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INTEGRATION OF OPERATIONS IN PROCESS SYSTEMS: COMPLEXITY AND EMERGENT PROPERTIES

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SUMMARY: *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 addressed by respective groups which consider their area as representing the entirety of the problem and they frequently ignore the other important dimensions. The aim of this paper is to consider first the general problem of integration from all its fundamental aspects and focus on the key paradigm of Global Operations. Within this area we consider the issues of system organization and in particular the problems relating to hierarchical organization of the different operational functionalities, the issues of aggregation and disaggregation and the related problems of the "top-down" and "bottom up" approaches. System complexity is considered within this framework and the notion of emergent properties is then considered as a problem of aggregation of behaviours, which may be also seen as projections within the setup of a control and information architecture. Such an architecture is defined for the multi-level hierarchical organisation we consider. We show that systems and control concepts and problems play a central role the development of an overall integration methodology and interpreting the features of the different emergent properties. The subject of modelling emerges with a central role in the effort to develop a methodology for systems integration, as well as quantifying the meaning of relevant emergent properties. The approach introduced here is intimately linked to Multilevel hybrid systems (Hierarchy of Operations), and provides a complementary dimension to issues of System Design (and Re-design) dominated by the theory of Structure Evolving systems (in the total Design and Life-cycle analysis) emerges as the central approach. The paper provides an overview of the subject area and focuses on the development of the general conceptual framework for integration.*

Keywords: Systems Integration, Organization, Complexity, Emergent Properties, Control Concepts

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. 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 that is central for systems integration. 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.

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. Issues of sustainability of performance in a fast changing environment cannot be addressed without an integrated view of the system. 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. The natural hierarchical organisation of operations and tasks defines a multi-model environment where understanding the role of interfaces becomes a critical issue.

The aim of the paper is to consider the system from a holistic perspective integrating business, process operations, the information systems dimension and finally the physical system (the production process) itself. This approach is essential in closing the loop between “top-down” and “bottom-up” approaches and thus eventually linking high level requirements to design of industrial processes and eventually to overall system redesign problem. Crucial to this effort is the identification of the general families of problems that arise, describe the associated modelling issues and then consider their solution. The objective here 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 of business and operations and their link to the physical system 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. An effort to link the above issues to design and system re-design is considered in [7], [16], [17] where the problems of: **(vi)** Model Structure Evolution in Design, **(vii)** Early-Late Design Variable Complexity Modelling and prediction of System Properties are considered in detail. Such clusters contain a plethora of specific problems, most of which are new and define new areas for research.

2. PROBLEM STATEMENT AND GENERAL ISSUES

The problem of system integration in manufacturing systems is examined here and it is considered [9] nowadays as a major technological challenge, but it is perceived by different communities from 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.

A general view of the manufacturing systems may be given by the following diagram

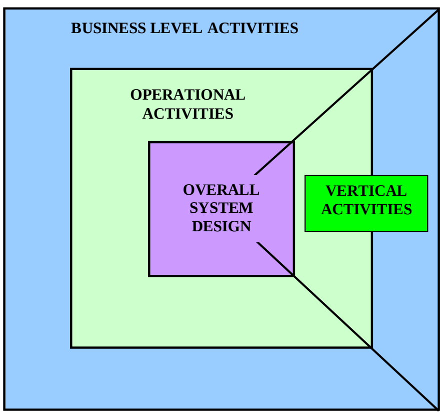

Figure (1): Industrial Enterprise level activities and their nesting

where the main areas are:

(i) Physical Process Dimension- System & Design
(ii) Operational Issues- Signals & Operations
(iii) Business Activities
(iv) Vertical Activities-Data, IT, Software

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 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, operations and business generate and rely on data and deploy software tools and such issues are considered as vertical activities. Compatibility and consistency of the corresponding data structures and software tools expresses the problem of software integration which relies heavily on adopting common standards.

The development of integration requires the formation of multidisciplinary teams, and the development of relevant educational programs, etc. Typical problems in each of the above areas are:

(a) Business Level Activities: They include issues such as Enterprise strategy, new products and processes, Investments, Improvements etc.
(b) Operational Level Activities: Include issues related to production such as 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: Include general activities such as Maintenance, Reliability, Quality assurance, Software system support etc.

