Implementation of Fuzzy Cognitive Maps for Production Planning of Plant Control Systems

Peter P. Groumpos, *Member IEEE*, Nikolinka Christova, and Chrysostomos Stylios, *Member IEEE*

Abstract— **In this paper, an integrated intelligent system for modeling and control of complex industrial plant is considered. A multilevel hierarchical control architecture with decentralized control and local stage optimization, as well as overall coordination of the production and resources supply by dynamic scheduler is studied. Implementation of Fuzzy Cognitive Maps to develop production planning models is proposed. The highest level of plant management of the hierarchical intelligent control system should meet the fluctuating demands in optimal way. The integration of operational and business management is carried out at the top hierarchical level using the soft computing technique of Fuzzy Cognitive Maps. The obtained results prove the applicability of the proposed methodology and the advantages of using soft computing modeling techniques for the sophisticated high level of hierarchical systems.**

Index terms—**Production planning, Intelligent integrated control system, Fuzzy Cognitive Maps**

I. Introduction

In recent years industry has experienced global competition, changes in management, increasing requirements for quality, increasing customer expectations, faster-paced advances in complex technology and rapidly expanding options in materials and processes. A great challenge for today's companies is not only how to adapt to this changing business environment but also how to draw a competitive advantage from the way in which they choose to do so. As a basis to achieve such advantages, companies have started to seek to optimize the operation of their production systems [9], [10]. Since traditional, centralized production planning, scheduling and control mechanisms were found insufficiently flexible to respond to this new situation, many companies decided to adopt intelligent solutions [7].

Coordination of the technological, operational and business management with the capability to meet the fundamental customers' needs and requirements are the leading power of modern competitive environment. Turbulent market imposes new decisions covering with optimal way almost every technological and business situation [10]. The research directions within plant control are aimed at the development of so-called intelligent plant control systems based on soft computing and other advanced information processing technology.

This study emphasizes on modeling the production planning functions of integrated control systems. Due to the high degree of uncertainty that characterizes the production planning procedure it is proposed the use of the intelligent soft computing technique of Fuzzy Cognitive Maps [6]. The resulting production-planning model is led by the key concept of market policy that represents the overall target for the supervisory top level, and especially for multifunctional dynamic scheduler. The proposed methodology has been applied to data of a real industrial plant and supplements an integrated intelligent system that was developed for the complex multistage industrial plant [3]. Discussion and analysis of the obtained results will be presented.

II. Production Planning Level In Integrated Control System

Current research directions within plant control are aiming at the development of so-called intelligent plant control systems based on artificial intelligence and other advanced information processing technology. Designing and operating complex process plants are knowledge intensive tasks and it is the expectation that these new knowledge technologies can make major contributions to the reduction of the risks and costs involved in the design, operation and maintenance of complex production plant [7]. The reason for this optimism is that artificial intelligence offers a range of techniques for representation and processing of knowledge that extends the role of the computer in control applications from a number crunching machine to also being a powerful information processor.

A control system would be intelligent if it is highly adapted to its environment i.e. that it is able to cope with complex plant control requirements. The purpose of intelligent plant control is to use artificial intelligence for improving the total operation of the plant and will include high level tasks in addition to the low level loop control such as configuration and fault management, supervision and planning.

The basic principle in architectures for intelligent plant control systems is to use hierarchical structures to organize and co-ordinate the complex processing of sensor data and the generation of control actions [10], [12]. In the following, a hierarchical concept for plant-wide control is briefly summarized. It consists of local control systems for

The authors are with the Dept. of Electrical and Computer Engineering, University of Patras, GR-26500 Rion, Greece.
E-mail: {groumpos, hristova,stylios,}@ee.upatras.gr

each single unit and a coordination control level. The main task of the local controllers is to simplify the quality-oriented I/O behavior of each unit in a desired way. The coordination control level has to enable information exchange between the idealized units in order to achieve specified quality and desired flow rate of the end product stream. The coordination control has the task to provide flexible operation of the plant during load or grade changes. Therefore, the coordination control problem is formulated as an optimization problem for changing the operating point of the plant. This new steady state is mainly specified by desired flow rate and quality of the end product stream, but also by the desired production of qualifying potential and the specified inlet stream. The steady state management has the task to optimize the internal variables of the plant with respect to the inlet flows and to represent this new operating point.

