-line and on-line control activities require models and relevant data that can lead to the identification of such models. Part of the supervisory activity, in collaboration with the design team, is the selection of the data, their validation, and then the identification of model parameters. Such an activity provides links with design, as well as model based diagnostics. This area is part of a wider activity referred to as Data Management.

The above activities are of supervisory nature and refer to the Control room; the role of the process operator is to supervise and integrate all such activities. The automated part of the physical process is referred to here as Process control and involves:

(i) **Regulation, End Point and Sequence Control:** This refers to the regulating control loops, usually embedded in the Process Control and Data Acquisition (PCDA) systems (i.e., DCS). Direct intervention on the process from the Control room is also included here.

(j) **Emergency Protection:** This refers to the Emergency Shut Down Systems.

(k) **Process Instrumentation and Information System:** This refers to the overall system for on-line Measurements, Creation of the System Data base and may involve direct Observations, Data Storing and Management.

It is apparent that the complexity of operating the production system is very high. A dominant approach as far as organising such activities is through a Hierarchical Structuring [6]. However, other forms of organisation are emerging at the moment, [12], but their full potential has not yet been evaluated in the context of process systems. The study of systems and modelling issues depends on the organisational form that is adopted. Here we will restrict ourselves to the Hierarchical organisation paradigm [6].

3.2 Modelling Issues in the Operational Hierarchy

The study of Industrial Processes has as main aspects those related to Design and Operation of Processes. For the study of both areas we require models of different type. The border lines between the families of Operational Models (OM) and Design Models (DM) are not always very clear and frequently the same model may be used for some functions. Models linked to design are "off-line", whereas, those used for operations are either off-line, or "on-line". In the strict sense these two types are not linked; however, in automated processes, on-line data can be used for revalidation and updating of off-line models and thus the usual distinction between off-line and on-line models tends to become blurred.

For process type applications, models are classified into two main families referred to as "line" and "support" models [1]. Line models are used for determining desired process conditions for the immediate future (set points for regulatory control etc.), whereas support models provide information to control models (i.e. parameter values), or they are used for simulation purposes.

Another major classification of models is those referred to as "black" and "white" models [1]. White models are based on physical, chemical and/or biochemical principles and their development requires a lot of process insight and knowledge of physical/chemical relationships. Such models can be applied to a wide range of conditions, contain a small number of parameters and are especially useful in the process design, when experimental data are not available. Black models on the other hand are based on standard relationships between input and output variables containing many parameters, require little knowledge of the process and are easy to formulate; however, such models require appropriate process data and they are only valid for the range, where data are available. Black models can be turned to grey ones [1], if we know the ranges of process variables; hybrid, "White/black" models also may arise, when part of the model is white, whereas difficult parts (such as chemical reactions etc.) are modelled as black models.

The overall problem of Process Operations is characterised by a high degree of complexity. The natural way of handling high complexity is through aggregation, modularisation and hierarchisation [7], and this is what characterises the overall OPPCP structure described in Figure (3). To be able to lump a set of subsystems together and treat the composite structure as a single object with a specific function, the sub-systems must effectively interact. Modularisation refers to the composition of specific function units to achieve a composite function task. Aggregation and modularisation refer to physical composition of subsystems through coupling, and it is essentially motivated by the needs of design of systems with dedicated operational function. Hierarchisation on the other hand, is related to the stratification of alternative behavioural aspects of the entire system and it is motivated by the need to manage the overall information complexity. The production system may be viewed as an information system and thus notions of complexity are naturally associated with it [7].

Hierarchisation has to do with identification of design and operational tasks, as well as reduction of externally perceived complexity to manageable levels of the higher layers. At the top of the hierarchy, we perceive and describe the overall production process as an economic activity; at this level we have the lowest complexity, as far as description of the process behaviour. At the next level down we perceive the process as a set of interacting plant sections, each performing production functions which interact to produce an object - the economic unit activity - at the higher level of description.

We can describe how the process at the lower level of logistic functions area works, if all the production units at this level of description effectively interact. At the next level down we are concerned with specification of desired operational functions for each unit in a plant section and so on we can move down to operation of units with quality, safety etc., criteria and further down to dynamic performance etc. In an effectively functioning hierarchy, the interaction between sub-systems at lower level is such as to create a reduced level of complexity at the level perceived above [7]. The hierarchisation implies a reduction of externally perceived complexity successfully, as we proceed up the hierarchy till the top level.

The natural way to specify the different types of models needed for OPPCP is to link them with the operational functions and thus follow the hierarchy described by Figure (3) and try to identify a clearer stratification of basic operational functions. A simpler representation of the overall operational hierarchy of Figure (3) is as shown in Figure (4), which is an extension of a standard process control hierarchy [8] that incorporates all functions described in Figure (3). Each of the above levels has the following modelling requirements [13]:

0-level: (*Signals, Data Level*). Physical variables, Instrumentation, Signal processing, Data Structures.

1-level: (*Primary Process Control*). Time responses, simple linear SISO models.

2-level: (Dynamic Multivariable Control). Linear, Nonlinear Multivariable Dynamic models.

3-level: (*Supervisory Control Level*). Process Optimisation Models, Statistical Quality Models, (SPC, Multivariate, Filtering–Estimation), Fault Diagnosis Models, Overall Process State Assessment Models (Heuristics, Neurofuzzy, Qualitative, etc.).

4-level: (*Plant Operation and Logistics*). Nonlinear Static or Dynamic Models for Overall Plant, Operational Research Models (Queuing etc.), Discrete Event Models (Petri Nets, Languages, Automata).

5-level: (*Global Production Planning Level*). Production Models, Planning, Forecasting, Economic Models, Operational Research, Game Theory Models.

