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FLOW-BASED APPROACH FOR HOLISTIC FACTORY ENGINEERING AND DESIGN

The engineering of future factories requires digital tools along life cycle phases from investment planning to ramp-up. Manufacturers need scientific-based integrated highly-dynamic data management systems for the participative and integrated factory planning. The paper presents a new approach for the continuously integrated product design, factory and process planning, through a service-oriented architecture for the implementation of digital factory tools. A first prototype of the digital factory framework has been realised by a comprehensive scenario for factory, equipment and process planning. The phases of factory operation and equipment maintenance are integrated, as well. The enabling technologies, grid computing and workflow management, which supports the comprehensive and integrated engineering of products, factory and processes are shortly introduced.

Keywords:
Digital factory, Workflow management, Grid engineering

1 CHALLENGES

Factories are complex and long life products, which have to be permanently adapted for changing products, markets and technologies to fulfil the economic and ecologic requirements. The environment of manufacturing is turbulent and paradigms change from cost optimisation towards sustainability and competitiveness in a global economy [1].

There are many and diverse transformability drivers which trigger the adaptation of factories and processes. This process includes the whole structure from networks and supply chains to sites infrastructure, manufacturing systems, machines, workplaces and processes. The time scales of all operations, which may change factories systems, reach from short to long-term [2]. The planning processes are multi-scale (space and time) processes, for which engineers and planners need efficient tools (Digital Factory). They should support all processes from the strategic planning of resources down to the parameters and execution instructions or programmes.

This paper presents a Reference Model for holistic Factory Engineering based on state-of-the-art Grid technology and Workflow Management Systems. The developed IT architecture is introduced through a system overview and an example scenario.

2 CONTINUOUSLY INTEGRATED FACTORY ENGINEERING AND DESIGN

The concepts, purposes and the tasks of factory and process planning have been approached in the research works of Kettner [3], Aggteleky [4]. A Reference Model for a holistic Factory Engineering and Design, proposed by Westkämper [5] integrates continuously all phases of the Factory Life Cycle structured in clusters, as presented in Figure 1.

Figure 1 – Continuously integrated Factory Engineering and Design.

The *strategic planning* sets-up the long-term vision, mission and goals founded on financial values of product markets and on product development. The factory capacity and performance planning are based on production data history, MRP data, scenarios and business plans for product and production technologies and production programs. A technology schedule establishes the chronology of strategy implementation and the indicators of progress measurement. Unfortunately there is a lack of tools for factory performance planning supporting the development and evaluation of scenarios and the planning of sales, capacity and manufacturing costs by taking into consideration the rationalisation effects and the conception of close to reality measures. The strategic planning prepares the premises for the structure planning.

The *structure planning* establishes on a medium and long term immobile and the long life mobile planning objects by considering the environmental aspects, the trend of material costs increasing and the prescriptive limits for the emissions. The planning of the production site and network concentrates today on the effects of product structure on the network set-up by approaching regional aspects like local know-how. In the middle stays the logistics focused on Just-In-Time principle, supported by various material flow planning and optimisation tools. The planning of buildings and infrastructure, of logistic connection to the traffic system, of media supply and of wastage disposal follow the classical methodology enhanced by sustainability aspects and new features as Corporate Identity, communication and motivation of employee in innovative working spaces. The planning of internal logistics and layout, supported by a large amount of systems aims at permanently adaption and optimisation of the space floor utilisation. The connection and synchronisation of all structure planning tools to the central factory data is achieved through simultaneous engineering, participative and collaborative technologies and tools.

The *planning of processes, machines and equipment* follows the changes of product world focusing on production resources like machines, tools, fixtures, work places and CNC programs for controlling of machines and equipment. These planning activities range from medium to short terms. The advanced Industrial Engineering methods and tools support the work planning regarding the material, processes, work sequences, used equipment and measurement tasks by having a relevant contribution to the synergetic optimisation of time, costs and quality.