A complex plant has been considered and a Hierarchical Control Structure has been designed to control and optimize the production process [4]. At the lower levels of the hierarchical integrated system the appropriate generic objective functions for control, optimization and coordination are well known: maximum capacity (with constraints); minimum unit's production expenses (for given capacity); and specific technological oriented objective functions. The coordination problem of the whole plant is considered using material and energy balances maneuvering, production capacity of different stages determining and local criteria of effectiveness agreement.

The hierarchical control system ensures the maximal profit over the period of the planning horizon. The basic problem is the development of a hierarchical multilevel strategy, taking into account all properties, features and factors of the plant from technological and management point of view. An intelligent integrated system with decentralized control and local stage optimization, as well as overall coordination of the production and resources supply by dynamic scheduler is designed. The hierarchical multilevel structure of control [10] is consisted of:

- *Basic level* of control addressed to the unit process variables - temperature, pressure, etc.
- *Optimization level* – to deal with the management and control of separate units.
- *Supervision level* – to coordinate the wide plant production by multifunctional scheduling and sequence generation.
- *Production planning level* – to meet the fluctuating demand in optimal way.

Alternative approaches are investigated in order to determine the appropriate for each hierarchical level attributes: models, control objectives and control algorithms as well as to find a realistic way for solving the multidimensional global optimization problem.

The purpose of planning in intelligent plant control is to enable the system to respond to changing goals of production and/or to be able to perform on-line scheduling of resources or to make plant reconfiguration in situations where a subsystem has failed.

The scope of the strategic production planning for complex industrial plants includes the realization of the aspects of total management and cooperation with the corporate level (Figure 1). The general production planning should determine two different aspects of corporate activities:

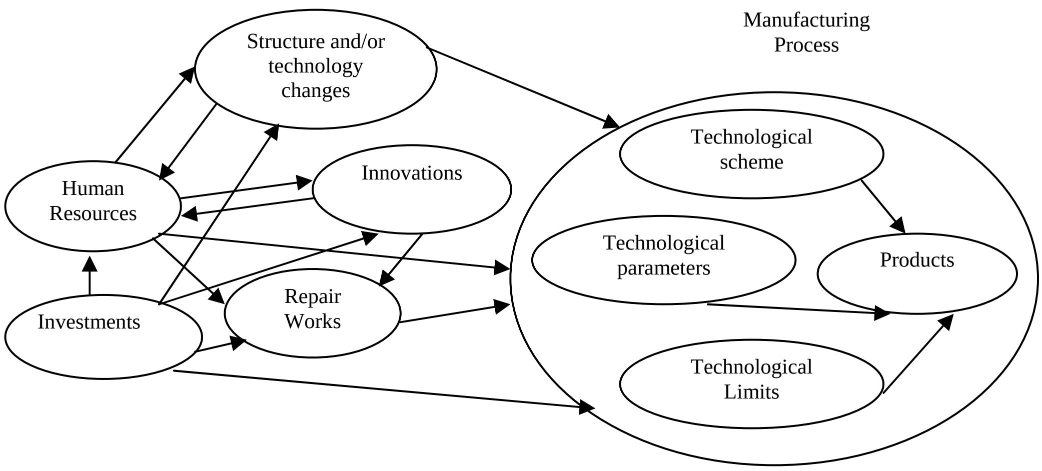

Figure 1. General Model of the production planning level

- Internal environment – optimization of the production, inventory and work force level, taking into account ongoing resources of the company (innovations, investments, human resources, changes in the structure or/and the technology, repairing, rehabilitation).
- External environment – optimization of financing, marketing, advertising according to the political and financial situations and the status of the production system.

The Production Planning level considers the products required by the market, required maintenance of equipment and installations, total cost of production for alternative production schedules, etc. The decision making is reduced to an optimization problem which is based on economic models of operation of the production system, product and material process, different costs, forecasting of future demands, etc. The result of this optimization exercise is a target planning which is used to determine the best operations planning and scheduling.

