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NEW CONCEPTS OF MODELLING AND EVALUATING AUTONOMOUS LOGISTIC PROCESSES

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Abstract: Due to the existing dynamic and structural complexity of today's logistics systems, central planning and control of logistic processes becomes increasingly difficult. This intensifies the ongoing paradigm shift in logistic processes from centralised control of 'non-intelligent' items in hierarchical structures towards decentralised control of 'intelligent' items in heterarchical structures. The paper explains the observed paradigm shift in terms of new requirements related to modelling and evaluating methods of autonomy in logistic processes. The opportunities of autonomous logistic processes in contrast to conventionally managed logistic processes will be discussed on an exemplary scenario.

Keywords: Adaptation, Agents, Autonomous and Adaptive Control, Evaluation, Manufacturing Processes, Methodology, Measuring Points, Modelling.

1. INTITIAL SITUATION AND CALL FOR ACTION

The field of production management and logistics is currently undergoing major changes, due to increasing structural (e.g. complexity and versions of products) and dynamic complexity of the production systems itself as well as to this production system is regarded as a sub-system of a logistics network.

This development is not new, and has been observed for the last years. Competition forces companies to develop new optimisation potentials. After nearly all internal possibilities of companies to improve their processes have been almost exhausted, some of the off-site concepts like Supply Chain Management (SCM) seem to be very promising to generate competitive advantages. On the one hand these changes are basically related to the fusion of several information- and web-technologies, which are technologically available and partly affordable like Radio Frequency Identification (RFID-) Technology and PDA-(Production Data Acquisition) within PPC-Systems, as well as on the other hand they are due to the deployment and fusion of a wide range of different methodologies of controlling and monitoring, for example from control theory and artificial intelligence. Coming from the field of control theory, new and further developed concepts have been discussed (Gassmann, 1998), for example related to adaptive controllers (Sastry and Bodson, 1989), or controllers using fuzzy-theory, as well as learning and knowledge based controllers (Luger, 2002). Even mixtures of these very different concepts have been sketched out, in the sense of so called hybrid approaches (Viharos and Monostori, 2001; Tsakonas and Dounias, 2002), sometimes integrating simulation models, as well.

This in turn will and has to lead to new ways of approaching complex scenarios of processes in production logistics. It may be pursuit for example in terms of locally modelling and linking, autonomous controlling and decision entities, e.g. multi-agent systems, which comprise several autonomous and heterogeneous agents acting together as a loosely coupled network to cooperatively solve given problems in an information-rich environment. These and similar understandings of the notion autonomy are currently under investigation within the Collaborative Research Centre (CRC) 637: "Autonomous Cooperating Logistic Processes - A Paradigm Shift and its Limitations" at the University of Bremen. Approaching these complex processes with different concepts of closed-loop control modelling e.g. based on cybernetics systems theory, as the basis for modelling, developing and building robust and reliable architectures for monitoring and controlling information systems, seems not only very promising, but rather inevitable.

In contrast to these aspects today's conventional control of an internal production chain or an external supply chain mainly pursue sequential, top-down planning approaches supported by different MRP (Material Requirements Planning) or ERP (Enterprise Resource Planning) concepts and information technologies in order to coordinate the supply flows within and between the different companies, which very often causes time lags. Sudden disturbances within the internal production chain or in an external supply chain basically ripple all the way through it and therefore easily make the complex and inherently local, distributed planning processes invalid. Expensive re-planning sessions concerning the quantity to produce or to deliver, the delivery times and in relation to this choices of new suppliers are the most likely consequences. The majority of today's conventional production planning and control systems is based on a collection of the following premises (Adam, 1992):

- predictable throughput times,
- no production bottlenecks,
- fix operation times per order,
- short downtimes of machinery.

But in some cases these premises are only able to support the mass production of more or less standard products with few different versions. Within other production situations, like for example sketched out in (Scholz-Reiter et. al. 2004), which considers a very customer specific job shop production of industrial pump sets, these traditional PPC-systems mostly do not lead to very useful results. According to (Rohloff, 1995) the following major weak points of PPC-systems in this context can be identified.

The built-in feedback loops and coupling between the different subtasks and -processes are not sufficient or missing. The main planning process pursues a single, sequential run. The two-way dependencies are basically not considered at all. Observed mistakes are regarded as mistakes originating from the preceding planning steps. This basically requires the already mentioned plan revision, which often is not supported by the conventional PPC-systems.

