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VIRTUAL ENTERPRISE (VE) TOOLS FOR SOLVING COOPERATION AND INTEGRATION ISSUES IN MANUFACTURING INDUSTRY

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Abstract. Virtual Enterprise (VE) frameworks (computer networks, as well as application systems for production engineering and management) enlarge the application possibilities of information and communication technology. An important novelty of VE is the fact that is offers various common tools for managing business and planning processes, as well as production, supply and customer relation processes including their operations, goals, monitoring and control. Integration and cooperation are the key issues for the continuous improvement and business process reengineering activities of agile manufacturing enterprises.

The authors propose a seven level cooperation model suitable for supporting discrete production engineering activities and processes in manufacturing enterprises. From the year 2000 up to the present two remarkable research and development projects supported by the Hungarian government have been organized by two consortiums with members from universities, an academic research institute, and large and small companies for solving integration and cooperation tasks with computer applications. In the course of the research new models, methods, optimization techniques and software prototypes have been developed. The paper also outlines some promising experiences with application.

Keywords: Virtual Enterprise (VE), integration paradigms, enterprise modelling, Computer Integrated Manufacturing (CIM), aggregate production planning.

1. Introduction

Globalisation is an economic and social tendency of great importance, which has an effect on the world as a whole. As a consequence of its emergence, geographic, national, regional and other boundaries have been disappearing. Globalisation is an objective process, the sources of which can be found in the objective tendencies of sciences, technologies, the world economy and world politics. At present the judgement on globalisation is a contradictory matter. On the one hand, it provides opportunities for faster development of relatively undeveloped countries. On the other hand, dangers of the global extension of crisis symptoms can also be perceived.

The economic organisations of the advanced world have been forced by globalisation to improve their competitiveness and innovation capabilities in a short time. One of the most typical phenomena of this tendency is the wide-spread application of new information and communication technologies in technical and business processes. One of the phenomena of large long-term effects at the turn of the twenty-first century, as reported in expert studies, is the implementation of an integrated, world-wide computer network, the Internet, which has brought the vision of an "information society" close to reality.

The fast progress of the Internet has resulted in a qualitative change in the environmental circumstances of economic processes:

- The technical possibility of accessing information has been increased to a great extent;
- Information is a fundamental value, which does not decrease proportionally when shared;
- Management, business and technical decision-making processes have also drastically accelerated.

These circumstances have a strong effect on business and technical processes, which can be observed in both the operation of economic organisations and their documentation. In developed countries some kind of local information systems have already been built up by the overwhelming majority of economic organisations and are connected to the Internet. Nevertheless, these systems are not integrated to the proper extent, i.e. the facilities for applications related to the organisation as a whole, and those concerning the cooperation with external partners, are missing.

Recognition of the information technology based integration of production processes was first declared by *J. Harrington* [8] more than thirty years ago. The major car factories have been forced to use electronic documentation to a great extent (e.g. for engineering models, NC/PLC and robot programs, operation sheets, measuring instructions), which leads to the paradigm of Computer Integrated Manufacturing (CIM). Putting this paradigm into practice has yielded considerable results in the automotive industry, but, at the same time, typical failures have also taken place in other fields.

The paradigm of CIM has been transformed to a significant extent during the past 25 years (see Fig.1) [24]. Computerised integration of physical manufacturing systems has been followed by the integration of engineering design and planning systems. In the third step the integration of enterprise management processes has made it possible to manage resources in a completely integrated way. At last, the concept of Virtual Enterprise (VE) can be considered as a result of a full integration of enterprise business environment, clients and suppliers.

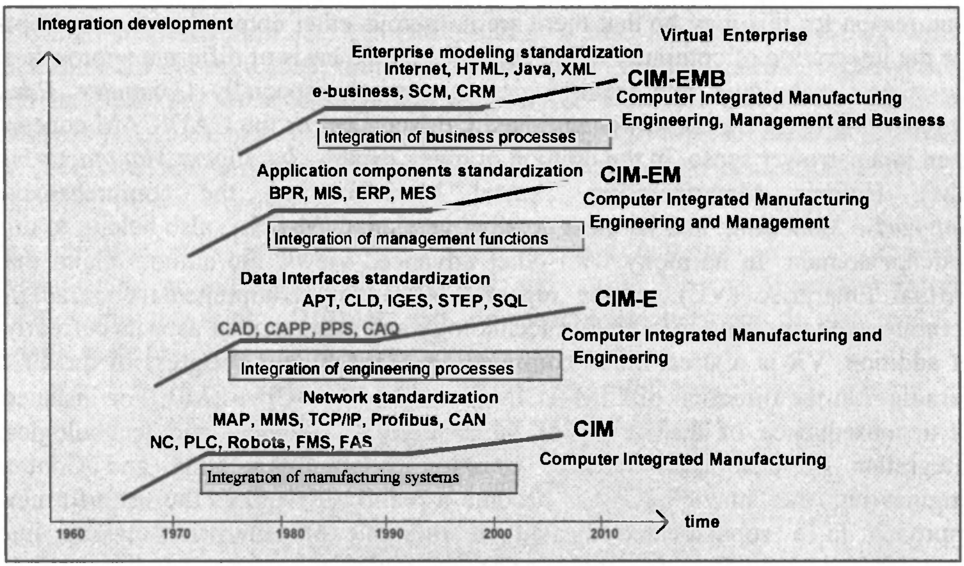

Figure 1. Evolution of the paradigm of CIM

As regards the integration of production processes, the most important factor was the introduction of network standards (MAP, MMS, Ethernet, TCP/IP, Profibus, etc.). Integration of engineering design applications has made data and model interfaces the focus of research (APT, CLD, IGES, STEP, etc.). The accomplished and accepted standards have been widely used. Integration of business processes has been established by the spreading of the large systems with integrated databases (*Enterprise Resources Planning* = ERP; e.g. Oracle, SAP). Integration has been extended by Internet and web technology to the complete business environment of enterprise. It has been proved that enterprise management functions can be integrated with the functions of cooperation in terms of the market, suppliers, clients and partners. The scope of these complex and far-reaching issues is summarized in some excellent monographs [14], [16], [1]. The book of *Francois B. Vernadat* is especially outstanding [24]. CIM has proved to be an extremely effective paradigm in the course of its fairly long evolution and has kept its importance up to now.

2. Virtual Enterprise

The concept of "Virtual Enterprise" came to be about ten years ago and has spread in the professional literature very rapidly [9]. In the opinion of sceptics it is only a vogue word or, if you like, just a slogan, and the content of the concept, from the point of view of engineering and especially from the aspect of science, is very poor.

One reason for this may be that there are numerous other comprehensive concepts for the integration of computer-aided activities on the basis of different approaches, e.g. CAxx techniques and technologies in general, especially *Computer Aided Engineering* (CAPE), the aforementioned CIM-concept or the CAD/CAM concept used in a narrower sense. In the opinion of many experts, *Intelligent Manufacturing* (IM), Holonic Manufacturing, Fractal Manufacturing, the comprehensive *Enterprise Modelling*, and its most detailed version, CIM-OSA, also belong to this concept domain. In harmony with other advanced views, the authors claim that Virtual Enterprise (VE) can be regarded as a new comprehensive paradigm combining engineering information technology and management aspects currently. In addition, VE is a streamlined continuation of the known progress of the CIM paradigm in the direction of CIM→CIM-E→CIM-EM→CIM-EMB. For instance, as a consequence of the results of the last years, technical and technological integration of Computer Science, Communication Engineering and Control Engineering (the "magic" 3C) has become a reality. It requires the use of a new approach to a sophisticated system of relations of enterprises taking into consideration organisational, marketing and technological interrelationships. VE, in this concern, is a new and comprehensive technical-business paradigm, i.e. a combination of principles, models and methods, which supports more effective and successful management of economic organisations, both for producing and supplying enterprises [6]. As a paradigm, VE promises successes for the companies and institutions functioning and competing in a globalised business environment.

Now, let us attempt to define the VE-paradigm. We may follow two approaches differing from each other to a certain extent:

(1) VE is an occasionally established cooperating system of autonomous organisations (enterprises, affiliated firms) based upon electronic information processing and organisational integration, which makes it possible for the participating organisations to be able to effectively utilise extra resources, and

not only those which are physically available at a particular organisation without significant expansion [6]. In this sense, VE is mainly a paradigm of *integration between enterprises*.