III. FUZZY COGNITIVE MAPS

Fuzzy Cognitive Maps have been introduced by Kosko [6]. The Fuzzy Cognitive Map (FCM) is a fuzzy signed directed graph with feedbacks, and it models the world as a collection of concepts and causal relations between concepts. The FCM structure is consisted of concepts, which illustrate different aspects in the behavior of the system. Each concept represents a characteristic of the system, which is modeled as an FCM. In general concepts stand for states, variables, events, actions, goals, values, trends of the system and these concepts are interconnected with weighted interconnections representing the cause and effect relationships among concepts that reflect dynamic behavior of the system. FCM infrastructure integrates accumulated experience and knowledge on the operation of the system, because of the method that it is created, i.e., using human experts that know the operation and behavior of system [11]. Each concept besides its description is characterized by a value A_i, which results from the transformation of the real value of the system's variable, for which this concept stands, in the interval [0,1] or this value represents the calculated value/outcome of the FCM. Actually, the values in the graph are fuzzy, and so weights of the interconnections have defuzzified and transformed the interval [-1,1]. The weight of the interconnection between concept C_i and concept C_j, is denoted as weight W_{ij}, and it can be either positive $(W_{ij} \succ 0)$ representing positive causality or it can be negative $(W_{ij} \prec 0)$ for reverse causality or there is no relationship between concept C_i and concept C_j, thus $W_{ij} = 0$. Knowledge and experience of the dynamic behavior of the system is stored in the causal infrastructure of the FCM and the weighted interconnections.

The value of each concept is influenced by the values of the interconnected concepts with the corresponding causal weights and the previous value of each concept is used in the formula. So the value A_j for each concept C_j is calculated by the following rule:

$$A_j^s = f\left(\sum_{\substack{i=1 \\ i \neq j}}^{n} W_{ij} A_i^{s-1} + A_j^{s-1}\right) \qquad (1)$$

where A_j^s is the value of concept C_j at step s, A_i^{s-1} is the value of concept C_i at step s-1, A_j^{s-1} is the value of concept C_j at step s-1, and W_{ij} is the weight of the interconnection between C_i and C_j, and f is a threshold function. Threshold functions squeeze the result of multiplication in the interval [0,1]. Equation (1) includes the previous value of each concept, and so the FCM possesses memory capabilities and there is a smooth change after each recalculation. The development and design of the appropriate Fuzzy Cognitive Map for the description of a system require the contribution of human knowledge [12].

Recently Fuzzy Cognitive Maps have been proposed as an alternative to knowledge-based systems for representing and analyzing complex systems [2]. Fuzzy Cognitive Maps have been used to develop integrated technological, operational and business management systems. Researchers have applied FCM to model a wide range of problems and have put forth many schemes to grow and combine FCM [2], [11], [12].

IV. IMPLEMENTATION OF FUZZY COGNITIVE MAPS TO PRODUCTION PLANNING FUNCTIONS

The aim of this research work is the development of an advanced model for the overall coordination of the production of a complex plant along with the dynamic schedule of the resource supply that will lend to the development of an intelligent integrated system [3]. The highest level of production planning should meet the fluctuating demand in optimal way. The coordinator of the system [3] represents very abstract information taking under consideration many complementary and sometimes controversial factors; thus for modeling the coordinator the soft computing technique of Fuzzy Cognitive Maps (FCMs) that can handle with this kind of systems is proposed. FCMs best utilize existing knowledge and experience in the operation of the system and are capable of modelling the behaviour of any complex system using a similar to human reasoning approach. FCM are an appealing tool for modeling the production planning using a similar to expert based approach. Required characteristics for production planning are the possession of human-like expertise adaptation themselves and learning to do better in changing environment of the complex plant.

Fuzzy Cognitive Maps are a symbolic representation for the description and modeling of the production planning of plants that can describe different aspects in the behavior and operation of plant in terms of concepts; and interactions among concepts show the dynamics of a system. A hierarchical structure is proposed following the principle of "decreasing precision and increasing intelligence" [8] where a FCM models the production planning.