The *planning of operation and usage* of factories starts with ramp-up and implementation, continues with factory operation and ends with maintenance and dismantling or replanning, by ranging on short time periods as weeks, days, and hours. The integration of Manufacturing Execution Systems and maintenance systems into the Factory Data Model and Management supports the synchronisation of the Digital Factory with the factory operation [6]. Innovative use of sensors and RFID technology enable the implementation of the Smart Factory through the so-called factory context-aware systems, e.g. failure management systems. The data, knowledge and best practices acquired in the phase of factory operation and maintenance represent a valuable base of learning for permanently adaptation and optimisation of factories.

As along all these planning phases are involved many organisations and are employed a large variety of IT systems and tools, the challenge of a central Factory Data Model and the corresponding Data Management arises. In analogy with the Product Data Management Systems, in the centre of the approach is the Factory Data Management, responsible for the project management, for the communication and the integration of the required IT systems and tools. It supports the data consistency and the workflow functionalities specific to the factory planning processes.

Aproaches the Factory modelling and simulation and its levels as follows: Factory structures (sites, network, manufacturing segment/area, system, processes); Areas and concepts (economic science, engineering, mathematics, physics, chemistry); Modelling and simulation methods (event-oriented simulation, finite elements, moleculardynamics); Spatial expansion (macroscopically or mesoscopically, microscopically, atomically); and Temporal expansion (years or weeks, days, hours, seconds, nanoseconds) [8]. This comprehensive modelling and simulation at all these scales brings the complexity consisting on migration of simulation models from numeric simulation for the process and material modelling towards the discrete simulation for the purposes of logistics simulation. The following Sections present a possible solution to these challenges.

3 ENABLING TECHNOLOGIES

This chapter introduces the main functionalities of Grid Computing and also Workflow Systems. These technologies found the base for the Grid Engineering Architecture and the integrated scenario, presented in Chapter 4.

3.1 Grid Computing

A computational grid is a hardware and software infrastructure that provides dependable, consistent, pervasive, and inexpensive access to high-end computational capabilities' [9].

The main challenge for a Grid is an architecture which enables the cross-organisational application integration and resource sharing - virtualisation.

To effectively operate between any participants in a virtual organisation, interoperability is the central challenge to be addressed which means common and standardised protocols. Hence, the architecture of a Grid is mainly a protocol architecture, which defines data exchange standards for the basic mechanisms by which users of virtual organisations can share computers, software, data and other resources [10]. The most famous organisation for the standardization of Grid Middleware which specifies these protocols and founds the base for a Grid Architecture is the Global Grid Forum (GGF). The main goal of this organization is the development of the Open Grid Service Architecture (OGSA).

Grid Computing can be applied in different ways and can be categorised according to Berstis [11] by the following types:

Computation: Computational Grids are used to run complex simulations, calculations or any jobs on different distributed computers in order to decrease the total execution time. There are two possibilities to run a simulation in Grid environments [12]:

- The application is implemented modular, that it can be executed on different processors in parallel.
- The application runs several times on different processors, for example the automated optimisation of a simulation.

Grid is not only the sharing of computing resources but it also contains all the functionalities to manage the life cycle of computing jobs: for example the handling of the storage of large datasets and the arranging of the data exchange required for the job execution [13].

Data Storage: A common file system in a Data Grid can provide a single uniform namespace for data [9]. The users can reference these data, not concerning where they are stored in the Grid. Thus large data capacity sometimes required for complex simulations and calculations can be partitioned over many machines and an immense overall data capacity is available.

Communication: To send jobs to different computers, it is required to provide the input data for the job and to collect the output data resulted from the job. Grid Com puting provides technologies to simplify this process, for example through workflow systems, and it also supports the efficient transmission of large data capacities.

According to these technologies and based on OGSA the Globus Toolkit was developed by the Globus Alliance [14].

3.2 Workflow Management

Factories have to be flexible and transformable, in order to remain sustainable and competitive. Therefore permanent planning processes are required, which have to be performed as fast as possible. For a systematic engineering of factories, equipment and processes, modern tools of the digital factory are employed. The planning goals and planning processes are however always situation-based. The main reason for that is the plurality of different transformability drivers like changes of the products, increasing cost pressure and fluctuating demands on the market.