The construction of a global model is often not possible. Traditional PPC-systems assume that during the planning phase all matters-of-facts and timing cohesions between the most important decision criteria are fully known and fix. The production planning and scheduling processes are usually carried out weeks before the real start of production. At the point of time where these plans are activated, the considered boundary conditions of the planning phase are not valid any more, which again often leads to plan variants.

The centralised planning approach is rather unsuitable. The top-down and centralised MRP approach, which is being conducted by just one organisational unit, is closely connected with the assumption of being able to build up a global planning model. As a result the assigned production units are provided with predetermined and precisely defined tasks and sub-tasks (e.g. processing times, work content) without any freedom for local decision making and therefore a further use of personal know-how.

Rigid and inflexible planning processes. The rigidness and inflexibility of traditional PPC-Systems can be clearly and best identified, because they hardly do consider any enterprise specialties at all (Kurbel and Endres, 1995), although the requirements concerning the design and configuration of PPC-systems for the different types of producing enterprises and job shops may differ fundamentally. The decoupled production planning process for an anonymous mass customer market is much easier than a pure customer driven processing of orders, which normally imply the absence of large lot sizes but include much more complex products.

Missing real time planning and control. The different centralised planning steps of the traditional ERP respectively MRP based PPC-Systems are run sequentially, therefore the adaptation to changing boundary conditions (e.g. planning data) is only possible within quite long time intervals. This means that changes of the job shop situation cannot be considered immediately, but the next planning run at the earliest. As a result the current planning is based on old data and the needed adaptation measures cannot be performed in time for a proper reaction of the discrepancy between the planned and the current situation.

To summarize, these principle entrapments and constructional flaws strongly support the idea to basically redesign the deployed PPC-systems. In this context, within approximately the last ten to fifteen years a collection of decentralised concepts for the field of production planning and control – each of them emphasising different aspects – have been developed. Two of the maybe most relevant within the context of autonomy or self control respectively, are going to be sketched out shortly and delineated from the concept of "Autonomous Logistic processes" within the following chapter. Chapter three will introduce an exemplary scenario to discuss some opportunities of autonomously controlled logistic processes within production systems. This discussion will be complemented by the chapters four and five through outlining of some of the most necessary modelling requirements, as well as measuring and evaluation criteria of such a new process paradigm.

2. AUTONOMOUS LOGISTIC PROCESSES WITHIN THE CONTEXT OF OTHER KNOWN APPROACHES OF AUTONOMY AND AUTOMATIC CONTROL

The questions raised concerning the design and implementation of autonomous logistic processes are manifold and therefore multidisciplinary. First of all the question has to be answered satisfactorily, what the characteristics of logistic processes are. According to (Schönsleben, 2000), it can be basically distinguished between the following sub-areas relevant to planning and control of logistic processes, each of which considers different relevant flows of physical goods (logistic or business objects) and related flows of information:

- sourcing and procurement logistics,
- research and development processes,
- production logistics,
- distribution logistics,
- disposal or redistribution logistics.

The already mentioned CRC 637 "Autonomous Co-operating Logistic Processes - A Paradigm Shift and its Limitations" is presently mainly focussing on the aspects of distribution and production logistics and its different requirements and specialties. Aiming at more intelligent modelling of complex production logistics as well as distribution logistics systems and at its autonomously performed logistic processes it is of major importance to first of all identify the relevant logistics objects (e.g. trucks, machines). Moreover it is very important to precisely identify the locally relevant methods, in the sense of an appropriate procedure, business rules (e.g. decision rules), or basic principles of procedures in terms of defining appropriate control strategies (including economic goals like costs and locally added value). Upon these foundations the modelling and design of the autonomous controllers still is a major challenge in order to improve the internal reliability and robustness (e.g. high variances of the throughput time) within an enterprise, for example regarding its manufacturing processes. Furthermore at least an initial set of different possible local states of the participating intelligent business entities respectively logistic objects needs to be specified as well as the notion of events (e.g. distortions) has to be defined. One problem, which may occur and currently is under discussion within the CRC, with the notion autonomous logistic processes, is that the understanding of autonomy in close relation to heterarchy (= co-subordination), originally founded by McCulloch (Goldammer, 2003), which for example originates from biology and the theory of living systems (Goldammer and Paul, 1995), is based on the so-called *closure thesis*. This means that every autonomous system is organisationally closed and rejects the traditional *input-output-system* approach. Furthermore this leads to the fundamentally raised question of an entirely different *system/enviroment-relationship*, for example in terms of an adaptive state observer and its environment (Scholz-Reiter et. al. 2004), which needs to be reflected in a new systems analysis and design approach. This basically has to lead to a more or less bottom-up analysis and modelling approach (e.g. deploying distributed problem solving approaches), by modelling the local goals, start set-up of decision rules regarding the different intelligent monitoring and controlling entities, while finally observing and judging the overall system behaviour after bringing them all together. Similar research approaches have already been discussed for quite a while, but they can be distinguished from the research approach of the CRC 637, by taking for example the activities like *holonic manufacturing* or *fractal factory* into account.