6-level: (*Business Level*). Enterprise, Business Modelling, System Dynamics, Forecasting, Structural, Graph Models, Economic Models, etc.

The overall range of models mentioned above may be classified into the following main classes [1]:

(i) Models for Logistic/ Recipe Functions (MLRF)
(ii) Models for Quality and Regulatory Control, and for Process Information (MQRCPI)
(iii) Models for the Supervisory Functions (MSF)
(iv) Models for Data Reconciliation (MDR)

A fundamental problem in modelling is, understanding the derivation of the different functional models and how they are interfaced. We shall refer to this problem as the *Functional Model Derivation and Interfacing* (FMDI). The different types of models in the above groupings are interrelated. Each of the model families on the unit level are simplified and aggregated to models on the plant level and then on the production site, business unit and possibly the enterprise level. Model composition accompanied by simplification is the dominant feature in the modelling task. The latter classification is of functional type and the Process Control Hierarchy implies a nesting of models.

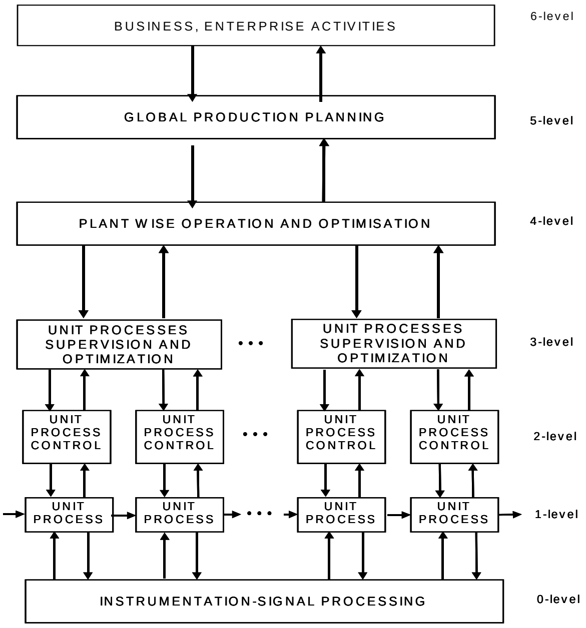

Figure (4): Overall Operational Hierarchy

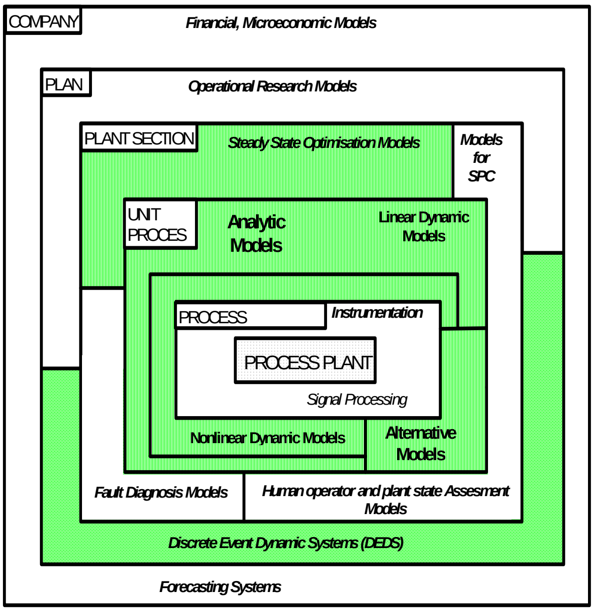

Figure (5): Model Nesting in Process Control Hierarchy

The above diagram indicates that at the level of the process we have the richest possible model in terms of signals, data, full dynamic models. Then, as we move up in the hierarchy, the corresponding models become simpler, but also more general since they then refer not to a unit but to a section of the plant etc.

The operation of extraction of the simpler models is some form of projection, whereas wider scale models are obtained by using plant topology and aggregations. The mechanisms of projection depend on the particular function the model addresses and they are not always well understood. These models, although of different nature and scope, are related, since they describe aspects of the same process. Dynamic properties of subsystems are reflected on simpler, but wider area models, although not in a straight forward way. This is what we may refer to as *Embedding of Function Models* (EFM).

3.3 Global Control and Measurement Issues

The hierarchical model of the Overall Process Operations involves processes of different nature expressing functionalities of the problem. Such processes are interlinked and each one of them is characterised by a different nature model. We adopt an input-output description of each of the subprocesses, with an internal state expressing the variables involved in the particular process and inputs, outputs expressing the linking with other processes. Such a model is generic enough to be used for all functionalities described in Figure (3) and can take a specific form determined by the nature of the specific process.

We may adopt a generic description for the various functions as shown in Figure (6), where $u_1,\ldots u_p$ denote independent manipulated variables of the function model, called system inputs; $y_1,\ldots, y_m$ are the independent controlled variables that can be measured and they are called the system outputs $d_1,\ldots, d_q$ are the exogenous variables which cannot be manipulated, but they express the influence of external to the particular function variables and they are called disturbances.

A model describing the relationships between the vectors, $\underline{u}$, $\underline{d}$, $\underline{y}$ is expressed as $y = H(u;d)$ where H expresses a relationship between the relevant variables, and it is called an input – output model. The construction of such a model is a major problem and involves:

(i) For the given function establish a conceptual model for its role in the operational hierarchy.