In order to achieve maximum of effectiveness and efficiency during the situation-based planning processes many planning activities have to be standardised. The possible solution to cope with this challenge is the situation-based factory, equipment and process planning implemented by using Workflow Management Systems. These type of systems represent a kind of middleware systems, which are application-independent and support the modeling, the enactment and the monitoring of workflows [15].

The Workflow Reference Model, developed by the Workflow Management Coalition describes the interfaces of a workflow management system. According to [16], the model defines the interfaces of the workflow enactment service to the following subsystems:

- process definition tools,
- workflow client applications,
- invoked applications,
- other workflow enactment services and
- administration and monitoring tools.

The enactment service provides the runtime environment for the progress of the processes.

In the context of a workflow management system, the modelling of workflows is usually performed through a graph-based process definition interface. Generally, the specification of the workflows is described by the Business Process Execution Language - BPEL, which is an XML-based description language. It uses web services for interactions with external applications [17].

The state-of-the-art Product Life Cycle Management Systems offer functionalities of workflows by supporting the management of all relevant data regarding the product development and factory engineering [18, 19]. The workflow management systems also provide huge potentials for the improvement of factory and process planning by embedding principles coming from simultaneous engineering and participative planning into the engineering process. The modelling of workflows before a planning project starts enables a maximum of coordination of planning activities. The communication between planners, which is dependent on the modelled workflow as well, is supported by task lists. The outcome of this is a clear definition of the process flow and of the work content, and their allocation to the persons which are involved in the planning project. A cooperation within and across departments with a clear allocation of responsibilities can be achieved. After finishing a task, the enactment of further planning activities can be initiated dependent on the workflow model.

The enormous complexity of planning processes can be handled by using tools, applications and systems like PPS, MRP and CAx. The automated passing of data, information and related documents supports the comprehensive use of digital engineering and manufacturing systems. The improved availability of data, the avoiding of data redundancy and the assuring of data consistency are relevant benefits of using that systems. Furthermore, the modelling effort can be considerably minimised based on the automated preparation of data. The integration of digital engineering and manufacturing systems can be performed by web services. The enactment of those engineering systems by workflow management systems supports their purposeful use in a planning project. A considerable reduction of the planning duration and a significant improvement of the planning quality can be achieved.

Standardised interfaces of the workflow enactment services are available. Thereby an always actual status of the planning project supports the planners' and controllers' activities. For analysing the costs and times, essential tasks of controlling can be supported by the workflow management systems. The implementation of quality gates, which brings together parallel activities to points of decision and where the degree of maturity and existing risks are evaluated, are provided along the planning workflow [5].

Regarding to the situation-based character of planning projects a holistic modelling of the planning workflow, which has to be individually prepared for each planning project, is required. The current states of the factory and the established planning goals have to be considered. For coping this challenge the storing of predefined workflows in a workflow library, which could be allocated to the planning fields of a factory, is conceived and developed. These template workflows can be used for the modelling of the aggregated workflow corresponding to a specific planning project through using a graph-based process definition tool. Furthermore, planning workflows, which are separately enacted by a different workflow enactment service could be coupled and synchronised by the interoperability of workflow engines.

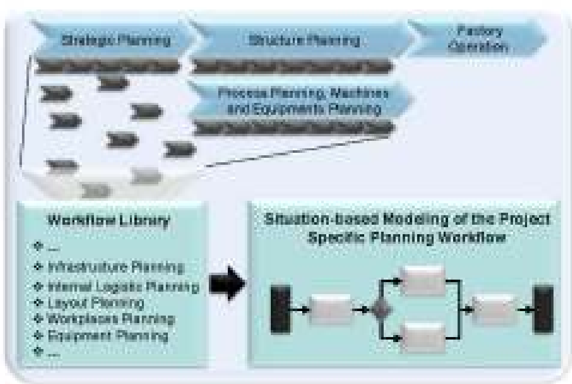

Figure 2 – Approach of the planning method based on workflows.

Figure 2 illustrates the planning methodology. After finishing a planning project, the modelled aggregated workflows can be stored in the library and best practices can be used furthermore by implementing the learning concepts in factory planning. A planning scenario which is performed in an implemented grid-flow-based planning environment is presented in chapter 4.2.