(2) VE is a continuous cooperating system of autonomous functional organisations (settlements, departments, factory units) based upon electronic information processing and organisational integration, which enables participating organisations to operate shared resources in an effective way, without any considerable extension of the resources available physically at the individual organisations [9]. In this formulation VE is mainly a comprehensive paradigm of *integration within the enterprise*.

It is easy to see that VE is a special form of firm operation based on electronic information system and services (the Internet is also included if needed), which facilitates the organisational units of the firm in question, its partner organisations and its customers in accessing data and service resources effectively, initiating business processes, and carrying them out in a safe way with no need to search for or access resources physically. In Figure 2 we attempt to demonstrate the VE-paradigm from this aspect.

In *Jan Hopland's* opinion, "It is clear we are entering an age in which organisations would spring up overnight and would have to form and reform relationships overnight. 'Virtual' had the technology metaphor. It was real and wasn't quite real." [9]

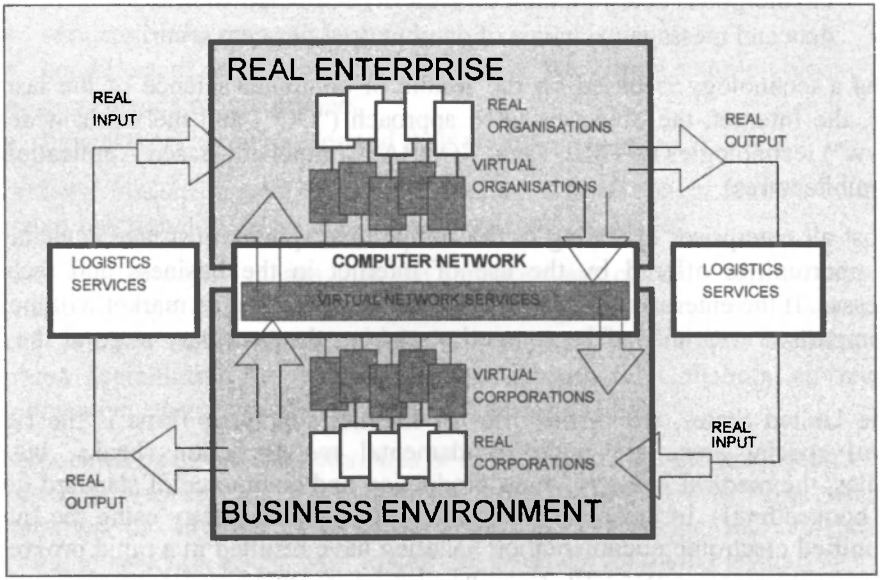

Figure 2. A computer network based functional model of VE

The tasks of establishing a VE can be drafted as follows:

- Integration of business and technology process, including all connections with internal and external suppliers, partners and customers;
- Deeper knowing, modelling and harmonising the processes, revising the constraints and objectives in order to create the conditions for optimization;
- Creating and implementing tools suitable for utilisation by human resources in order to promote real time data exchange, knowledge sharing and cooperation.

The more detailed requirements for VE require that it should support:

- coming into existence of dynamic relationships, groupings and co-operation,
- existence of organizational and geographic dividing,
- different types of communication,
- all kinds of teamwork and undertaking of different roles,
- exchange of information in different forms as much as possible,
- changing the organizational frames and the different life-duration of groups,
- shared use of resources,
- integration of existing working tools and working methods,
- unambiguous determination of authority and responsibility,
- data and message exchange of one-hundred-per-cent security.

VE as a technology is based on the results of computer science of the last five years, the Internet, the object-oriented approach ("OO") and the world-wide-web ("www") technologies (HTML, Java, CORBA, Component Based Applications, 3-tier architectures).

Almost all enterprises operating in the competitive sphere must take advantage of the opportunities offered by the use of Internet in the business and technical processes. If the enterprise does not do so, the risk of losing its market will increase in comparison with that of its competitors taking the necessary steps at the right time.

In the United States, where the offer of Internet supplying firms is the richest, several special areas are under fundamental reconstruction (banks, business supplies, the medical industry, mass production and commerce of standard quality (e.g. bookselling)). In these areas Intelligent Agent Technology using the Internet and unified electronic documentation handling have resulted in a rapid progress. A similar revolutionary reconstruction can also be expected in the areas of supplier and logistic systems as well as in the field of recycling technologies.

3. Integration and Cooperation as the Key to VE

The general architecture of VE is demonstrated in Fig. 2. As can be seen, the physical subsystems (organizations) of the real enterprise are integrated with virtual organizations through a total virtual transformation. Connection of the physical and virtual subsystems is maintained by means of data acquisition sensors, programmable automatons and data input actions of intelligent human agents. Clients of the virtual organizations use virtual services of the suppliers on a network promoted to independent agents. Virtual organizations and agents are present not only within the firm but in the market (business) environment as well Certain differences can only be found in responsibility, authority and the sphere of action of the partners.

The main components of VE are as follows:

- virtual organizations (subsystems),
- virtual services (functions),
- virtual resources and documents,
- virtual working processes,
- a computer network.

A VE is a designed system in which the following entities and attributes are designed:

- classes of the partners participating potentially in the virtual system,
- properties and responsibility of the current classes,
- services of the current classes,
- conditions of coming into being in case of the current sample-objects,
- competence of the partners,
- typical working processes and their results.

The well-established success of the VE paradigm is to be sought in the principle of integrated functionality. What is the meaning of this principle?

Integrated functionality means that the functions are carried out by specialized (optimised) agents in an effective system. The agents, however, are capable of solving complex tasks characterized by temporary or durable collaboration, integrated (combined) by means of interrelationships. Collaboration requires communication, co-operation and co-ordination capabilities.

As a consequence of the characteristics of the VE-paradigm the principles, models and methods represented by it require different tools in the organizational collaboration of different types. It is expedient to arrange the collaboration according to layers. A seven-layer model can mean the following layers:

(1) Collaboration of competitors in the case of contradictory posed interest (open system);
(2) Collaboration of business partners with partially agreeing interest (e-business);
(3) Customer-vendor collaboration with temporary interest (e-commerce);
(4) Collaboration of suppliers with close interest (supplier chain);
(5) Collaboration of affiliated companies with the same interest (virtual factory);
(6) Collaboration of functional organizations under the same conditions (CIM);
(7) Collaboration of operators working on the base of the same plans (CAM).

VE supposes that the same or similar technology can be used for collaboration of the different layers.

The VE-paradigm presumes that the intelligent partners of the collaboration layers mentioned above are capable of following the same samples and principles within the same framework, in their own interest.

VE supposes that collaboration is a behaviour strategy that can be regarded as an optimum strategy for partners giving a positive reply to the initiative. This assumption is well-supported by the results of modern game-theory, established by *John von Neumann*. The latest results of artificial intelligence research also support the fact that optimization of the decision-making series for longer terms has always suggested the conceptions open for collaboration as successful, in contradiction to aggressive strategies.

4. Production Planning in Integrated and Cooperative Environment

The production planning and scheduling (PPS) system is one of the most important functional subsystems of modern digital enterprises. The functions and the services of the PPS systems have significantly changed in the VE environment. In recent years the development of control and product information systems has yielded special application structures. These structures are functionally layered and consist of four horizontal levels with many components in every layer. These layers are the following (see Fig. 3.):

1. Enterprise Resource Planning, ERP
2. Computer Aided Engineering, CAE (CAD/CAP)
3. Manufacturing Execution Systems, MES
4. Manufacturing Automation, MA.

The main horizontal layers are connected by special communication bridges. The production planning and scheduling systems take a prominent role in this situation, forming a functional and integrated „bridge” over all four layers connecting the control and decision functions, as well as the production process controlling and execution systems.