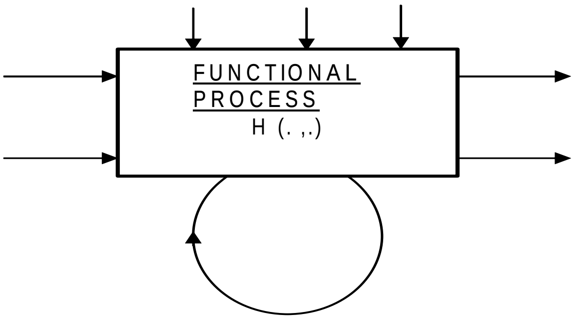

Figure (6): Generic Function Model with Internal Structure

- **(ii)** Define the vector of internal variable $\underline{z}$ associated with the problem and determine its relationships to input, output vectors by using any physical insight that we may possess about the functioning of the internal mechanism.
- **(iii)** Establish the relationships between the alternative vectors $\underline{z}$ associated with problems of the operational hierarchy.
- **(iv)** Define the appropriate formal model to provide an adequate description for the H functional model.

These generic steps provide an approach, which involves many detailed modelling tasks. Typical problems here are issues such as classification of variables to inputs, outputs, disturbances, internal variables [9], specification of formal description for H, definition of performance indices etc. When the classification of internal variables is completed, the key issue is the establishment of relationships between such variables; such relationships may be classified to implicit and explicit (oriented) forms respectively as:

$$M\ (u,y,d\,;z)\begin{cases} F\ (\underline{z},\underline{u},\underline{d})=0 & (1)\quad \text{(IMPLICIT)} \\ y=G\left(\underline{z},\underline{u},\underline{d}\right) & (2)\quad \text{(ORIENTED)} \end{cases}$$

The nature of variables and the type of problem under consideration determines the nature of the F, G, functions. This model structure also shows how constraints F(z,u,d) can be propagated from higher to lower levels. The selection of $\underline{z}$ implies that the modelling exercise, expressed as an attempt to specify F, G includes the modelling of the interface of higher level operation to the level defined by $\underline{z}$. The model M($\underline{u}$, $\underline{y}$, $\underline{d}$; $\underline{z}$) in (1), (2) will be referred to as a *z-stage model*. The selection of the operational stage (i.e., logistics, scheduling, steady state optimisation, quality control etc.) determines the nature of the internal vector $\underline{z}$ and thus also of the corresponding $\underline{z}$-stage model.

The dimensionality and nature of $\underline{z}$ depends on the particular functionality under consideration. Describing the relationship between different stages internal vectors is an important problem and implies an understanding of interfaces between functions; this is closely related to the problem mentioned before as *Hierarchical Nesting*, or *Embedding of Function Models*. The fundamental shell of this hierarchical nesting architecture is described below.

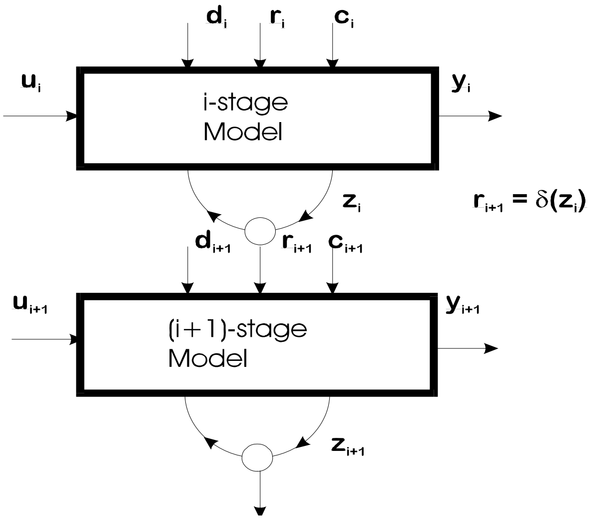

Figure (7): Nesting of models in the Hierarchy

Note that the vector reference image $\underline{r}_{\,i+1}$ of operational objectives of the (i+1)- stage is defined as a function of the ith-stage internal vector $\underline{z}_i$. A scheme such as the one described above is general and can be used to describe the meaning of the hierarchical nesting. Furthermore, such a scheme can be extended to describe relations between models associated with functions at the same level of the hierarchy, extend upwards to business level activities and downwards to the area of the physical process.

The fact that each stage model in the hierarchy is of different nature than the others makes the overall system of hybrid nature. It is clear that the theory of hybrid systems [4], [5] is crucial in the study of the control problems defined on the overall process hierarchy. Most of the work in the hybrid area has been concerned with two types of models; the characteristic of the present paradigm is that we have a multilayer hybrid structure. On this multilayer structure we have two fundamental problems:

- **(i)** Global Controllability Problem
- **(ii)** Global Observability Problem

The first refers to the fundamental issue of whether a high level objective (possibly generated as the solution of a decision problem at a high level) can be realised within the existing constraints at each of the levels in the hierarchy and finally at lowest level, where we have the physical process (production stage). This is a problem of *Global Controllability*, or alternatively may be seen as a problem of *Realisation of High Level Objectives* throughout the hierarchy. This open problem requires development of a multilevel hybrid theory and it can take different forms, according to the nature of the particular stage model. The Global Controllability problem described above is central in the development of *top-down* approaches in the study of hierarchical organisations, such as the process operations considered here.

The second problem refers to the property of being able to observe certain aspects of behaviour of the production layer of the hierarchy by appropriate measurements, or estimation subprocesses which are built in the overall scheme. This is a *Global Observability* property and it is related to the ability to define *Model Based Diagnostics* that can predict, evaluate certain aspects of the overall behaviour of the manufacturing process. It is assumed that the observer has access to the information contained at all stages of the model apart from the production layer, where only external measurement provide the available information.

The Global Observability problem is intimately linked to the *bottom-up* approach in the study of hierarchical organisations. The measurements, diagnostics defined on the physical process are used to construct the specific property functional models and thus global observability (ability to observe all types of behaviour of the physical process) is linked to the quality of the respective functional model.