The notion *holon* basically refers to the philosopher Arthur Koesteler (Koestler, 1968). It describes a strictly hierarchical open (social) system by deploying a *whole/part-systematics*. This idea was used during the late 80-ties and the early 90-ties to design so called *holonic manufacturing systems* (HMS), built from more or less modular cooperative Information and Communication Technology (ICT) components (e.g. products, resources). As a whole, these systems could be regarded as technical multi-agent systems (Lüth, 1998), in order to implement and scale machinery faster and more reliably. During the HMS-Project a now available conceptual framework was developed (Bongearts, et. al. 1997; Langer and Bilberg 1998; Bochmann et al. 2000). According to Langer (Langer, 1999) the *holon* in its latest version is defined as an autonomous and cooperative basic building block of a manufacturing system for the transformation, the transport as well as the storage and/or validation of the information and physical product. The *holon* comprises a part capable of information processing and a part capable of the physical transformation of the produced good. Therefore a *holon* can be and often is a part of another *holon*.

The concept of the *fractal factory* first introduced by Warnecke (Warnecke, 1993) is basically focussing on the organisational units – fractals – and a principally discovered respectively assumed self-similarity between different analysed organisational units. The units operate autonomously with their own set of goals and their own exactly definable input and output parameters. The fractals conduct self-organisation and self-optimisation under consideration of their local goals either on the strategic or on the operative level. The process level is, if at all addressed just very indirectly and without considering any certain methodology. The core concept of the *fractal factory* still is a classical *input-output-system* approach, which leads to the same questions as already mentioned above.

To summarize, this already displays the fundamental difference to the approach choosen for the CRC 637, which basically assumes a heterarchical system set-up and a more or less non-determined process flow. Nevertheless, the adaptation and further development of the multi-agent systems paradigm, whose characteristics can be considered important (Jennings et. al., 1998) especially for the requirements of autonomous logistic processes seems to be very promising:

- Multi-agent systems always emerge when several more or less autonomous and heterogeneous agents act together as a loosely coupled network to cooperatively solve a given problem.
- Each agent has incomplete information or capabilities for solving the problem, thus each agent has a limited view.
- There is no global system control.
- Data is decentralised.
- Computation is asynchronous.

Finally, all definitions of agent technology can be summarized by the following statements, which can easily act as guidelines for the development and application of suitable agents (Jennings and Wooldridge 1998; Wooldridge and Jennings 1999):

- Agents are a powerful, natural metaphor for conceptualising, designing, and implementing many complex, distributed applications.
- Agent systems typically use AI techniques – in this sense, they are an application of AI technology – but their “intelligent” capabilities are limited by the AI’s state of the art.
- The development of any agent system, however trivial, is essentially a process of experimentation. Unfortunately, the experimental process encour-

ages developers to forget that they are actually developing software.

- It has to be considered as common to all agent-based applications that they are no overall system controllers and have no global perspective, already by definition.

This means that the deployed agents are situated (situatedness) in and experiencing (embodiment) a *system/environment-relationship*, according to the complexity of the conducted tasks (universal versus specialised agent) and due to the complexity of the environment (low versus high) (Kordic et. al., 2001). As a result the broad range of requirements on how to derive and design a “complete monitoring and controlling entity” are discussed under the focus of autonomous logistic processes in one of the following chapters of this paper. To summarise, the modelling and design of industrial, agent-based and autonomous controlling systems still is very challenging and up to now not solved satisfactorily. This is mainly due to the lack of systematic methodology for the systems analysts and designers as well as the lack of widely available industrial-strength multi-agent system toolkits (Jennings et. al., 1998; Wooldridge and Jennings 1999).