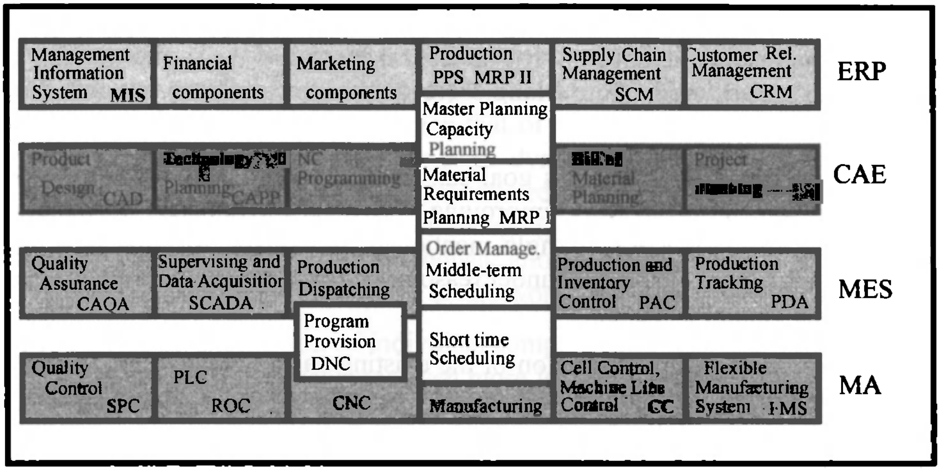

Figure 3. Multi level computer application system for manufacturing

The most widely accepted form of production planning and scheduling systems is the Hierarchal Production Planning (HPP) structure. The greatest advantage of this approach is the realization of the hierarchal modelling which is the only opportunity in case of a large-sized scheduling task (even using the current tools of information technology) to allocate an effective solving system and easy-to-survey Human Machine Interfaces (HMI) to the scheduling tasks.

Production planning and scheduling is one of the most important technical activities for enterprises in the machine manufacturing industries. Production planning is carried out at several hierarchy levels in general. The task of aggregate production planning is to generate quantitative and scheduling data on production in the medium and long run (usually for three months and one year, respectively). The input data of aggregate planning are: the orders based on market demands, specification of the products and technology processes, the internal and external (supply chain) capacities available, as well as stocks [21]. The output is the *aggregate production plan* and the *master schedule*.

In order to summarize the requirements for production planning we have to start from the goals of the business policy of the firm in question. They can be as follows:

- *Improved customer service.* Nowadays this business goal is top priority. Keeping the market and attracting new customers is a precondition of realization of every other business goal. This goal can only be obtained by means of guaranteed quality of products, meeting deadlines and product specifications, as well as offering advantageous prices.

- *Increasing revenue.* This business goal, at the level of production planning and control, requires continuous improvement and control of the macro-parameters of the so-called production triangle (readiness for delivery, stocks level, capacity utilization).

- *Lowering working capital.* This goal can also be achieved by simultaneously and in a synchronized way improving the macro-parameters (production indices) of the production triangle mentioned previously. Meeting deadlines and minimizing the stock level under reasonable constraints have a direct effect on working capital demand.

- *Managing fixed assets.* Utilization of the existing capacities invested in earlier is a fundamental condition to realize effective production capable of ensuring the profit expected. In case of well-proven products, successful accomplishment of the accepted external orders depends on, in most cases, the capacities available.

- *Reducing operation costs.* Under the conditions of the prices agreed and fixed in contracts the net profit can mainly be influenced by decreasing the operation costs and lead times, as well as by optimal utilization of the resources (machines, workers, materials).

It is easy to see that the concept of competitive enterprise can only be defined in a complex manner. The primary business goals can only be influenced through improving the secondary manager (or performance) indices. Effectiveness of production planning and control can only be ascertained after the results obtained in money, i.e. with a delay. Factual influence of the previously made decisions related to scheduling of the production activities (i.e. concerning their quantitative and time-based distribution) can only be ensured by means of a smoothly operating activity-based controlling system.

5. VE and Production of Individual Machines

Nowadays there are numerous examples of the implementation of VE application systems in different branches of industry. The production of individual machines to customer order is one of the most typical application fields. The production of individual machines, machine systems, technological equipment and establishments requires more flexibility and organization and it is necessary to cooperate with the suppliers, partners and customers to a higher degree than usual, both inside and outside the enterprise.

The tasks of aggregate production planning are very different in mass production and in one-of-a-kind production. In large series and mass production the most important viewpoint is to harmonize prediction of the market demand and utilization of the capacities available. In the case of production of complex products, production planning has to be subordinated to the interest of successful realization of the external orders obtained. Here the demand for flexibility of production is significantly greater than that of mass production and the deadlines are stricter. Production planning has to be dynamic and incremental. This means that aggregate production planning is controlled not by the start of planning periods but by the order-events appearing in changing dates. The new orders necessitate rearranging the work quantities previously allocated to production but this is also limited by the conditions determined by the work in progress.

In the case of the production of individual complex machines and machine systems the project-like approach becomes even more important [15]. Project-like planning became a typical aspect of production planning in a make-to-order machine manufacturer firm. A complex machine of great value, that has been made to order and is to be assembled of numerous parts, can be considered as the project product. Such a complex product is usually made as a special version of another similar machine made and sold in a previous period, i.e. the new machine to be made to order can be considered as a further developed and more-or-less modified version of a similar one previously made and sold in a successful way. The activities and processes of a project are based on experience of previous similar production activities and processes on the one hand, as well as on the unchanged and standardized engineering documentation and specific data of the new project including the new technical documents attached, on the other hand.

The task of production planning is the decomposition of the projects in question into production activities, determining the resource demand (specification, machines, workers, material, energy) for all of these activities. A fundamental feature of the resource model is the available capacity of the given *resource class* depending on the *production calendar*. The resource model used by aggregate production planning is an abstract one and is connected with the high-level activities of production process. Every aggregate activity requires at least one resource suitable for carrying out it.

The typical activities in the practice of an enterprise producing individual machines are the following:

1. Engineering design
2. Electrical design
3. Part manufacturing
4. Component purchasing
5. Mechanical assembly (mounting)
6. Electrical assembly (wiring, mounting)
7. Putting into operation, testing

8. Product delivery.

According to the demands of the production planning we can more or less define activities as we did above. The task of production is the realization of the activities A_i, belonging to the project-set $P=\{P_1,P_2,\cdots,P_j,\cdots,P_J\}$ under determined deadline, capacity and precedence constraints. To the activity type set $A=\{A_1,A_2,\cdots,A_p,\cdots,A_P\}$ a resource type set $R=\{R_1,R_2,\cdots,R_k,\cdots,R_K\}$ is allocated where $K \geq P$ The effective projecting models make it possible to utilize several resources by a given activity, too.

Available capacity is defined as the capability of resource class R_k for doing a certain job, available in the course of the given work-week (the unit of measurement is working hours/week). In the aggregate planning models it is expedient to model the time by means of a series of discrete time intervals δt In most cases the discrete time unit is one work-week. On the discrete time scale let t be the serial number of time interval, i.e.: $t=(1,2,\cdots,T)$. At the planning time horizon the so-called *relative time* is $\tau = t\cdot\delta t$ At the end of the time horizon used in modelling we have $\tau_s = T\cdot\delta t$ Considering this time horizon there is an internal resource capacity for every time unit according to the calendar: $c_k(t)$, $k=1,2,\cdots,K$ The production scheduling model treats the available capacity, after it has been fixed, as a strict constraint.

The production of individual machines can be accommodated to the changing demands of orders only by applying extremely flexible capacities. If there are few orders obtained then the utilization of capacities might be very unfavourable. On the other hand not only the internal capacities should be taken into account but the external capacities based on suppliers as well, in order to fill the external orders obtained. The external capacity $s_k(t)$ $k=1,2,\cdots,K$ similarly to the internal one, is more expensive in general. The external capacity generally is also constrained. Further the planning of the rate of the internal and external capacities depends on the expectations and circumstances of the market as well.

6. Production Planning Scenarios in Individual Machine Manufacturing

In the production of individual machines, production planning can be classified into three different scenario types. They are as follows:

1. ***Project work for tender***
   This is the basic version of project planning. It consists of the analysis of demand (or interest) of the potential purchaser (or customer), a feasibility study of the project and determination of the main data of the project. The

deadline of the project previously accepted has to be determined on the basis of such a model, in which the activities and their work demand are only known at an estimated level.

2. ***Detailed project work***

   This is the detailed, main version of project planning. It consists of all the known phases of product design, technology process planning and production planning on the basis of the customer's order. The project must be included in the actual projects running in the same period. Scheduling of the project is to be carried out by taking into consideration the actual business goals and by fixing the constraints and the objective function.

3. ***Redesign, replanning and rescheduling of projects***

   This is a correcting and modifying version of project planning. It is used when certain modification is needed because of an unexpected factor that has arisen in the course of parallel project execution. The factor can be a change in the business processes, in the production policy or in the engineering specifications. Other reasons are unexpected business events or unexpected events in the technology process, changes in the constraints and objective functions or uncertainty factors.