Integration of Operations requires study of fundamental problems such as Functional Model, Global Derivation and Interfacing, Model Embedding of Function Models, Global Controllability and Global Observability of the Process Hierarchy. These problems are linked and establishing these explicit relationships is a challenging problem that may be referred to as *Process Operations Design* (POD).

These problems have been hardly addressed from the Systems viewpoint so far, with the only exception the recent work on hybrid systems, which covers only partially some of the issues raised in the above problems. Of course, Process operations are based always on a physical system, process. Establishing the links between Operational criteria (desirable goals) and Engineering Design Objectives – criteria, is a major challenge and it is referred to as *Operations–Design Interface* (ODI) problem. When operational objectives cannot be realised on the existing physical process, then the problem of Process Redesign arises and this is a problem that addresses together problems of Process Operations and Integration of Design simultaneously and can be considered within the current framework. In summary, the Integration of Operations involves a number of fundamental problems of the Systems, Modelling, Control and Measurement type which may be summarised as:

(O.P.1) Formulation of special Process functionalities as dynamic decision making problems

(O.P.2) Study of alternative forms of organisation of the Overall Process Operations and Business environment.

(O.P.3) Multimodelling aspects of the Integrated Extended Operations hierarchy and multilevel Hybrid Systems.

(O.P.4) Global Controllability of the Integrated Extended Hierarchy and realisation of strategies.

(O.P.5) Global Observability of production process and Model based Diagnostics.

(O.P.6) Integrating design aspects of alternative process operations.

(O.P.7) Interfacing Operational issues and Engineering Design of the production process.

(O.P.1) involves the formulation of individual function studies in the standard control framework, whereas (O.P.2) deals with the alternative forms of organisation, rather than the traditional Hierarchy adopted here. The areas (O.P.3)-(O.P.7) have been already discussed.

4. OVERALL SYSTEM DESIGN AND THE PROBLEM OF ITS INTEGRATION

4.1 Introduction, Background

The problem of overall design of large engineering processes is very complex multiobjective with very ill-formulated definitions and vague a priori ranking and qualification of preferences. It has a multidisciplinary character, and a cascade nature due to division of the overall problem into subproblems; working out solutions is a highly iterative process and the resolution of conflict (alternative objectives) is still an art. In fact, creating flowsheets will always be an art whereby more creative designers will obtain better results than less creative ones. Furthermore, plant-wide control strategies are implemented by the plant-wide control system of controllers. Control Engineering and Theory plays a key role in the development of an integrated philosophy for overall design; in this section we examine the fundamentals of the problem and a more detailed presentation may be found in [20].

The configuration of control systems for a complete chemical process is required to satisfy a multitude of diversified control tasks, such as:

(a) Regulate production and product quality,
(b) Satisfy environmental regulations,
(c) Provide safe and reliable operations,
(d) Achieve optimum economic operation,
(e) Reduce utilities consumption,
(f) Improve flexibility etc.

This diversity of high-level goals makes the process of designing control systems for complete chemical plants an activity in the province of expert designers, where experience and heuristics are important factors. In other application areas, such as discrete manufacturing, similar issues also arise. Indeed, no general theory is available for the systematic modelling of the process that leads to the design of such control systems. The existing analytical and to a certain extent, synthetic tools from control theory can only tackle isolated and fragmented issues, such as, analyse interactions of control loops, analyse the effect of model uncertainty on the stability and performance specifications, propose decomposition of control systems with minimum interactions etc.

There is no unifying Control Theory that answers all questions that arise in the overall process design. The area of integrated Process and Control Design has been recognised as very important, especially in the Chemical Process applications area [1], [2], [3], [15], [17], [18], however, the existing approaches largely depend on the specifics of the application area, rather than providing a general framework that may be used in different areas. The EU Projects EPIC [16], and SESDIP [19] have been some initial attempts to develop an integration philosophy assisted by appropriate concepts and tools [20].

4.2 Description of the Problem Area and Overall Philosophy

Within the area of overall design of chemical processes, issues related to integrated design have been addressed in areas such as [17], [18]:

(i) Evaluation of Process topology (flowsheets) with operability, stability, controllability, and economic criteria.
(ii) Steady State Process Optimisation
(iii) Selection of Controller and Control Structure.
(iv) Evaluation of the overall control performance in terms of plant reliability and economy.
(v) Advanced Control System Design.

and an overall configuration of the Design Hierarchy is given in Figure (8). For large dimension problems we have additional problems arising due to the large dimensions and the difficulties in computations, and coping with many design objectives simultaneously. Further areas of interest for such cases are:

(vi) Process decomposition
(vii) Decomposition into unit goal
(viii) Sequencing of the design process

Process decomposition is the reduction of a large problem into a sequence of smaller problems at the expense of having to deal with the co-ordination of the sequence of these sub-problems. In (vii) the decomposition of operations of each subsystems into Specific Unit Goals is considered, which in turn have to be co-ordinated.

These problems are not trivial since the goals of each unit are not specified a priori and the relations between the goals and the respective nodes of the decomposition are also unspecified. The sequencing of the design is the result of the Process design decomposition; that is having effectively decomposed the plant into segments that may be treated independently we have now to co-ordinate the individual goals into a sequence that involves the plant as a whole. None of the above activities can be undertaken without adequate modelling of the process.

Thus:

(ix) Process Modelling is essential prerequisite in any of the (i)-(vii) activities.