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 design and system operations lifecycle. **(v)** Develop methodologies for redesigning existing systems to meet new operational requirements.

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 (2). Such general activities may be grouped according to certain criteria described below (see also [3]):

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

The process unit with its associated Instrumentation are the primary sources of information. However, processing of information can take place at the higher layer. Control actions of different nature are distributed along the different layers of the hierarchy. The functions shown in Figure (2) are of the 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.

These logistic activities deal with general issues of production and 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.

(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.

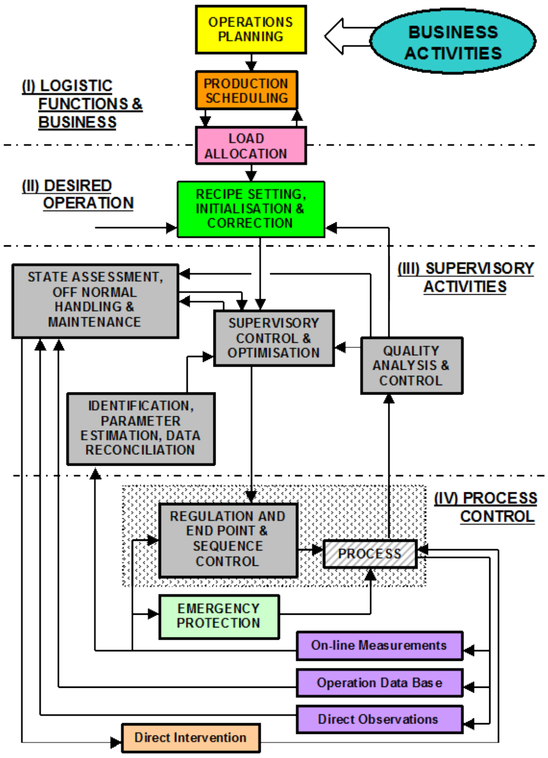

Figure (2): Functions for Operations of Process Plants

This above is referred to as *Desired Operation*, and it is a set of technical procedures required to produce the desired product. This procedure is determined in a general way by a priori knowledge. The main layer of technical supervisory control functions involve:

(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: These 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 Emergency protection).

(g) Supervisory control and Optimisation: Integrating the results from desired operations, quality analysis, state assessment, the general business objectives, as well as taking into account the operational and regulatory constraints to produce an optimal policy, is the aim. 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.

These are of supervisory nature activities and refer to the process operator. The automated part of the physical process refers to Process control and involves:

(i) Regulation, End Point and Sequence Control: This refers to the regulating control loops, embedded in the Process Control and Data Acquisition (PCDA) systems (i.e., DCS).

(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 [5] considered here. However, other forms of organisation are emerging at the moment, [11], but their full potential has not yet been.

3.2 Modelling Issues in the Operational Hierarchy

The study of Industrial Processes requires 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". 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, whereas support models provide information to control models, or they are used for simulation purposes.

A major classification of models is in to those referred to as "black" and "white" models [1]. White models are based on understanding the system (physics, chemistry etc) 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 are of the input-output type contain many parameters, but require little knowledge of the process and are easy to formulate; 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 are modelled as black models.

One way of handling the high complexity of the overall system is through aggregation, modularisation and hierarchisation [7], and this is what characterises the overall OPPCP structure described in Figure (2). 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. Hierarchisation 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 [6].

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 interacting to produce the economic activity of the higher level. 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 [6]. The hierarchisation implies a reduction of externally perceived complexity successfully, as we proceed up the hierarchy till the top level. A simpler representation of the overall operational hierarchy of Figure (2) is as shown in Figure (3) having blocks with following modelling requirements:

0-level: (*Signals, Data Level*). Physical variables, Instrumentation, Signal processing, Data Structures.
1-level: (*Primary Process Control*). Time responses, simple linear SISO 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.