For project-like production planning another key issue is what we consider to be the optimal production plan. As is known [16], in order to qualify as achieving the production goals three natural state variables (macro-parameters) are needed and they are also sufficient at the same time. These complex state variables can be labeled the "Production Triangle" [22]. They are as follows:

1. The average utilization of resources;
2. The readiness for delivery, i.e. the reciprocal value of the average lead time of the external orders;
3. The average stock level fixed in production.

These complex state variables, of course, are not independent of each other. Any of them can be improved to the detriment of the other two.

In the production planning of individual machine systems the alternative objective functions of a project scheduler suitable for optimisation appear as the special descriptions of the Production Triangle (see: Fig. 4.). The objective functions are:

1. The weighted sum of the external capacities utilized;
2. The weighted sum of due-date tardiness of the projects;
3. The number of projects released at the same time.

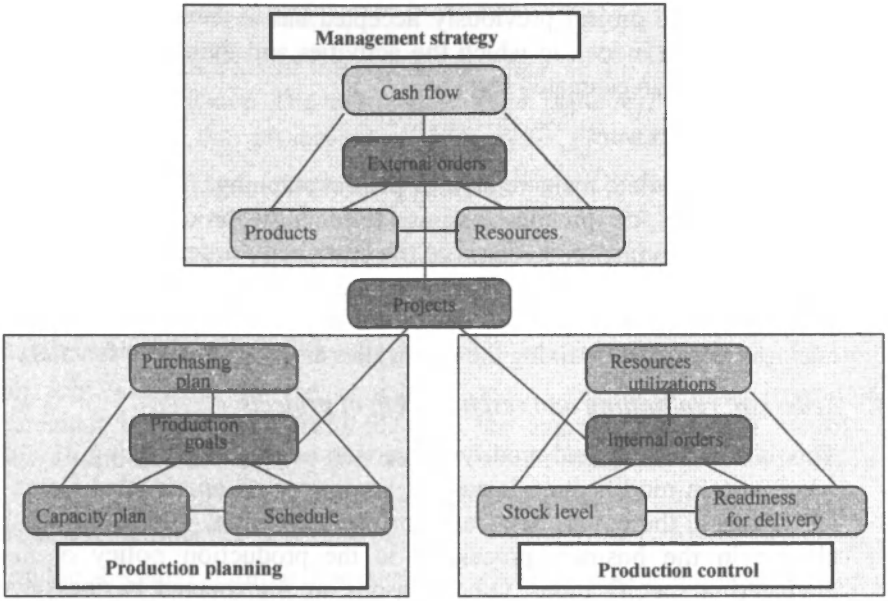

Figure 4. The integrated goals and tools of production management

In project-based production the successful realization of external orders is an essential and primary business goal that has to be supported by the utilization of external capacities as well. However, the maximal utilization of internal capacities is also expected. The most important characteristic of readiness for delivery is to meet the due dates (terms of delivery) fixed in the contract. Any deviation from the term of delivery either may not be allowed (hard constraint) or may be an objective to be minimized.

The task of the scheduler of project activities is to determine those production activities (both in quantity and in time) that meet all the constraints and minimize the objective function in the domain allowed.

The first objective function of project work gives a good solution, typically, in the case of overloaded resources. If the jobs required by the actual order-book of the firm cannot load the resources in the planning period then the value of external capacity demand is equal to zero and there can be numerous scheduling solutions suitable for meeting the constraints. In many cases it is difficult to decide if improving the stocks level or improving the readiness for delivery should be the objective targeted at such a time. The conflict between the short-term and long-term goals makes the situation even more complicated.

The philosophy of the schedulers used at present is, in general, that the constraints are the important ones; they have to be met by all means. There can also be several production plan solutions (schedules) meeting all the constraints. It is possible to select the most suitable of them on the basis of heuristic considerations. Of course, an exact optimum is out of question here. The larger the number of permissible solutions, the more robust the optimum is, and the less sensitive it is to the changing circumstances.

7. The Role of Rates in Production Scheduling Models

Production processes are typically cumulative ones. This explains the important integrating role of the rate-based state variables in the planning and controlling of production processes.

These kinds of state variables are state characteristics concerning a time unit.

Some typical examples:

- *Material removal rate , Cutting rate* (cm^3/min)
- *Operation rate* (pieces/min)
- *Production rate* (working hours/time unit)
- *Activity rate* (working hours/time unit)
- *Demand rate* (number of products/time unit)
- *Capacity rate* (specific source work volume/time unit).

In order to control the production processes the rates must be controlled in time. The production scheduling plans specify the work volume engaged capacities and their dependence on time with which the production processes can be realised successfully or optimally in some sense, of course meeting the described requirements. The characteristics of rates have a great influence on the scheduling models and the methods needed to solve them. Figure 5 represents the four basic types of production rates.

The four basic types appear in the production scheduling model in the following manner:

1. The typical shop floor level scheduling model of part manufacturing processes. The combinatorial optimization task is NP hard. The solution can be achieved by heuristic considerations, constraint programming or a searching AI procedure.

2. The scheduling model in large series and mass production or in continuous production (for instance in the chemical industry). The extent of the series (production mass) varies. The optimization process can be carried out by heuristics or by the method of hybrid dynamic activity control.

3. The flexible model of low level Production Activity Control. The time period of operations can be controlled in a limited way (*Process Management*). There is only heuristics (OPT).

4. The scheduling model of high level project-like activity. It can be modelled by methods of large size from the field of the mixed integer linear programming. The solver has to meet high requirements.

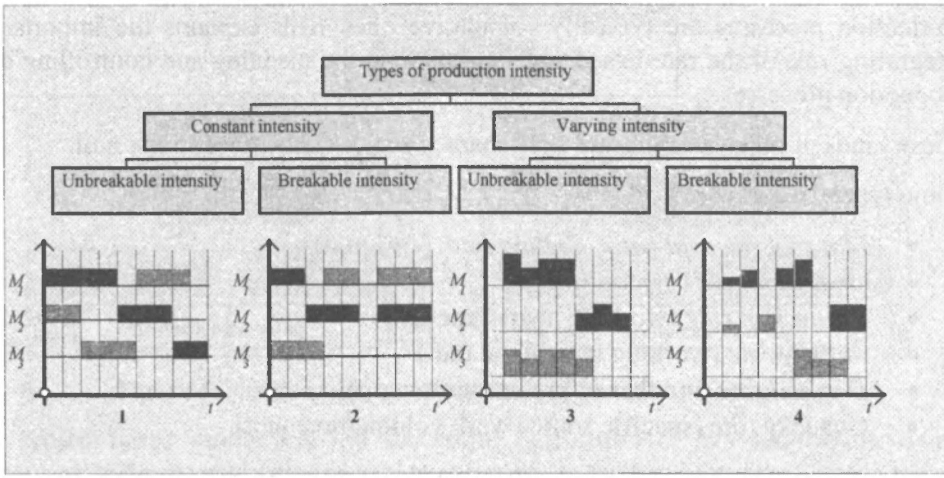

Figure 5. The effect of production rate upon the scheduling model

In the Department of Information Engineering at the University of Miskolc, scientific investigations have been carried out for a long time related to the role of production rate type state variables at the different hierarchy levels of production management, from the well-known material removal rate (MRR) to the rates of the main production activities.

Based our experience in the control of production processes, it is clear that the *process rate* (process intensity) is of great importance. If we consider production control as a closed control loop then the basic signal of control is the production rate. The rate of production processes can be measured in the measuring unit [working hours used/time unit] in the most general manner. At the level of operations the production rate depends on the *technological rate* that can be measured in measuring units [number of products/time unit], [removed material volume/time unit]. In cutting technology processes where the finishing processes are of great importance, the measure of rate is [machined surface/time unit] and in case of chemical technology processes [processed mass (volume)/time unit] [18].

The technological rate for cutting, as a state variable in time, can be defined in an indirect way:

$$\int_0^t Q(\tau)d\tau = V(t) \quad \text{i.e.} \quad Q(t) = dV(t)/dt,$$

where $Q(t)$ is the cutting rate changing in time and $V(t)$ is the material volume removed until the time t. In case of technology process planning it is expedient to use the cutting rate related to one revolution of the main spindle.

Then $Q(t) = A(t) \cdot v_e(t)$, where $A(t)$ is the momentary effective cross section of cutting and v_e is the feeding speed. This equation can also be used in case of multiple-edged tools (see Fig.6.).