Additional important design tasks are:

(x) Process and Control Design for Safety
(xi) Process and Control Design for High Quality and Reliability
(xii) Process and Control Design for Flexibility of Operations

The latter two of the topics may be considered as more related to the final, detailed design; however, it is always desirable to incorporate generic characteristics from those two areas into the Early Design Stages. It should be noted, that all issues considered above do not always have the same nature, when continuous, or batch type processes are considered.

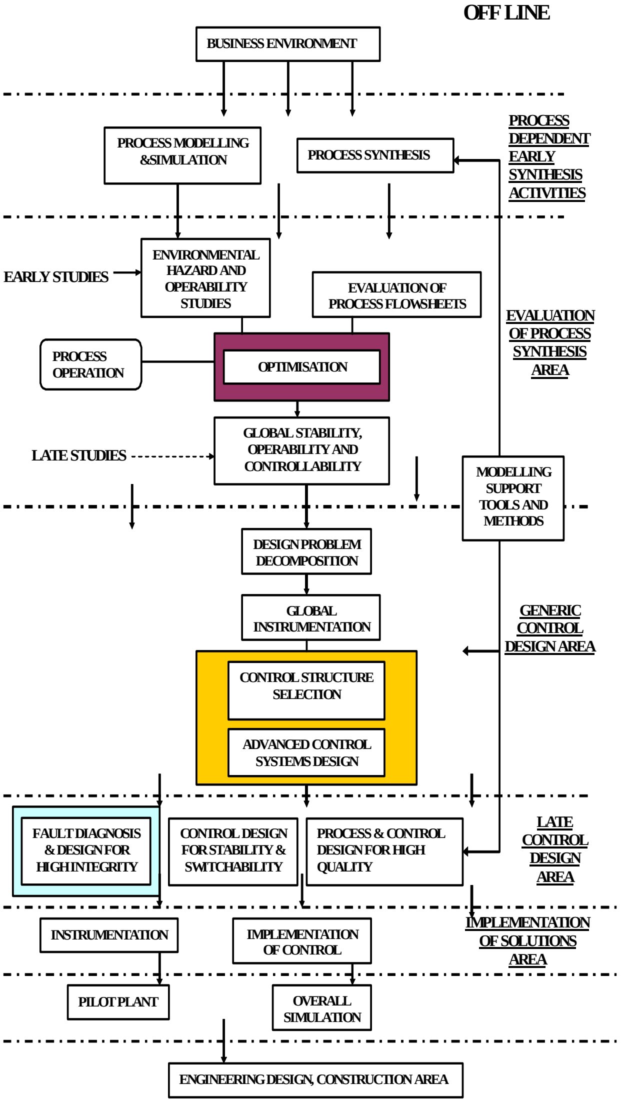

Figure (8): Overall Hierarchy of Systems Design

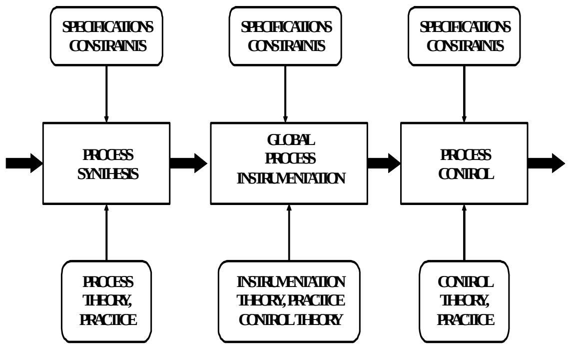

Figure (9): Simplified diagrams of design stages

A simplified diagram illustrating the main technological states of the overall design is described in Figure (9). The cascade nature of this design procedure has a number of dominant characteristics. In fact, the main inputs at each design stage are the skills, knowledge, theory, local objectives and specifications and the final result of the previous design stage expressed into the form of a model. Secondary inputs expressing transfer of information between different stages is mostly empirical, or expressing simple facts coming out of simulations. For most cases, there is no “a priori” knowledge of the implication of decisions taken on early design stages on the nature of possible results that may be achieved at the successive local stages. Defining “a priori” a tight set of specifications for every local design stage is also difficult, since what is best with local criteria, is not necessarily best when we look at the overall result.

The cascade design procedure is dynamic, in the sense that what is feasible to achieve at a given design stage is influenced by the decisions taken at the previous design stages. The trial and error procedure may be essential for small corrections and changes, but major alterations are time consuming, uneconomic and very frequently not possible. A body of knowledge, theory, techniques that can guide the overall design process taking into account both local and global criteria may be referred to as *“Global Integration Methodology”* (*GIM*) . The wholistic nature of the task implies that system theory and modelling are central in the effort to build GIM. Given that the easy, or difficult nature of the final control problems is usually the overall evaluator of the design, that makes Control Theory and Design also a crucial ingredient in the effort to develop GIM.

4.3 Systems, Modelling, and Control Issues in Process Synthesis

Process synthesis is an act of determining the optimal interconnection of processing units, as well as the optimal type and design of the units within a process system. The structure of the system and the performance of the process units are not determined uniquely by the performance specifications. The task is then to select a system out of the large number of alternatives which meets the performance specifications. The basic problems in Process synthesis are [18]:

(i) The Representation Problem,
(ii) The Evaluation Problem,
(iii) The Strategy Problem.

The first deals with the question of whether a representation can be developed, which is rich enough to allow all alternatives to be included without redundancy. The second problem deals with the question of whether the design alternatives can be evaluated effectively, so they may be compared. The final problem deals with whether it is possible to locate quickly the better alternatives without totally enumerating all options. Problems (i) and (iii) heavily depend on the specific applications areas; Systems and Control provide generic results which can be used to formulate alternative approaches based on generic concepts. Some of the generic problems requiring attention are discussed below.