3. EXEMPLARY SCENARIO OF AN AUTONOMOUSLY CONTROLLED PRODUCTION SYSTEM

Applications of autonomous cooperating logistic processes are manifold and possible over the entire supply chain. In detail it is necessary to analyse, in which scale and in which logistics domain (procurement, production, distribution and disposal) it will be efficient to establish autonomous logistic processes and to find their limitations.

Because of the high complexity of this research project here it seems reasonable to focus on a concrete object of investigation in the form of a specific, exemplarily scenario. Based on this scenario of logistics in an autonomously controlled logistic production system the changes compared to conventionally controlled processes will be explained as well as arising benefits pointed out. By means of these changes new modelling and evaluation requirements of autonomous logistic processes will be deduced in the following chapters.

3.1 Basic Scenario.

In the context of this paper an exemplarily scenario of production logistics is examined. **Figure 1** gives an overview of a scenario of a two-stage job shop production. The material flow layer on the lowest layer shows the material flow net of the manufacturing system. The process layer is based on the material flow layer and describes the lead and performance processes of the manufacturing system. The layer of production controlling lastly assigns activities of the process layer to measurement points. With theses measurement points relevant logistics metrics and performance figures are deduced.

Material flow layer. This level of abstraction describes the material flow of a two-stage job shop production. The first production stage contains the manufacturing of a part on two alternative machines (M_{ij}). The raw materials that are needed for production are provided by the source (So). In the second production stage the assembly of the parts that have been made in the first stage is executed alternatively on two machines (A_{ij}). The manufactured items leave the material flow net at the sink (Si). Every machine of this scenario has an input buffer (I_{ij}) and an output buffer (O_{ij}), in which the raw materials or parts are stored temporarily.

Process layer. The process layer represents the lead and performance processes of the job shop production scenario. These processes are assigned to the underlying material flow net. Lead processes can be defined as planning and control or coordination processes (Krüger, 1993). In this case the production planning and control processes are lead processes. Performance processes can be characterised as production or service processes, which are directly involved in adding value (Krüger, 1993). So the production logistic processes in-house transport, stocking, manufacturing and assembly belong to performance processes.

Layer of production controlling. The layer of production controlling is based on the process layer. Several measurement points can be defined between the processes. These measurement points allow determining diverse logistics metrics. For example throughput times of manufacturing orders can be developed from adequate measurement points. The throughput time of a manufacturing order is composed of operation time, consisting of setup time and processing time and of transit time, which is divided into waiting time before and after handling and transportation time (Wiendahl, 1997).

3.2 Scenario of an autonomously controlled production system.

In this chapter the approach of autonomous logistic processes in production logistics will be explained on the basis of the adapted exemplarily scenario of the two-stage job shop production displayed in figure 2. In detail it will be pointed out, how the weak points of traditional production planning and control systems, described in chapter 1, can be eliminated by establishing autonomous logistic processes. Furthermore expected changes concerning production controlling will be introduced.

A precondition to autonomy of logistic processes in the considered scenario is that the logistic objects of the material flow net (machines, buffers, parts etc.) have their own intelligence. For example the logistic objects could be equipped with RFID chips, which