The cutting rate defined in this way is a suitable tool for optimization of cutting operations. In planning and production control the average rate $\overline{Q}$ is advantageously used for a given operation or operation element that makes it possible to estimate the primary time of cutting (the machining time) t_m; $t_m = V/\overline{Q}$. Here V is the material volume removed in the given operation.

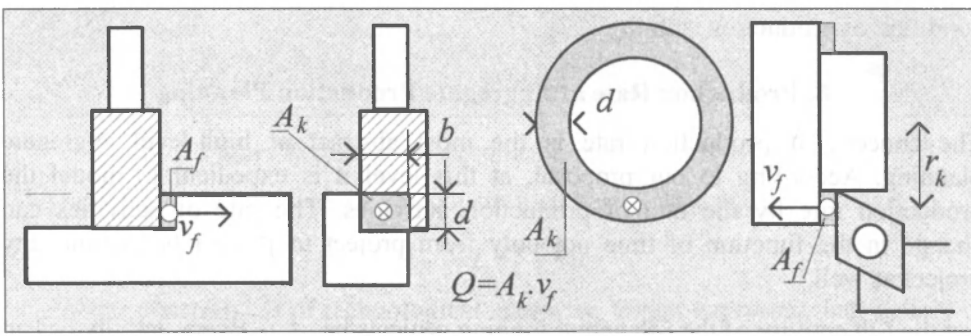

Figure 6. The technological rate for cutting

The term of cutting rate is suitable for formulating the new model of optimal technological data. The cost of cutting operations can namely be expressed as a function of cutting rate. Some factors of this function decreases by increasing the rate (for example time proportional costs) while other factors increases as well (tool cost, loss because of rejects, etc.). The average optimal rate – in the sense of minimum cost – can be determined and this makes it possible to increase the number of alternatives in production control decisions (especially in case of NC machines).

The rate of technological operations is the reciprocal value of the operation time, its measuring unit is [1/min]:

$$q_0 = \frac{1}{t_0} = \frac{1}{t_m + t_a}, \text{ if } t_m >> t_a \text{ then } q_0 = \frac{\overline{Q}}{V}.$$

Here q_o is the rate of operation, and t_0 is the operation time, which can be approximated by the machining time in case of short auxiliary time t_a.

In general, part manufacturing demands a consecutive series of operations, and therefore the average rate of part manufacturing, referring to work pieces or series, is an aggregate production characteristic:

$$q_p = \frac{n_p}{t_f} \text{ [pieces/min], where } t_f = \sum t_{prep} + \sum t_o + \sum t_w$$

Here n_p is the lot size, t_{prep} is the preparation time and t_w is the time of the work piece spent in waiting. Summing has to be extended to all the operations of the series executed so far. The average rate of part manufacturing referring to work piece series plays a great role at the shop-floor level and in medium-term scheduling where the equilibrium of demand rate and production rate is the condition of production stability [17].

8. Production Rate at Aggregate Production Planning

The concept of production rate is the most abstract at high-level aggregate planning. According to our proposal, at this level it is expedient to model the production rate by the rate of production activities. The rate of activities can change in the function of time not only from project to project but within any project as well.

Let the *i*-th activity of the *j*-th actual running projects be $A_{i,}$ Every activity has an earliest starting date and a latest completion due date (deadline). The former is determined by the precedence of the activities and the latter depends on the project deadline. Let us denote these two dates with e_i and d_i, respectively. Both dates will be determined in the course of aggregate planning. Any project means a defined product to be manufactured, the technology process planning of which gives the engagement $r_{i,k}$ [working hours] demanded by the project activity to the resource used by the activity, in a cumulative way. At preliminary planning for a bid this, of course, can only be based on engineering estimations, however after having carried out detailed process planning it can be calculated from the technology process plans. For a given activity one or more resource engagements can also be allocated but this fact will have importance in the planning phase of the capacity-constrained production scheduling only.

We can give an implicit definition for *activity rate* in the case of aggregate planning:

$$\sum_{t=e_i}^{d_i} q_{i,k}(t) \cdot \delta t = r_{i,k}$$

Hence, the activity rate $q_{i\,k}(t)$, changing in time discretely, is the activity concerning the time unit (for example a week) demanded by the i-th project, which loads the k-th resource. The "stepped" function $q_{i\,k}(t)$ is called the profile of activity (Fig. 7.). For the profile numerous constraints can be defined, which must be taken into consideration in the course of production planning and scheduling.

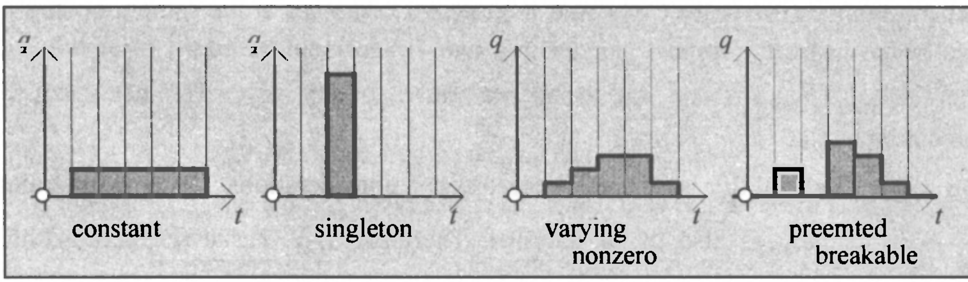

Figure 7. Discrete time profiles of production activities

The rate of a project activity can be constrained from below and from above:

$$q_{mi} \le q_i(t) \le q_{Mi} \,.$$

The upper constraint is of technological character, which expresses that the rate of the given activity cannot exceed the maximum value even if there were free capacity available for this purpose. (It is not possible to design or to assemble a machine with optionally great rate even in the case when working capacity is available.) The lower constraint can express the fact that if we have already started with a certain activity then a minimum expenditure is needed for it in every time interval. If $q_{mi} = 0$ then the activity in question can be interrupted, otherwise it cannot be done. A correct modelling of the rate constraints is of fundamental importance for the scheduling of projects because the model of the scheduler is obviously sensitive to the right boundaries.

From the viewpoint of a feasible scheduling plan the maximal rate allowed q_M is a key issue. The maximum value of the rate can be constrained as follows. Let the "time window" of the i-th activity be $\Delta t_i = d_i - e_i$. The activity rate has a minimum (and maximum at the same time) during which the activity can be executed keeping this rate every week:

$$1 \le \left\lceil \frac{r_i}{q_{Mm}} \right\rceil \le \Delta t_i \quad \text{from which we obtain} \quad q_{Mm} \ge \frac{r_i}{\Delta t_i}.$$

This means a lower constraint for the maximum of the activity rate, i.e. if the last inequality is not satisfied the project deadline cannot be met even with constant working without any interruption. Another constraint for q_M can be originated from technological features of the competent resource of the activity. For each activity a minimum time interval for completion of the activity can be determined according to experience. Hence the maximum of the activity rate cannot exceed this number even there were greater parallel capacity available. This limit can depend both on the project type and the utilized resources at the same time and it can be given for the project planner in a two-dimensional table (p_{ik}). Obviously, the relation $p_{ik} \cdot \delta t \le \Delta t_i$ has to be performed, otherwise the project deadline cannot be met.

On the basis of the aforementioned considerations, the constraint $\frac{r_i}{p_{ik} . \delta t} \ge q_{MM} \ge q_M$ is also to be satisfied. Therefore q_M has to be kept within bounds:

$$\frac{r_i}{\Delta t_i} \le q_{Mm} \le q_M \le q_{MM} \le \frac{r_i}{p_{ik} . \delta t}.$$

We showed the limits for the maximum value of the rate related to project activities. (see Fig.8.) We can define the relative value of the rate by $x_i(t) = \frac{q_i(t)}{r_i}$

Here x_i means the actual fraction of the rate and can be expressed in percent. The relative value of the maximum rate allowed can also be defined in a similar way, as follows: $a_{iM} = \frac{q_{iM}}{r_i} \cdot 100\,\%$.