4.3.1 The Representation Problem

The key issue in the Representation area is the generation of the required interconnection structure and this is based on the specifics of the application area. There exist however degrees of freedom in any engineering design and it is this space we would like to explore with Systems and Control results. Three important classes of problems linked to this area are:

(a) *Variable Complexity Modelling (VCM)*
(b) *Feedback Representation of Process Synthesis (FRPS)*
(c) *Structure Evolving Systems (SES)*

The *VCM* family is linked to the design procedure where we have a fixed interconnection structure but at the Early Stages we require *simple modelling* for subprocesses and Physical interconnections, whereas at the Late Stages of design *more detailed*, full dynamics models are required for subprocesses and interconnection structures. The study of such problems requires the development of a framework that permits the transition from simple graphs to full dynamic models and allows study of Systems and Control properties in a unifying way. Here, we essentially observe an evolution of the given structure of the system in the *design stage time* axis and this problem expresses the *Early-Late Design Variability of Model Complexity* [20], [21]. Important problems for this area are:

(a.1) Input-Output based Structural Analysis
(a.2) Variable dimensionality Structural Analysis
(a.3) Representation and properties of graph structure evolving systems

The first involves an extension of the graph theoretic approach from its current fixed state space set up to an input-output basis. This will provide the means for Structural Analysis which is based on input-output descriptions and are more relevant in the process setup. The second problem also involves an extension of the graph theoretic approach from the standard context of scalar transmittances to vector transmittances. This reflects the need that in early stages few variables may be used for a process stream, whereas at later stages more physical variables may be included in the modelling. The generation of overall system models from the general graph (scalar, or vector) and the available for the different design stages models for the subprocesses in a concise and uniform way is the subject of the third area and needs the previous results. These problems describe a new family of Systems, where their structure evolves as a function of the design time and this is referred to as *Design-Time Evolutionary Systems* (D-TES).

The second problem area (FRPS) deals with the problem of representing the overall interconnection of sub processes as an equivalent feedback design problem for which traditional Control Theoretic Tools may then be used. For linear systems this has been introduced in [21], but for more general subprocess model families (nonlinear etc.) the problem is still open. Transforming synthesis problems to standard representations, such as the feedback allows the use of existing methodologies; in fact, the equivalent feedback configuration allows the design of the interconnection graph in terms of feedback theory. This work is clearly related to issues of input, output selection and this introduces some additional aspects for evolving systems related to the problem of Global *Instrumentation* [9].

The third area relates to the notion of *Graph Structure Evolving Systems* (*SES*). This also emerges in a different form in the context of transition from conceptual to qualitative and then quantitative models of the process synthesis area, as well as the area of redesign, modification of existing processes. The distinct feature here is that we start with an elementary system cell and then progressively develop the overall structure by adding new sub processes and building appropriate interconnections. In this sense, the basic cell grows and eventually leads to the final design. This is a different form of evolution than those described above and it is reminiscent of similar processes in biology, crystalography, data structures and business modelling. In fact, the original system cell and those subsequently built determine a range of possible structures that may be constructed and thus act as carriers of a genetic mechanism, which however evolves.

4.3.2 The Evaluation Problem

The variety of alternative structures, process flowsheets, generated have to be evaluated with a variety of criteria. There are two main schools of thought relating to the evaluation process [1]:

(i) **Ideal Evaluation:** Assess the behaviour of a system with a controller of specified complexity, which is tuned optimally.
(ii) **Realistic Evaluation:** Development of low effort analysis tools which give a reasonable

indication of the quality of closed-loop behaviour and which allow the designer at least to rank order alternatives according to controllability, operability etc.

The first requires a complete system (with instrumentation and Control) and it is rather unrealistic (although scenarios based on models may be deployed). The view taken here is the development of realistic Evaluation Criteria and techniques which may assist in the overall evaluation. The following properties are important.

(1) *Flexibility*: Is defined as the ability of the system to handle a new situation at steady-state and thus express the ability to operate at different steady states.
(2) *Switchability*: Considers ability of a plant to be moved from one steady state operating point to another. This also involves start up and shut down of the process.
(3) *Controllability*: Is the "best" dynamic performance (set point following and disturbance rejection) achievable for a system under closed loop control.
(4) *Safety*: Examines the hazards that may be involved with particular designs and using process dependent heuristics provides a classification.

It is worth noting that Controllability here should be referred as *Process Controllability* and it is a much more general notion than the traditional system controllability. Note also, that Flexibility depends mainly on the structure of the process, whereas switchability and controllability depend on the system structure, as well as the selected control structure. It is also worth noting that controllability requires flexibility. The various tools and techniques from the above areas are classified according to the level of complexity of information required for evaluation, as well as the nature of disturbances. We may distinguish two approaches for handling the above issues:

(a) Process Based Criteria
(b) Control Theory and Design Criteria

The first of the above approaches is based on the heuristics and techniques of the particular application filed. Control Theory and Design are also involved in (a), but not in a formal way. The second approach relies explicitly on generic Systems and Control problems and it is based on the following two clusters of problems:

(b.1) Interpretation of Evaluation Criteria for Process Synthesis (IECPS)

(b.2) Prediction of Full Model System Properties (PFMSP)

The evaluation criteria for the Process flowsheets describe aggregates of properties of the resulting system. The exact System and Control context of these properties is not specified, i.e., interpretable in terms of values, properties of design indicators, invariants etc. Specifying exactly the meaning of all such properties is essential prerequisite to the Control theoretic evaluation of the alternative process structures. The final objective of the work here is a library of properties of values, types of design indicators, graph structural characteristics and parameter dependent invariants characterising the good or bad nature of the list of evaluation criteria.