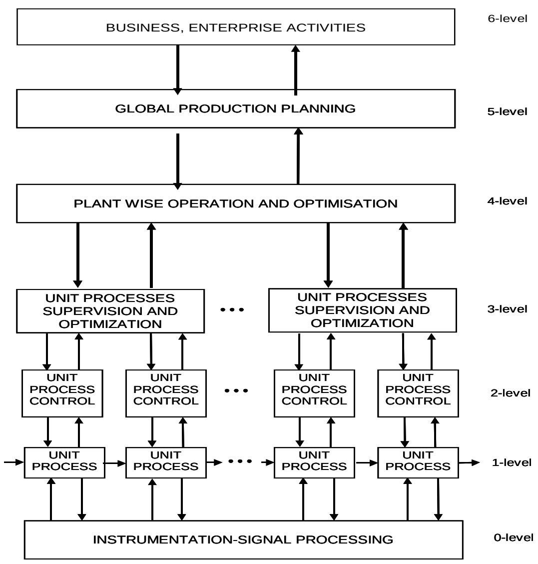

Figure (3): Overall Operational Hierarchy

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 is accompanied by simplification. The latter classification is of functional type and the Process Control Hierarchy implies a nesting of models to a layered hierarchy with variable complexity as shown in Figure (4). This 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. 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).

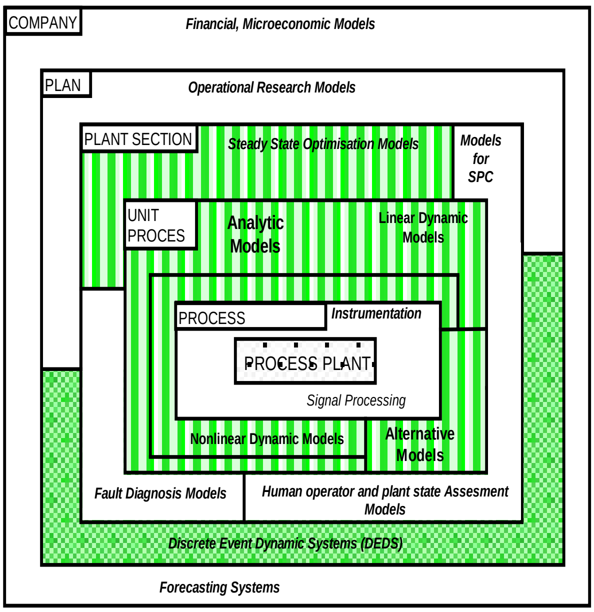

Figure (4): Model Nesting in Process Control Hierarchy

4. CONTROL & MEASUREMENT

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 use input-output descriptions for 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 (2). We may adopt a generic description for the various functions as shown in Figure (5), where u_i denote independent manipulated variables of the function model, called system inputs; y_j are the independent controlled variables that can be measured and they are called the system outputs d_k are the exogenous variables, the disturbances. A model describing the relationships between the vectors, $\underline{u}$, $\underline{d}$, $\underline{y}$ is expressed as y = H($\underline{u}$;$\underline{d}$) where H expresses relationships between the relevant variables. Constructing such models involves:

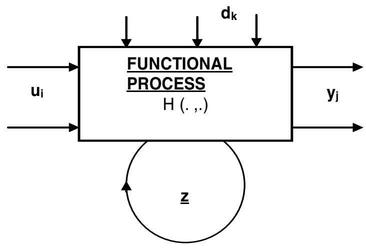

Figure (5): Generic Function Model with Internal Structure

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

(ii) Define the vector of internal variables $\underline{z}$ 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 [8], specification of formal description for H, definition of performance indices etc.

The above generic steps are providing an approach, which however, involves many detailed modelling tasks. Typical problems here are issues such as classification of variables to inputs, outputs, disturbances, internal variables [14], 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:

$$M(u, y, d; z) \begin{cases} F(\underline{z}, \underline{u}, \underline{d}) = 0 & \text{(Implicit)} \\ y = G(\underline{z}, \underline{u}, \underline{d}) & \text{(Oriented)} \end{cases}$$

The nature of variables and the type of problem under consideration determines the nature of the F, G, functions. The model M(u̲, y̲, d̲; z̲) above will be referred to as a *z-stage model*. The selection of the operational stage determines the nature of the internal vector z̲ and thus also of the corresponding z̲-stage model. The dimensionality and nature of z̲ depends on the particular functionality under consideration. Describing the relationship between different stages internal vectors is a problem requiting deep understanding of interfaces between functions and it is closely related to the problem that is referred as *Hierarchical Nesting*, or *Embedding of Function Models*. The fundamental shell of this hierarchical nesting architecture is described below.