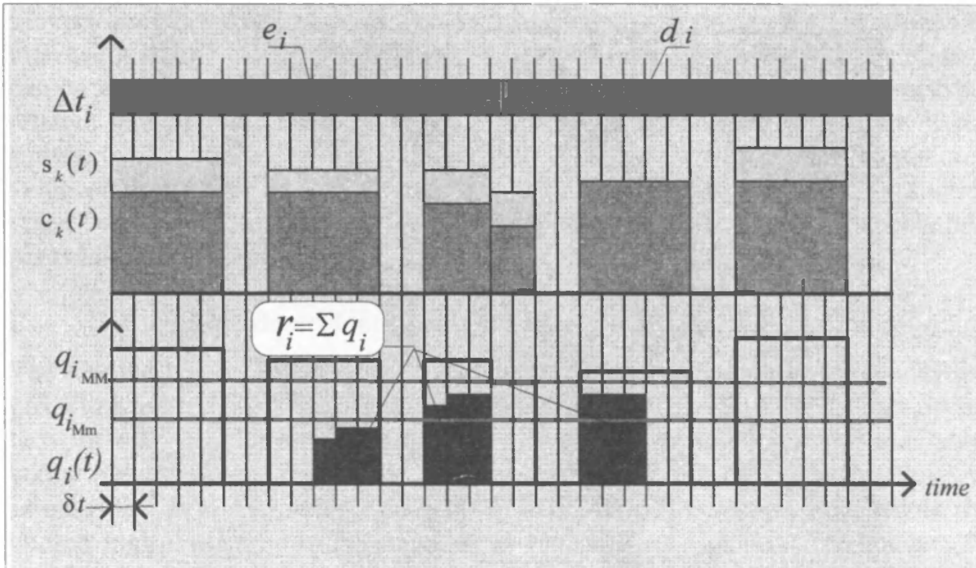

Figure 8. Constraints for activity rate and capacity

Fine modelling of the loading profile of project activities is a problem treatable in a more complex way.

The profile can be modelled with a graph or a conventional *Gantt*-diagram in a rough way only, because these graphic tools only concentrate on the time conditions and partial deadlines. As regards the resource demand of the project, only a constant or periodically constant rate can be modelled.

Demonstration of the loading profiles with a set of time-functions is better but there exists the danger of it being not easy to survey (see Fig. 9).

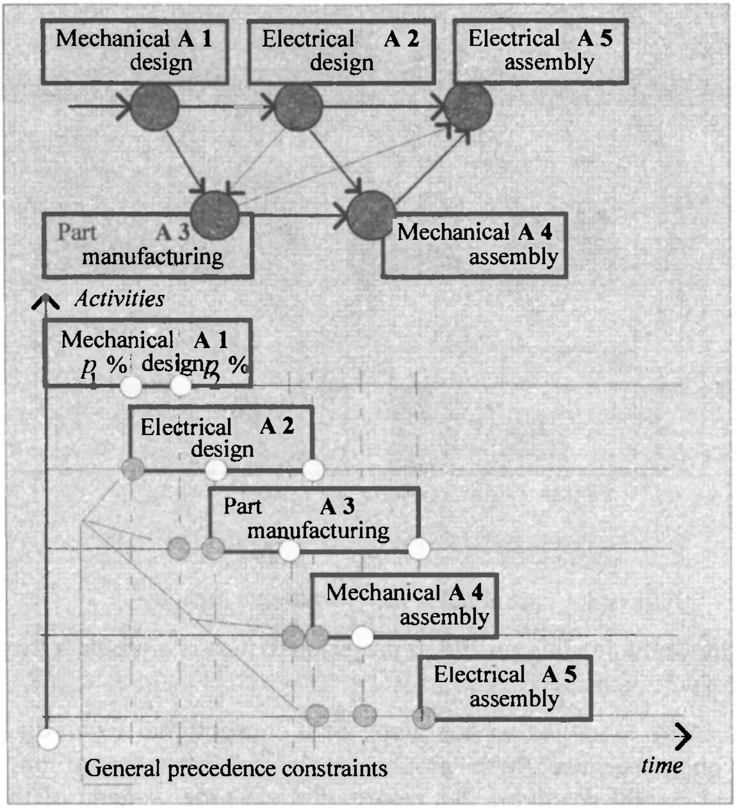

Figure 9. Modelling of precedence constraints for different activities

There are precedence constraints between the activities. On the one hand, they originate from the technology process itself; on the other hand, they can be deduced from business goals and considerations between the projects. Precedence, for instance, can be described by a directed acyclic graph $D=(N,A)$. The simple or special precedence $A_i \rightarrow A_j$ means that activity A_j can only start if A_i has ended. It can also be interpreted as a more general precedence $A_i \xrightarrow{p} A_j$, which means the activity A_j can only start if A_i was completed to p %. In aggregate production planning the latter is typical. For modelling precedence a binary variable can be allocated to every activity fraction, $x_i(t) \Rightarrow z_i(t)$, which shows whether the rate is allowed in the given time interval. The function $z_i(t)$ for activity A_i is a "stepped" function, which separates the interval $\Delta t_i = d_i - e_i$ into two sections. One of the sections is allowed for the activity, the other is not.

Further complicated constraints can be specified, for instance, for the gradually increasing profile of the rate. In case of two activities depending on each other it can be required that the relative rate of the dependent activity cannot exceed the relative rate of the other one. This might mean a cumulative restriction, if the summed value of a rate within a limited period cannot be greater than the summed value of the rate of any previously started activity. In such cases the activities "feed" each other, for instance, the delivery of the part drawings and scheduling plans in folders is a precondition of the beginning of part manufacturing.

9. Rate Based Optimization Model for Production Planning

The first basic task of aggregate production planning is to choose those production goals that are to be achieved in the planning period. Planning is carried out on the basis of market predictions, the orders of customers and the capacities available, taking into consideration the specifications and quantitative data of the products to be manufactured. The second problem of production planning is to schedule the chosen high-level production activities in time and in a quantitative manner. In project-like production planning this can be done by choosing those specific production loads (i.e. discrete production rates) that appear on the resources in the chosen planning horizon.

These tasks can also be solved in several ways and the task of computerized production planning applications is to support this solving process. In general, aggregate production planning models yield constrained discrete optimum problems, and the solution process of these problems is supported by the results of Operations Research.

Considering the fact that there are effective computer solvers suitable for solving linear programming problems, it is worth investigating those models of the aggregate production planning that can be solved by these solvers. The problem has been investigated by a research consortium consisting of five Hungarian partners for the last two years: the Computer and Automation Research Institute of the Hungarian Academy of Sciences (CARI-HAS), Budapest University of Technology and Economics, the University of Miskolc and two firms from the competitive sphere. Several models of the joint research work show promising results [5],[12].

The next model was developed for supporting the aggregate planning activities of a factory manufacturing individual machine systems. The model is elaborated by the researchers of CARI-HAS collaborating with research workers of Budapest University of Technology and Economics and the University of Miskolc within the framework of the research project Digital Factory.

The relative production rate as a state variable is defined by $x_i(t) = q_i(i)/r_i$ and means the loading fraction of the activity in the t-th time interval. It is obvious that

$$\sum_{t=e_i}^{d_i} x_i(t) = 1 .$$

The relative production rate of project level can have a value between the limits 0 and 1. For the sake of simplifying the model let us assume that every activity can be interrupted and therefore any value of $x_i(t)$ can also be equal to zero.

Let the goal of business policy be the maximal utilization of internal resources. In this case the rate of utilization of external capacities is to be minimized so that the objective function of the project scheduler is to minimize the utilization of external capacities. Hence, the objective function is:

$$\sum_k [w_k \sum_t y_k(t)] \Rightarrow \min ,$$

where $y_k(t) = \max[0, (\sum_i q_{i,k}(t)) - c_k(t)]$ is the rate of external capacity used in the t-th time interval and w_i is the weighting factor expressing the properties of the resource in question.

The task of the project-based production scheduler is to determine those relative production rate fractions $x_i(t)$ and external demands $y_k(t)$ which meet all the constraints related to times, capacities and sequences, as well as to minimize the objective functions.

The constraints are as follows:

$x_i(t) = 0$ if $t \le t \le e_i$ and $d_i \le t \le T$ (The activity has to be completed in the given time window.)

$\sum_{t=e_i}^{d_i} x_i(t) = 1$ (Every activity has to be carried out entirely);

$\sum_{i,k} r_{i,k} . x_{i,k}(t) \le c_k(t) + y_k(t)$ $1 \le t \le T$ (All the demands are covered by the internal and external capacities);

$y_k(t) \le b_k(t)$ (The external capacity is also limited);

$x_i(t) \leq a_{iM} . z_i(t)$ (The rate of activity cannot be greater than that allowed and it can only be different from zero in that interval where it is allowed by the precedence control condition).