A support system for strategic planning management by using FCM is proposed. The graphical illustration is presented at Figure 2. The concepts of the FCM are defined as follows: C1 – Production of the plant (Productivity), C2 – Profitability, C3 – Investments, C4 – Financing of the investments, C5 – Market position, C6 – Competitiveness. These concepts are linked by concrete relationships, i.e. when a strong market position is built in some market segment it will have an immediate impact on profitability through links running from key assumptions on expected developments to the projected income statement. There are similar links making the competitiveness interact with the market position, and the productivity interact with both the market and the competitive positions, and with the profitability and financing positions.

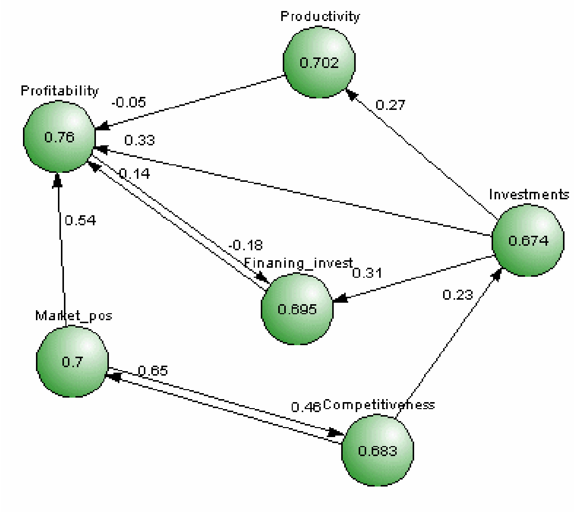

Figure 2. FCM for strategic planning

It's shown that the effectiveness and usefulness of a knowledge based support system can be further advanced using fuzzy cognitive maps.

V. Applications And Results

The proposed methodology has been applied to control complex multistage technological processes, where a number of output control variables are unmeasured or available from laboratory analysis only after a large time of delay and thus inconvenient for real time control [4].

Here, the problem of plant wide optimization of Dimethyl terephthalate (DMT) production is under consideration [3]. DMT production plant involves about 40 units. The generalized flow sheet diagram of the plant is presented at Figure 3. The whole technological process could be grouped in five main stages: oxidation, esterification, distillation of row ester, crystallization and DMT-distillation, as well as regenerative subsystem. The oxidation is semi-batch process, crystallization is batch one and the rest processes are continuous. The multistage DMT production plant includes a number of buffer tanks. The recycles and the tanks influence considerably on the static and dynamic behavior of the plant wide. Detailed description of the DMT production plant and the integrated control system is given in [4].