4 APPROACH OVERVIEW AND IMPLEMENTATION

The reference model of a grid-flow-based approach for holistic factory engineering and design was validated by a comprehensive planning scenario. The Grid Engineering for manufacturing lab – GEMLab at Fraunhofer IPA/IFF represents a planning environment which provides the shortly presented enabling technologies for the purposes of systematic, integrated and comprehensive factory, equipment and process planning. In the following chapters, a planning scenario is presented, as well as the integrated digital engineering and manufacturing systems and the way of data integration and data exchange. Firstly, the innovative GEMLab Architecture is over-viewed.

4.1 GEMLab Architecture

A flow-grid-based architecture has been conceived and developed in the Grid Engineering for Manufacturing Laboratory – GEMLab at the Fraunhofer IPA/IFF (Figure 3). It enables dynamical generation of situation-based workflows which can be executed to process a continuous and systematic factory planning.

The used Grid Workflow System manages the orchestration of distributed data, models and planning systems and also computing resources. The different planning systems for product development, factory and process planning are integrated through the service-oriented Grid Engineering Integration Middleware.

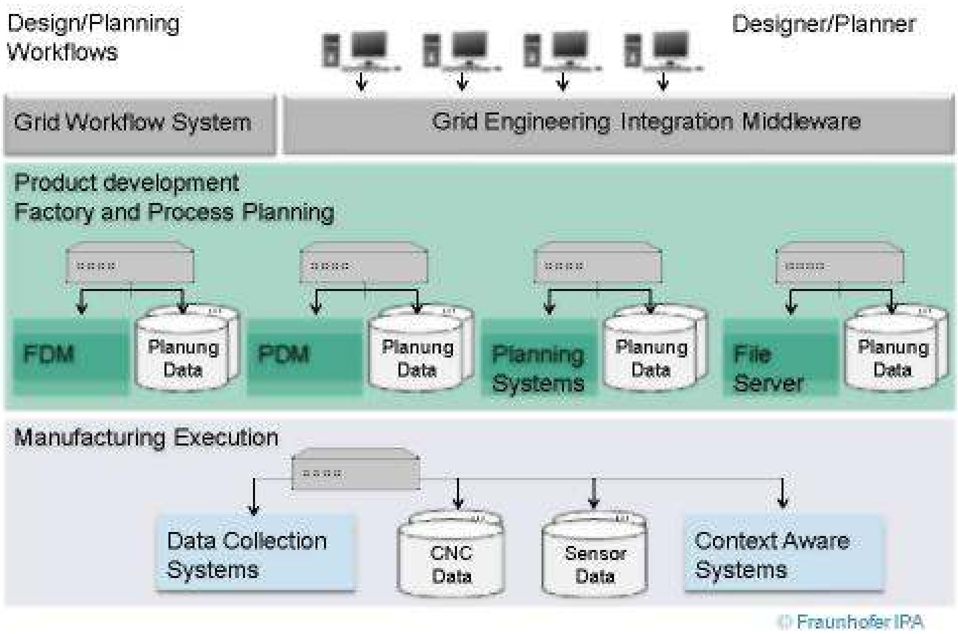

Figure 3 – Grid Engineering Architecture

The central data exchange points for the planning process are the Product Data Management System (PDM) and the Factory Data Management System (FDM). To solve the bridge between product planning and factory planning an automatic change propagation method synchronises these two components. The systems of the manufacturing execution are coupled through the middleware and allow the synchronization of the current factory status and the factory planning. The Grid Engineering Architecture is additionally supported by collaboration systems which enable functionalities like project management, task management and communication. Therewith distributed and interdisciplinary projects can be systematically organized.

Each digital tool is integrated to the Grid Engineering Architecture through a standardised Grid Engineering Service implementation which adapts the heterogeneous systems by different suppliers to a common interface. The WSRF – Web Service Resource Framework standard is used to implement these services and the Globus Toolkit Service Container is extended for the deployment of this services.