If there is no solution of the planning task with the given data then it is the task (or decision) of the production engineer to intervene interactively in the computer-aided planning process. In order to solve the problem it can be expedient to slacken certain constraint(s) or to define a new production planning task by changing the demands of the project.

The aforementioned strategy of project work results in a solution most typically in resource-overloaded cases. If the task is not resource-overloaded then the value of the objective function is obviously zero and there can be numerous solutions for meeting the constraints. At that time the task of the project scheduler is to suggest those solutions from the possible and allowed solutions considering which profile of rate changing is the most suitable for meeting the requirements of the production goal.

If it is not important or not possible to take the external capacities into consideration, then the objective function can be an expedient function of the deviations from deadlines. This function, for instance, manages the exceeding of deadlines stricter than completion before due date, because the latter only increases the stock level.

It is clear that project activities in several aspects differ from the activities of part manufacturing at the shop-floor level. In general the operations as activities cannot be interrupted, and in scheduling processes it is not common to define operation by a changing rate. The precedence constraints are stricter and the scheduling plan can be well represented by a Gantt-diagram.

The nowadays commonly-used applications for aggregated production planning separately manage the tasks of Material Resource Planning and Capacity Planning in order to cope with the difficulties of hard calculation. The result is an aggregated Master Schedule which guarantees meeting the constraints even in the case of large-sized problems, however it gives little information about the alternatives and possible solutions.

10. Estimating Procedures at Similarity Based Production Planning

Important tools of the aggregate production planning are those estimating procedures that estimate the probable structure of activities and the utilization of resources on the basis of the similarity of the products. Under such circumstances the modular structure of these products, the principles of Group Technology (GT), and similarity-based estimations can have an important role.

Machine manufacturers meet the task of aggregate production planning in the period of tender, when obtaining the order is an outstanding business goal. If the production plans of the product meeting the requirements of customer are not available then inserting the project into the running tasks requires careful aggregate planning that includes planning alternatives of the "What would happen if..." type as well. Here the most important factors are a well-established delivery deadline and a reliable estimation of the probable capacity overloading.

In the course of the realization of a project two different hierarchies have to be taken into consideration:

- the structural hierarchy of the product (complex machine) constituting the base of the project in question,
- the technological hierarchy realized in the manufacturing process.

Structural hierarchy reflects the physical reality of the product, as well as subordination of the main machine units adequate to the major functions. We assume that a product can be dissected into four hierarchy levels at the very most:

(1) the complex (complete) machine

(2) a machine unit

(3) an assembly unit

(4) a part group.

We hold it natural that only those projects that belong to the same structural hierarchy level can be compared to each other.

In the hierarchy of the production process we allow two levels, namely

1. the level of aggregate activities of a complete project,
2. the level of operations of the production activities.

The first step of similarity-based production planning is to allocate the project to be planned to a product hierarchy level. After this, at the given hierarchy level, we select the similarity projects from the projects previously completed. This is an algorithm consisting of several steps. We make a list including the operations executed in the projects, the utilization of capacities, and the times for planning, manufacturing and assembly. The operation set obtained in this way can also be supplemented with several specific operations if needed for realization of the new project, and if they have not appeared in any similar project so far. So we thus obtain a possible set of operations. We allocate the operation times occurring already in the completed projects to these operation sets in a primary table. The similarity based selection, after all, will be executed by means of a secondary table that qualifies the similar projects on the basis of the occurrence of operations and the operation times within defined tolerances. On the basis of activities of the projects selected in this way we can get a fairly good estimation for the production time requirements of the project activities planned.

11. Application Experiences in Industrial Environment

As we have already touched on the fact in Section 9, in 2001 a three-year long research and development project started in Hungary. The project, entitled Digital Factory, was led by CARI-HAS, and several departments of universities and industrial factories participated in it. One of its clusters aimed at the elaboration of a large-sized project scheduling system, which can be applied in an industrial environment [15].

During the development and application process of a technical system several well-proved methodological results were used (*Enterprise Modelling and Integration*). These results are based on the experiences of several great paradigms, for example CIM, Concurrent Engineering, Virtual Enterprise, TQM, BPR, IMS, etc.

One of the best summaries (but not the only one) of the development methodology is the reference model CIM OSA [24]. In the course of our work this framework system was considered as a reference model. This framework is suitable for giving a clear survey and nodes of the determination and solution of the partial tasks in the course of research and development process (see Fig.10.).

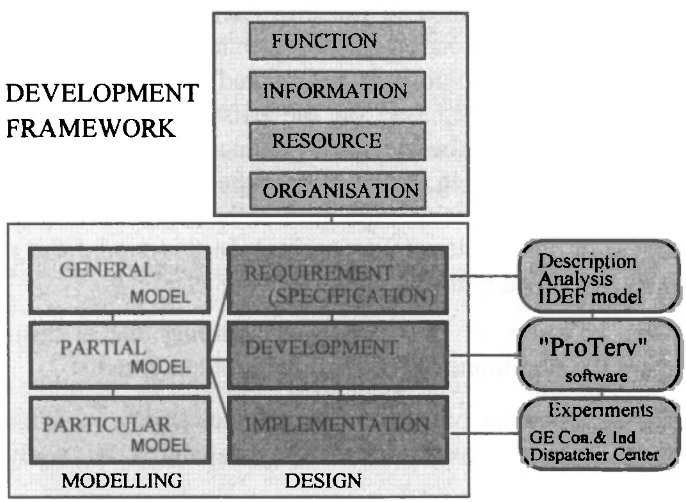

Figure 10. Application of the development framework CIM OSA

The *general* requirements of the integrated production planning and scheduling system were based on the results of the basic research. The main requirement is modelling the activities of the projects competing for the finite resources, as well as the scheduling of the resource loading capacities of these projects considering the constraints and the objective functions for optimization.

The *partial* requirements were determined by the production tasks of a factory making individual machines. The *particular* solution aimed to satisfy the special requirements of the machine factory *GE Consumer & Industry.*

The requirement analysis was followed by the system- and program planning. The next step was the implementation of the project planner and capacity scheduler software application ProTerv. We had to find a functional and mathematical model suitable for the functional requirements and at the same time we had to elaborate a solver algorithm. In the course of the information planning it was necessary to develop an application data model and an integrated input/output model; both of them in several iterative steps. The organization tasks determined the Human Machine Interface (HMI) of the production planner and scheduler systems and the different ways of operation and utilization. The most important software components were the efficient solvers (CPLEX and ILOG Solver) and the program developing tool (Windows.NET).In order to formulate the functional requirements of ProTerv we elaborated a detailed text-centred descriptive model, an SADT-type hierarchal graphical model and a mathematical model for presenting the operations research task.

When planning and scheduling a project in the production of individual machines the requirements are to be allocated to the characteristics of the production. In production planning the project-based model provides the most advantageous conditions. Decisions of the medium run aggregated production plans (projects) and their scheduling in time are based on the existing and expected customer orders, the running projects and the available production and supplier capacities. The primary goals are the following: realization of the obtained orders meeting the deadlines, utilization of the production capacities at the highest level, minimization of the quantities of supplier's orders (outsourcing). In this model the set of high-level activities to be scheduled typically consists of 4-8 elements.

For improving the solution of the project scheduling tasks the production management stresses the importance of the following requirements:

- Increasing the efficiency of the management decisions;
- Enlarging the set of possible decisions, capability of analysis of the alternatives;
- Reducing the production costs, increasing effectiveness and profit;
- Meeting deadlines in a safer way;
- Decreasing the risk of erroneous decisions.

At the project planning process the roles and tasks of the material plans, capacity plans and production scheduling plans can be easily distinguished. The requirements of the project scheduling method of new approach are given below.

The scheduling has to cope with the problems arising from the partiality of scheduling, the uncertainty of data and events, as well as the periodic validity of plans (see Fig.11.).