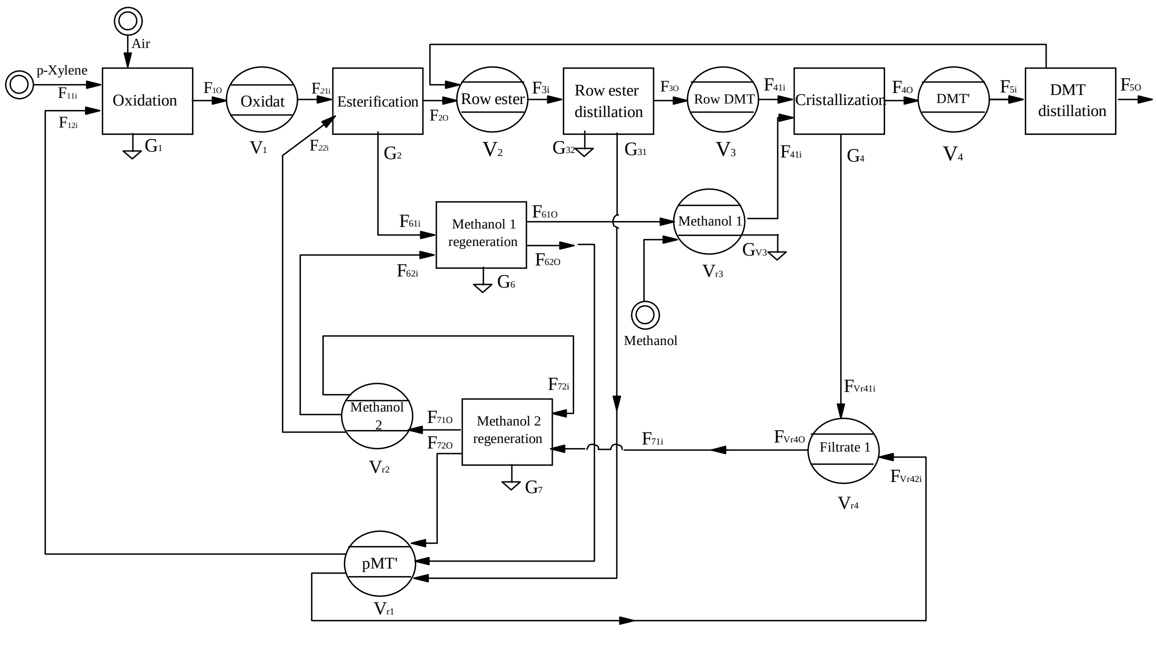

Figure 3. Flow sheet diagram of DMT installation

The supervision level should accomplish the following tasks:

- To meet the planned demand with the plant production by generation of schedule for the main stages and regeneration system.
- To generate optimal schedules for the units in every stage operating in parallel and out of phase, taking into account all constraints.
- To address adequate values of the key parameters into the relevant control systems at the second level for re-optimization.

The Plant Supervisor defines production rates for each planning period and for each stage on the base of DMT demand given from the Production planer for the all predicted horizon and co-ordinates the satisfying of the process constraints. The Plant Supervisor sends its control actions to the Stage Supervisors. The generic scheduling approaches, developed in [13] for the case of DMT production should be extended at the supervisory level to solve a number of particular problems:

- Monitoring and control of some important technological characteristics of the process.
- Taking into account the behavior of the buffer tanks.
- Coordination of cyclic state scheduling in the separate stages in order to keep the stages and the plant as a whole within the bounds of critical constraints.

This study emphasizes on developing the production planning model based on the required functions at the Production planning level. An aggregated generic model has been designed, keeping all main properties of the treated multistage process. The production planning FCM model was developed with the procedure described above. The FCM model is illustrated in Figure 4 and it is consisted of 14 concepts that represent the main technological characteristics of the production process, as follows:

Concept C_1 – Flow rate of p-Xylene (pX);
Concept C_2 – Flow rate of working p-methyl toluate (pMT);
Concept C_3 – Ratio of feeding rate of p-Xylene (pX) and working p-methyl toluate (pMT);
Concept C_4 – “Acidity number”;
Concept C_5 – Concentration of p-methyl toluate (PT) in the working p-methyl toluate (pMT);
Concept C_6 – Flow rate of oxidate;
Concept C_7 – Volume of oxidate buffer;
Concept C_8 – Flow rate of row ester;
Concept C_9 – Volume of row ester buffer;
Concept C_{10} – Flow rate of row DMT;
Concept C_{11} – Volume of row DMT buffer;
Concept C_{12}–Volume of the working p-methyl toluate (pMT) buffer;
ConceptC_{13}–Concentration of undesirable by-products in whole multistage process, accumulated during the operations;
Concept C_{14} – Flow rate of the produced DMT.

Experts described the FCM structure, they determined the weights of interconnections and they suggested initial values for concepts. The FCM model simulates the production planning procedure; it starts to interact for the initial values of concepts. Some of these initial values are measurements from the plant and have transmitted from the lower levels; other values represent desired values for the concepts, which stand for the planning variables.