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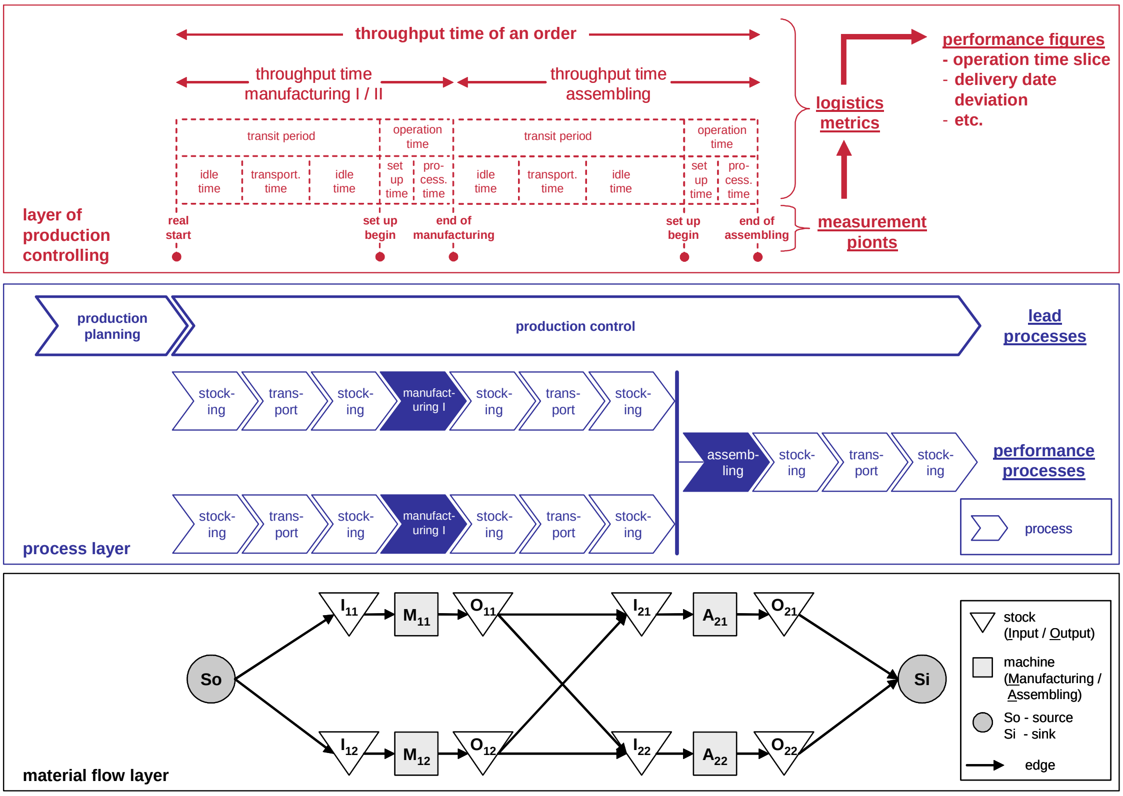

Fig. 1. Scenario of a two-stage job shop production.

feature processing and data-storage capacity. The existence of a communication infrastructure as well as appropriate software is preconditioned, too. So the logistic objects are able to interact with each other and to make decisions, which is meant with intelligence. In consideration of these technological requirements there are several changes to the material flow layer, the process layer and the layer of production controlling, which will be described below.

Material flow layer. The sequence of the production steps of this exemplary scenario persists independently of the production planning and control method. The production of goods in this scenario requires at first a stage of production and afterwards a stage of assembling. That means that the sequence of production steps in this scenario is technologically predetermined, but not the material flow. For example intelligent parts can autonomously choose one of the alternative assembling stations. Consequently establishing autonomous logistic processes excerts influence on the – not predetermined – material flow.

Process layer. Compared to traditional production planning and control systems the PPC processes in this scenario are partially linked to the performance processes. Some production planning processes do not take place in a centralised manner a long time before manufacturing, but in a decentralised one while producing. For example every machine can continuously plan and adapt its own allocation by communicating and negotiating with intelligent parts. Also a conveyor could negotiate with a commodity its transport from one machine to another. Other production planning processes like master production scheduling or rough-cut planning are still part of the centralised production planning and control. In addition to planning of production processes the logistic objects of the material flow net, e.g. machines or orders, assume the production control. Machines autonomously initiate the release of self-planned production orders, monitor their production processes and react immediately to a possible breakdown during the manufacturing process.

As a result autonomous production systems are characterised by distributed production planning and control. Some PPC functions are still part of the centralised production planning and control system, some functions belong to decentralised PPC systems of several logistic objects. The limitations or transitions between conventional and autonomous planning and control will be investigated in the CRC 637.

Layer of production controlling. Conventional performance measurement systems are based on a set of logistics metrics, which are determined by several measurement points. Some of these logistics metrics and possibly dedicated performance figures of conventionally managed production systems were described above. Autonomously controlled production systems offer new potentials.

As explicated in this scenario logistic objects are able to store, process and exchange data at any time and any place. So the amount of measurement points is no longer limited. Logistic objects can provide information regarding the status of the current processes at every time.