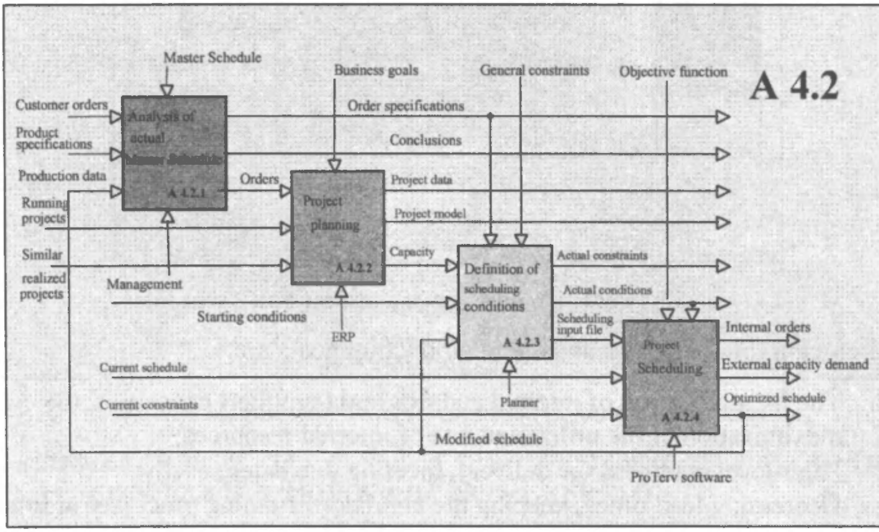

Figure 11. A SADT-type graphic functional model element of ProTerv

As far as possible the production planning, the engagement of capacities and high-level scheduling are to be managed together, although these tasks are traditionally separated in ERP systems.

It has to take into consideration equally the economical and engineering aspects of production, the duality of constraints and manager goals, the demand of the profiles of scheduling plans.

The quick and clear definition of project scheduling conditions has to be supported by an interactive graphic interface (Fig. 12).

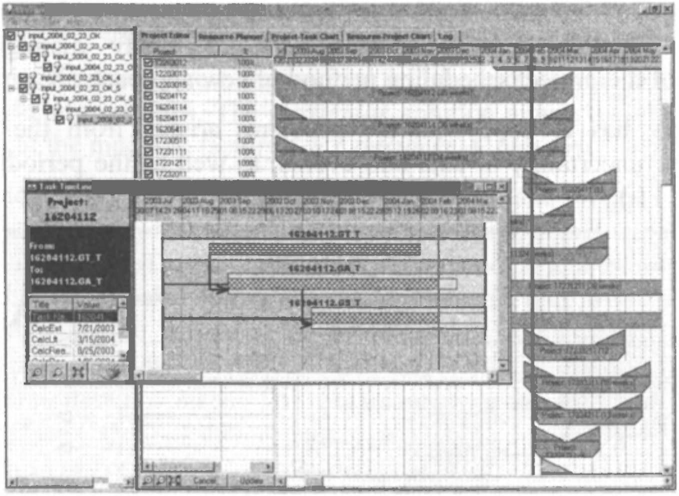

Figure 12. Interactive interface of a project-based scheduler

Requirements concerning business and production goals are:

- The harmonization of internal and external (supplier) capacities, the maximization of the utilization rate of internal resources;
- High-level readiness for delivery, meeting due dates strictly.
- Decreasing lead times, keeping the number of running processes at low level.

Software requirements for the scheduler:

- Modern information platform (Windows XP and .NET are used by the prototype);
- Effective algorithm for the task and solver (CPLEX and ILOG solver);
- Modular structure, maintenance services;
- Possibility of improvement and reutilization.

The most important application requirements:

- Pure model, functional correctness, examinations of consistence;
- Reliability, tested menus;
- Graphical human-machine interface, easy to manage;
- Possibility of integration (ERP, MES; Text-type I/O files).

The improved application software ProTerv is based on many components. The model generating process, the examination of consistence and database treatment ensure the controlled task description for the scheduler component. The main source of input data is the database ERP and the interactive human-machine interface (Fig. 13).

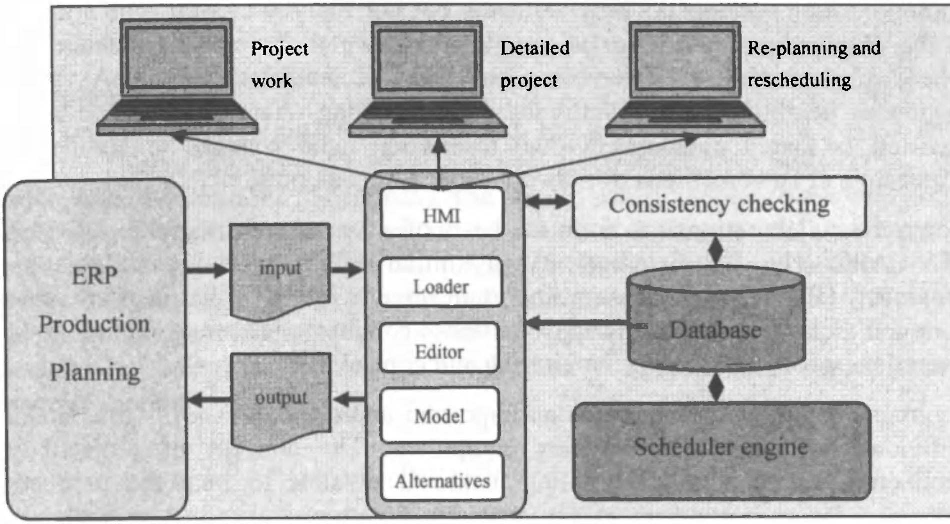

Figure 13. Structure of a project-based production scheduler

The scheduler provides the scheduling plans for project activities as output, representing them in tables and in a graphical way (Fig. 14).

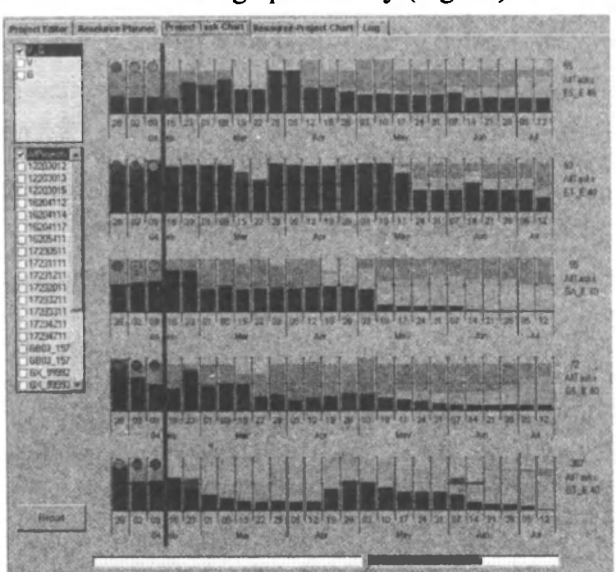

Figure 14. Graphic form for scheduling plans of ProTerv

12. Conclusions

VE-frameworks enlarge application possibilities of information technology and communication systems not only vertically but horizontally as well. The principles of the VE paradigm have revealed new possibilities at the layers (for instance CIM) where a great deal of experiences has been accumulated so far. As typical examples, flexibility and re-configurability of joining, shared knowledge-base in addition to shared databases, virtual teamwork, rapid changes in competence, application of BPR methods by network-organisational tools, etc.

The same collaborations can form the basis of a reassessed integration of CAPP-PPS-CAPC. The VE paradigm has a similar effect on the paradigms used previously (JIT, TQM, CIM). An important novelty of VE is that it offers several common tools for production-supply-business-commerce processes including their operations, goals, scheduling, monitoring and control.

Aggregate production planning is an important and difficult task of firms making individual machines and complex equipment. The concept of project-based production planning and scheduling makes it possible to treat the production activities and the engagement of capacities together. A production scheduling model can be based on the rate of project activities. The model of project activities is significantly different from the scheduling model of shop-floor control. The high-level activities of the projects can be interrupted and can be planned at a changing rate. The activities can also use several different resources. The profile of rates in time can be influenced by additional constraints.

We have applied the rate-based model of aggregate production planning in R&D work carried out within the framework of a consortium. The model proved to be successful for different products and production profiles as well. The experimental computerized applications are being tested at present. The advantages offered by the rate-based aggregate production scheduler are as follows:

- The number of occasions when the deadline is over-run decreases;
- The lead times of projects decreases;
- The set of external orders can also change advantageously;
- Utilization of capacities increases and will be more balanced;
- The use of overtime and external capacities decreases;
- The bottle-necks can be recognized and can be treated in a better way than earlier;
- The number of jobs in process decreases.

In addition, an important benefit can be the increase of the co-ordination of engineering functions and the improvement of the integration of the chief engineer department and shop-floor levels. Alternative solutions of modelling of the production processes increase efficiency of management decisions. On the basis of experience, a reengineering process of greater scale can be realized for improving and controlling the working process of the production planning organization.

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