The data is exchanged through a specific XML-based format which has been extracted from a factory data reference model. A service library for transformations is used to adapt the output data of the different tools to the common data exchange format. The transformation library uses specific transformation technologies like Extensible Stylesheet Transformation Language - XSLT. The graphical workflow system GridNexus by University of North Carolina in Wilmington is introduced and customised to the requirements of factory and process planning. It provides an intuitive graphical user interface, supports WSRF services and allows the dynamic creation and execution of workflows without time-consuming workflow deployment.

4.2 Implementation Scenario

In order to validate this new approach and to identify its advantages and benefits, a continuous planning scenario was developed. In this scenario a holistic planning and optimisation of a factory, that produces desktop accessories with many variants, shall be considered. For performing the planning tasks the planning environment, which is available in the GEMLab and which consists of different state-of-the-art digital engineering systems will be used. Therewith the potentials of powerful tools can be demonstrated as well as the innovative approach for data exchange in order to achieve an integrated and comprehensive factory, equipment and process planning.

The planning scenario starts with the extension of the spectrum of variants of the scenario`s product desktop accessories. There already exist different modules existing like cans for writing utensils and clocks, which can be commissioned and assembled to customer specific products. The modules shall be enlarged by a desk lamp. The factory consists of a manufacture of parts, cleaning, sub-assembly and a final assembly (Figure 4). The extension of the spectrum of variants requires adjustments in the production processes, in the factory layout and in the internal logistics.

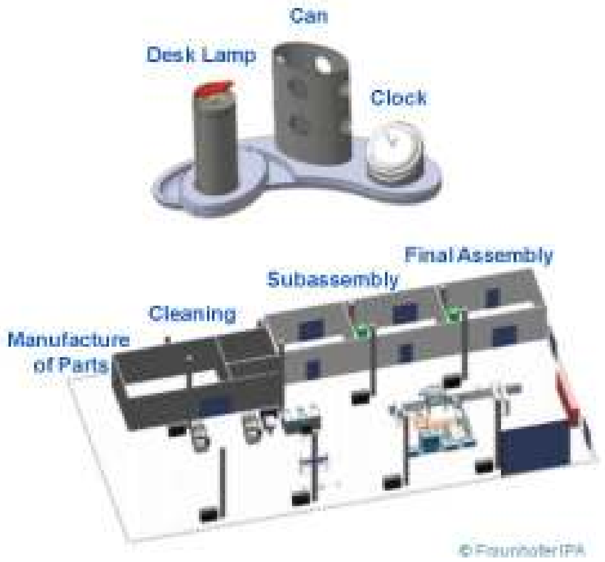

Figure 4 – The product and the factory layout

In the following an overview of the sequence of the planning tasks and the applied planning tools shall be described (Figure. 5)

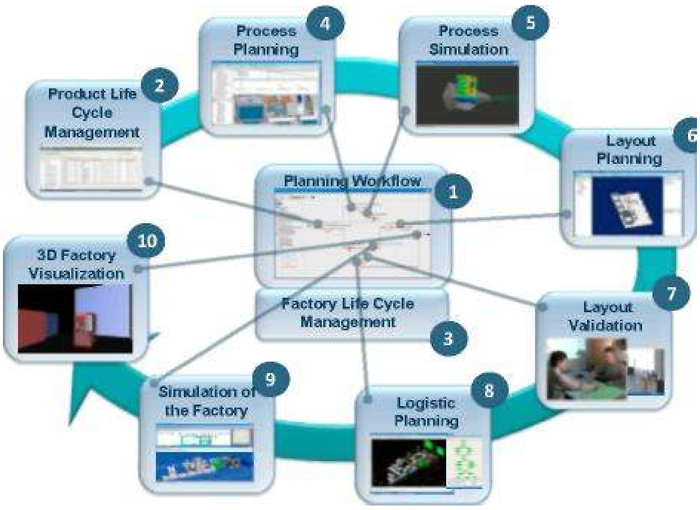

Figure 5 – Workflow of the planning scenario

1. Modelling the Planning Workflow

At first the planning workflow is modelled by the grid-flow system GEMFlow which bases on the open source system Globus Toolkit and GridNexus. These systems support the modelling and enactment of the planning workflow. Along this workflow the data exchange between the Factory Life Cycle Management (FLM) system Teamcen-ter from Siemens PLM Software and the other digital tools is performed using Grid Services.