The area in (b.2) involves an alternative, but closely related task that is the evaluation of process structures from the Systems and Control perspective. The essence of the work is the prediction of full model properties based on the knowledge gained in (b.1) and the understanding coming from the model structure evolution examined in the previous section. We use simple models and under the assumption that instrumentation (next phase) delivers the best possible final structure (model structure evolution continues under instrumentation) we try to establish some criteria predicting the fundamental system properties on the final that will emerge. Studies on the evolution of properties as the local model complexity increases (time based evolution) or the system structure progressively evolves are essential parts of the work here. Linear systems may provide the initial field of work and bifurcation theory has an important contribution to make. The field of multiobjective optimisation [23] is proving to be powerful for certain types of problems.

4.4 Control Theory and Design in the Context of Integrated Design

Control Theory and Design have developed around the classical servomechanism paradigm. The area of Systems Integration for large Complex Systems introduces many new challenges and a number of new paradigms which generate new requirements for future developments. For the case of integrating operations, the major challenges stem from the multimodelling context of the problem; this makes hybrid systems, issues of global controllability and observability in the hierarchy, as well as development of Systems and Control Theory for families of models describing specific functions the key areas for future work. In the case of design the challenges come from the evolutionary nature of the design process and its large scale, complex character which generates needs along the following two areas:

(i) Controlling the development of the Evolutionary Design Process

(ii) Addressing special requirements for Control Design of Large Complex Systems

For each of the above areas topics of importance are:

4.4.1 Control Theory and Design Problems for Evolutionary Systems

The overall philosophy, which is adopted, is that each particular design stage, in the overall design process, shapes a local model; the structure of this local model has important implications on what can be achieved at the next design stage, and it thus determines overall cost, operability, safety and performance of the final process. The formation of structural characteristics of the overall process is reminiscent of an evolution process. In fact, each design stage starts with a model and decisions taken there contribute to the gradual shaping of the final structural characteristics; however, this happens within a range of possible options. Structural properties and thus performance, operability, etc. characteristics evolve, but not in a simple manner. The main objective is to drive the model evolution along paths avoiding the formation of undesirable structural characteristics and where possible to assign desirable ones. In the effort to formulate a generic system/control based framework, as part of GIM it is essential to address issued referred to as Systems and Control Theory Problems (SCTP) which are listed below:

(DP.1) Characterisation of desirable, undesirable performance characteristics and the limits of what can be achieved.
(DP.2) Relate the best achievable performance characteristics to system model structure.
(DP.3) Establish functional relations between model structure and characteristics and model parameters.

4.4.2 Control Theory and Design for Large Scale, Complex Systems

For large dimension problems (systems with many inputs, outputs and many units) we have additional difficulties for their study both from the computations viewpoint, as well as handling many design objectives simultaneously. Furthermore, the large dimension of the problem, as well as the geographical separation of process units requires decentralisation in the structuring of the control scheme. Two of the main design problems in this area are:

(a) Design Problem Decomposition
(b) Selection and Design of Decentralised Control Schemes

The area of Design Problem Decomposition has as key issues: **(i)** Process decomposition, **(ii)** Decomposition into unit goal **(iii)** Sequencing of the design process. Process decomposition is the reduction of a large problem into a sequence of smaller problems at the expense of having to deal with the co-ordination of the sequence of these subproblems. In (ii) the decomposition of operations of each subsystem (unit) into Specific Unit Goals is considered, which in turn have to be co-ordinated. Interactions between process units introduce additional complications. These problems are not trivial since the goals of each unit are not specified a priori and the relations between the goals and the respective decomposition are also unspecified. The sequencing of the design is the result of the Process design decomposition: that is, having effectively decomposed the plant into segments that may be treated independently, we have now to co-ordinate the individual goals into a sequence that involves the plant as a whole. Important areas for work here are:

(D.P.13) Process decomposition for optimising steady state control.
(D.P.14) Process decomposition for regulatory control.

The above two types of decomposition are not independent: in fact, the second is only feasible within the bounds established by the first (1).

5. DATA AND GENERAL ASPECTS OF SYSTEMS INTEGRATION

The problem of Systems integration has a technical dimension, expressed by issues of Process Operations, Design and IT, as well as general aspects dealing with the Human support of the integrated framework and involving education and formation of interdisciplinary teams. Here we examine certain aspects of the IT framework, which have a system context and discuss briefly the educational requirements stemming from the needs to support the new integrating, multidisciplinary activities.

The development of methodology and techniques for integrating operations has also a software, information and data dimension such aspects support the local modelling, analysis and decision making and the problem of their integration is crucial for the design of integrated IT support for the Operations problem. The problem of software integration has dominated the overall area for many years and essentially is a problem of adopting common standards. Integrating data structures and information is however a more difficult problem since data structures for each of the production functions represent “primitive forms” of models, which support the functional modelling, and thus obey the same rules of connectivities and interrelationships coming from the production organisation. The interaction between data bases supporting the individual activities is thus a problem that has a systemic dimension and couples two key sub problems:

(SDP.1) Representation and Modelling of Lifecycle of Data Structures for individual Processes.
(SDP.2) Interconnection and Organisation of Data Structures of interacting Processes.

The first area deals with the study of data structures associated with a particular operational activity and aims to provide a systems based approach that explains the process of transformations in the data and provides a suitable framework for database integration. The need for such work was motivated by the requirements of business process modelling where, the continuously changing and restructuring business can only be modelling where, the continuously changing and restructuring business can only be modelled by a dynamic system supporting life cycles of its components (PRIMA project [11]).