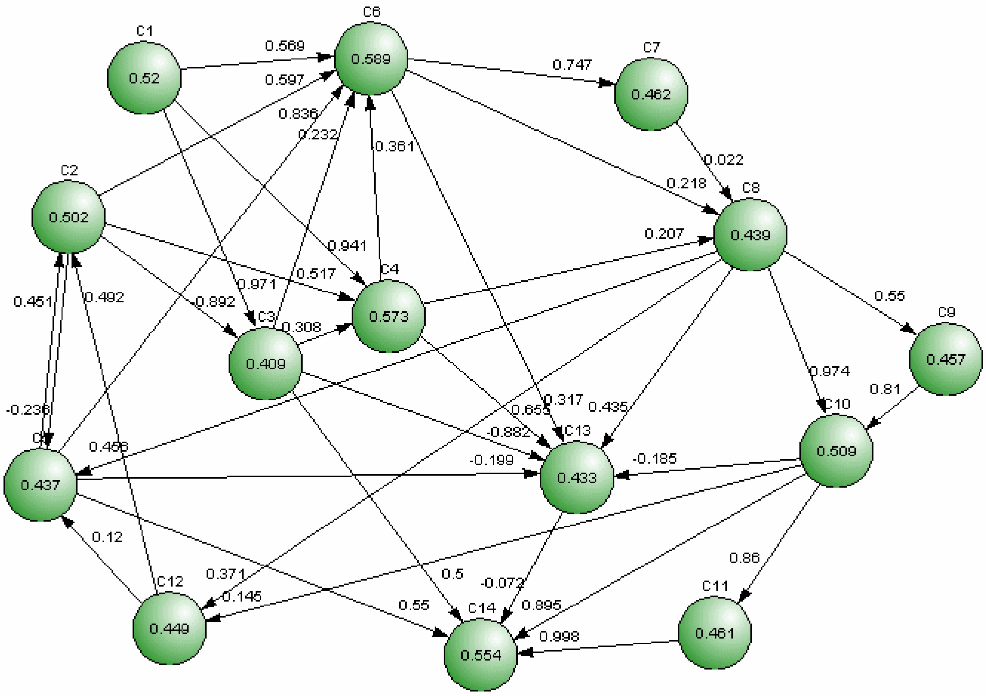

Figure 4. FCM of DMT production plant

Figure 5 depicts the variation of the values of 14 concepts for 10 simulation steps and it is shown that after the 4th step the FCM model reaches an equilibrium region, where values of concepts do not further change. The values of concepts at equilibrium region represent the values that plant variables must take in order to achieve the desired corresponding production-planning scheme. Values of concepts are transmitted to the lower level of the integrated control system influencing the corresponding variables of the plant. Such an interaction procedure among the levels of the hierarchical system will continuously repeat, transmitting actual values from the plant to the production model and vice versa. The resulting market policy represents the target for the supervisory level, and especially for multifunctional dynamic scheduler.

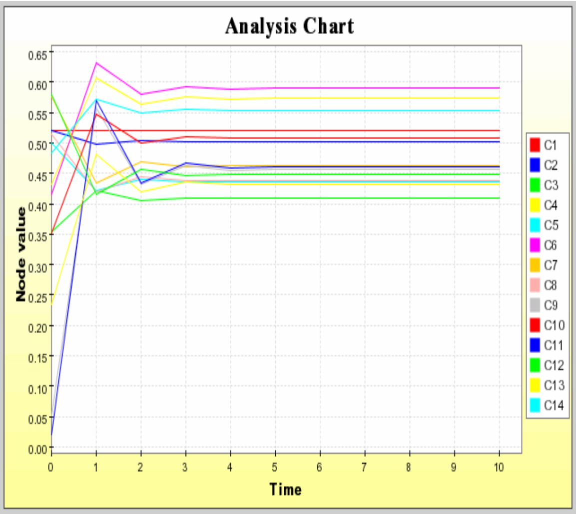

Figure 5. The surface of values of 14 concepts for 10 simulation steps

An extensive analysis and evaluation of the proposed methods have shown their ability to be implemented into integrated control systems. The presented methodology could be implemented successfully in more common cases of heterogeneous multistage interconnected processes.

VI. Conclusions

In this paper an intelligent integrated system is studied. The highest level of production planning in integrated control system should meet the fluctuating demand in optimal way. The coordinator of the system represents very abstract information taking under consideration many complementary and sometimes controversial factors; thus for modeling the coordinator the soft computing technique of Fuzzy Cognitive Maps (FCMs) that can handle with this kind of systems was proposed. The strategic planning for the case of a complex industrial plant was presented. The efficiency of using FCMs to develop integrated technological, operational and business management system has been discussed. The problem of plant wide optimization of dimethyl terephthalate (DMT) production was studied. The obtained results prove the applicability of the proposed methodology and the advantages of using soft computing modeling techniques for the sophisticated high level of hierarchical systems.

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