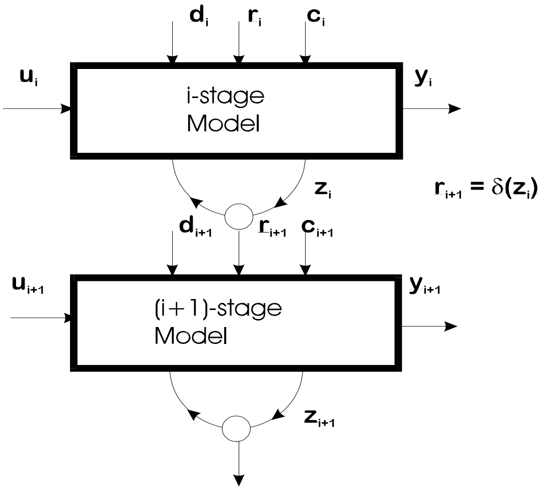

Figure (6): Nesting of models in the Hierarchy

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 $\underline{\mathbf{z}}_i$. 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. If the vector of internal variables in a certain model in the hierarchy is a state vector x̲', then its state space $\mathcal{X}'$ is linked to the overall system state space $\mathcal{X}$ in terms of projection (aggregation). The overall state space $\mathcal{X}$ of the system corresponds to all variables associated with the Overall System and expresses the event and time evolution of them. The overall scheme may be represented as in Figure (6). 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.

The fact that each stage model in the hierarchy is of different nature than the others makes the overall system of hybrid nature [4]. The characteristic of the present paradigm is that here we deal with 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 crucial 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.

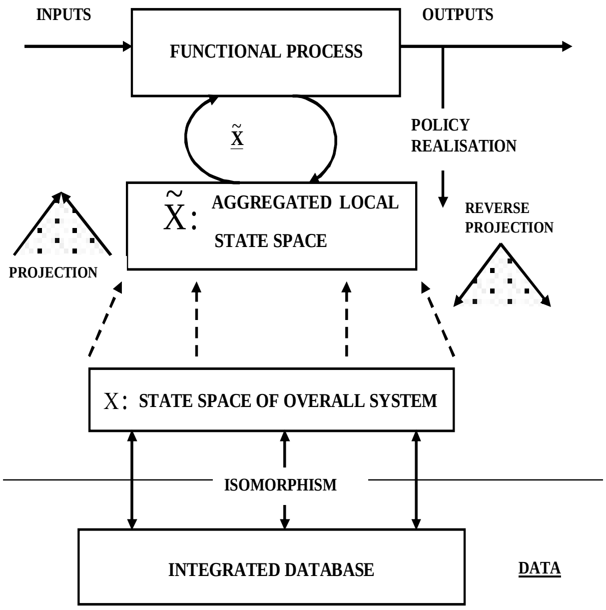

Figure (6): Functional Models and Aggregation

The second problem is of dual nature and refers to the property of being able to observe certain aspects of behaviour of different layers of the hierarchy by appropriate measurements, or estimation processes 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. It is assumed that the observer has access to the information contained at all stages of the hierarchy, 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 indicates the quality of the respective functional model.

Integration of Operations requires study of fundamental problems such as Functional Model Generation, 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 in the area of *Process Operations Design* (POD). Establishing the links between Operational criteria (desirable goals) and Engineering Design Objectives, is also 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 as a natural consequence of not being able to satisfy the new requirements.

5. CONCLUSIONS

The paper has addressed the problem of *Systems Integration* as a multidisciplinary activity and has considered many of the major challenges involved. The emphasis has been on the issues of Integrating Operations for continuous industrial processes and in doing so it has specified a range of new open issues of the Systems and Control type. It provides a very challenging agenda for research in the Systems, Modelling and Control area linked to this challenging problem. The two central emerging themes for control and measurement are those of Global Controllability and Observability, which have to be addressed in a multi-modelling context. Such issues have only been partially addressed so far and need proper definition and then development of methodologies capable to produce criteria for testing the properties for given hierarchies. Attempts to address the problem of systems integration from a single discipline perspective are adequate to yield the required results. Part of overall effort the successful creation of multidisciplinary training and educational initiatives and the creation of multidisciplinary teams.

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