The study of such problems reveals the existence of a new class of systems based on primitive objects and their relations, where transformations linked to their lifecycle are time and event driven. The distinguishing feature in this form of systems is that the notion of state space (attributes set) is not of fixed dimension, but may vary as time evolves and events occur and relations, connectivities, also follow a similar pattern. Describing the lifecycle of data linked to a specific functionality, provides the most primitive form of a model for this function; such models, provide the basis for the development of advanced behavioural models for the corresponding function.

To handle the problems of this challenging area, a very general new class of systems has been recently introduce referred to as *Object Dynamic Systems* (*ODS*) [14]. The development of ODS was based on the time and event driven evolution concepts of classical systems theory, the structured lifecycle approach of Object Oriented methodology and the experience of conceptual modelling, data modelling, systems analysis and database design. This new family of systems belongs to the general area of evolving systems and brings a new dimension through the variability of dimension of state and respective relationships associated with the primitive element, the *object*. The development of the ODS framework is a major challenge in (SDP.1) area.

The family of Object Dynamic Systems belongs to the general cluster of Structure Evolving Systems. Their distinguishing feature is that their basic cell, the object, is characterised by a variation in the dimensionality of its state and by a variability, evolution of the relations associated with it. Furthermore, the definition of the object and that of the associated relations are intimately linked. From this viewpoint, the modelling and dynamics of data structures is a paradigm that is closely linked to that of Business Processes. In fact, the life cycle of Business Operations involves a continuous structure modification (existing connectivities) and structure growth (development of new activities), as well as parameter changes. The example of Business Process Reengineering is a typical manifestation of this evolution of structure. The general experience from the technical Structure Evolution Systems, including that of ODS is expected to provide a new insight to the study of Modelling and Dynamics of Business level activities.

With the operational hierarchy of Figure (3) we have a variety of functions which are based on the given physical process and they are naturally interlinked, although not always in clear way. This implies that their respective databases are interacting as dynamic processes and this makes the problem of their integration described in SDP.2 an important one. A systems framework based on ODS seems to be a natural way to address the problem of interconnecting databases, since the methodology of interconnected and organised systems may provide a useful avenue for study of such problems. Integration of data structures has also an alternative meaning, stemming from the need to link the different families of models in the overall hierarchy. The linking and relationships between the different types of models (including data models) may be summarised in Figure (10).

The modelling of individual functions is a process that has many more additional features than those described above. If the vector of internal variables is a state vector (independece of associated attibutes) $\underline{\tilde{x}}$, then its state space $\tilde{X}$ is linked to the overall system state space X in terms of projection (aggregation). The overall state space X of the system corresponds to all variables associated with the Overall System and expresses the event and time evolution of them. Defining $\tilde{X}$ and X involves modelling and definition of appropriate measurement schemes; such measurements are not only physical, but they may be linked to specific metrics associated with the functional process. The time evolution of overall process generates data. The integrated database of the system contains all measurable information about the time and event avolution of X and additional information (issues related to physical process etc.). Specifying the nature of such relations is not a simple problem; ideally, when all $\tilde{X}$ is made up from measurable variables, this relationship (Data

$\rightarrow \tilde{X}$) is a projection. Creation of an integrated database that supports all processes and functions is a major challenge that cannot be addressed without understanding the more general aspects of integration of operations. Such knowledge is essential for the exact specification of links between individual databases. Issues of aggregation of data due to the projections involved in the operational hierarchy are also important, since they introduce additional dependencies between data structures at the different levels of the hierarchy.

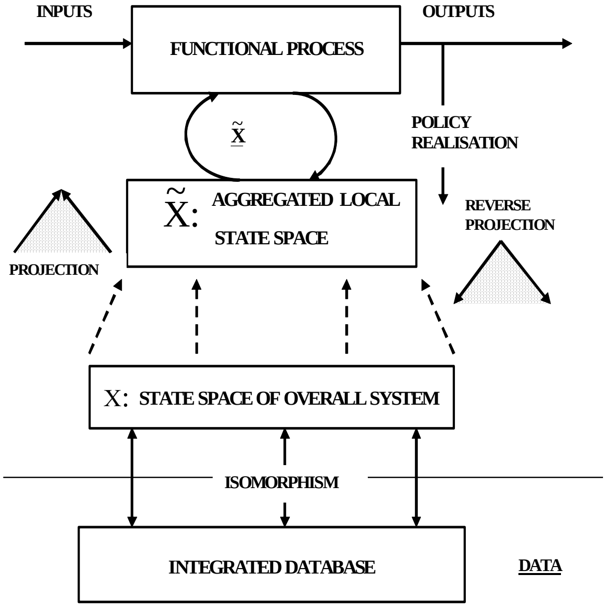

Figure (10): Abstract Functional Model and Dependencies

6. CONCLUSIONS

The paper has provided an overview of those technological aspects of systems integration which have a Systems, Modelling and Control dimension. It has been mainly preoccupied with the issues of Integrating Operations and Design aspects for industrial processes and in doing so it has specified a range of new open issues of the Systems and Control type as well as new families of systems which are intimately linked to the new applications paradigm. From this viewpoint, it provides a very challenging agenda for research in the Systems, Modelling and Control area. The two central themes which emerge are the needs for control and measurement in a multimodelling context, which makes multilevel hybrid theory a key area, and the development of theory and methodology for the different types of Evolving Systems. Such systems emerge in many different areas and with variability in their statement and form and require a fundamentally different approach and methodology to those of the traditional (non-evolving type).

Integration is a multidisciplinary activity and it is considered by many as one of the major challenges of the new technological revolution. Supporting multidisciplinary activities has many important additional dimensions, such as training and education, creation of multidisciplinary teams etc. Designing new educational activities and programmes are issues deserving a special attention.

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