2. Product Life Cycle Management

The data, which were generated during the development of the new product variant, have to be stored in the Product Life Cycle (PLM) system Windchill from Parametric Technology Corporation - PTC. The functions of the PLM system support the planning team to manage the structure of the product, the related CAD data and the documentations. It further supports the development of a generic process plan by combining product and process data.

3. Factory Life Cycle Management

The data, which were generated and stored within thePLM system Windchill, will be passed to a FLM system(Factory Life Cycle Management). As FLM system,

Teamcenter is applied, which was originally developed as a PLM system. It is used for the central management and storage of the data for the products, processes, resources and factory structure. All tools which are applied for the factory, equipment and process planning are coupled with Teamcenter.

4. Process Planning

The generic process plan and the product structure are exchanged between the Product Life Cycle Management and the Process Planning tool over the FLM system. This process plan includes a rough sequence of the manufacturing steps. They have to be adjusted to the given facts of the specific factory. The analysis of the capacity requirements and of the available capacities shows whether an adaption of the capacities in the factory is required or not. The tool Process Designer from Siemens PLM Software supports the allocation of equipments and personal to manufacturing processes and the calculation of times for those processes. It also supports a line balancing for the most efficient association of processes to resources.

5. Process Simulation

Critical processes like the cleaning of complex parts with spray jets have to be investigated by a process simulation tool from Fraunhofer IPA. Therewith the optimal adjustments of the devices like the jet distance, the angle of impact and the duration of impact can be determined as well as the required process times. Therefore distributed simulation optimisation methods are used to improve these adjustment parameters to an optimum. To prepare the optimisation, the CAD data of the product and the adjustment parameters for the cleaning machine are transferred from the FLM system to the simulation tool.

6. Layout Planning

In the process planning phase the requirement for a new assembly resource was identified. For this reason the factory structure was enhanced with a new assembly station using the software Process Designer. Therefore the current factory layout was imported from the FLM system to Process Designer and exported back to the FLM system after the modification.

7. Layout Validation

For the participative validation of the factory layout, the IPA Planning Table was used in this scenario. Experts, coming from different disciplines of factory planning, are enabled to work together on a factory layout by the Planning Table. Thereby the planning is positively influenced by the different points of view of those experts and their implicit knowledge [20]. The Planning Table provides full capability to import the current factory layout from the FLM-system and export it back after the modification.

8. Logistics Planning

The changes of the product cause new logistics processes and connections of the material flow. The current layout is imported from the FLM system and visualised by the CAD system FactoryCAD from Siemens PLM Soft ware. A static optimisation of the factory, supported by the extension FactoryFlow, is performed by statically analysing the different material flows and visualising them in the factory layout.

9. Simulation of the Factory

With the simulation data exchange module SDX from the simulation system Plant Simulation from Siemens PLM Software, a simulation model is automatically generated, based on data coming from process and layout planning. The key performance indicators (KPI), which can be analysed by this simulation, are cycle times of products, capabilities of machines and intensities of material flows. These KPIs provide a good basis of factory optimisation.

10. 3D-Visualisation

At the end of the scenario, the application GEM Factory Immersion from Fraunhofer IPA generates a 3D model of the current factory layout which is stored in the FLM-system. This factory model is projected as a 3D environment for evaluation of interdisciplinary experts using a stereoscopic projection wall.

5 CONCLUSIONS

The paper presents the main results in the field of continuously integrated factory engineering and design through the Reference Model for a holistic Factory Engineering based on state-of-the-art Grid technology and Workflow Management Systems. The developed IT architecture is introduced through system overview and an example scenario is presented.

The innovative integration of digital manufacturing technologies and of the corresponding tools for modelling, simulation, optimisation and visualisation of factories by following the Life Cycle philosophy gives to the factory the Life Cycle orientation. It supports the synchronisation with the phases and tools of Product Life Cycle Management. The orchestration of Workflow and Grid technologies enables the distribution and networking of manufacturing resources like data, models, engineering systems and computing resources.

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