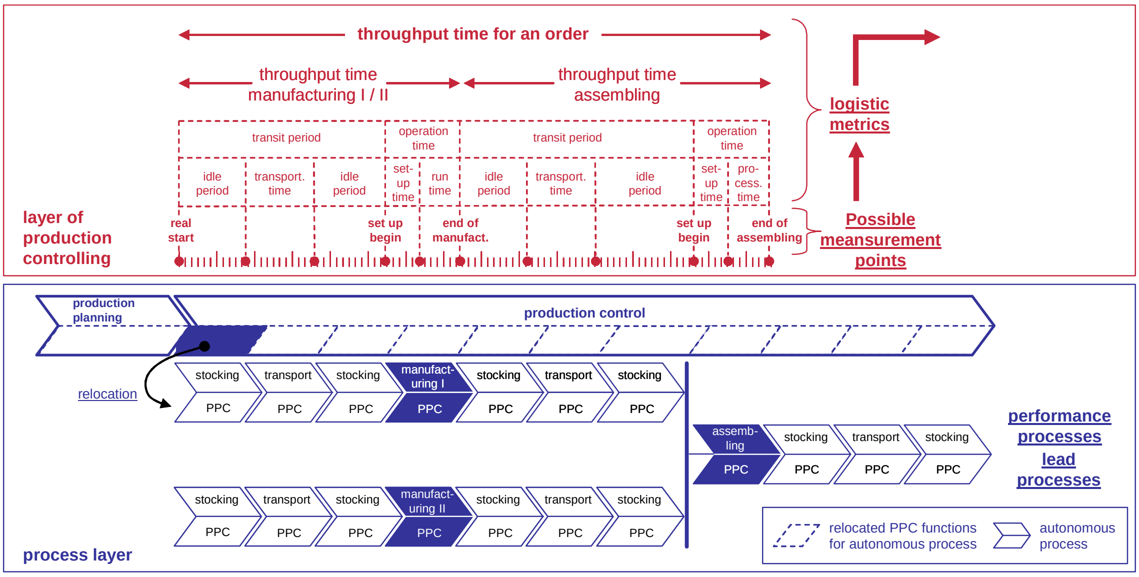

Fig. 2. Scenario of an autonomously controlled two-stage job shop production.

This high amount of measurement points allows the development of new, previously not possible logistic metrics and performance figures and thus a higher transparency of manufacturing processes within the scope of production controlling. For example an appearing delay of a machine can be identified during the assembly process by a decentralised monitoring system. The monitoring system permanently collects data of the current status of the assembly process and compares them with the data of the planned status. This discrepancy between current and planned process status can be represented by new performance figures, for example current plan deviation. The performance figure could be used as an indicator for an early detection of manufacturing delay. On the basis of this new performance figure the machine is able to recognise its delay and to initiate necessary steps immediately (e.g. capacity adjustment in form of extra shifts).

By means of the description of the autonomous production system scenario it becomes apparent that the weak points of traditional PPC systems described in chapter 1 can partially be reduced. Some planning processes do not pursue at one time and sequential run any more, but basically happen during the production process. In case of disturbance the logistic objects autonomously detect the problem, for example by a sensor system, and immediately initiate appropriate steps. One essential step is the adaptation of its own production planning. The dependencies of the current planning step from preceding planning steps can be reduced because of the ability of the logistic objects to adapt their decentralised planning at every time. Therefore the need for construction of a global model is no longer existent. In fact there are a lot of local models that show a high quality because of the short planning horizon and the lower complexity than in hierarchical systems. The hope is to show during the CRC project time that planning deviation in the form of discrepancy between current and target plans will be avoided.

As one result of the decentralised planning the know-how of the organisational units which are assigned to the several production processes can be involved.

4. REQUIREMENTS RELATED TO MODELLING METHODS OF AUTONOMOUS LOGISTIC PROCESSES

On one hand there are general requirements to modelling of autonomous logistic processes that can be formulated based on general considerations related to modelling of conventionally managed logistic processes. On the other hand there are specific requirements that have to be fulfilled, which call for extensions of existing modelling methods and development of new ones respectively. Figure 3 gives an overview of these requirements, which are described in detail in the following sections.

4.1 General Requirements

An important contribution to the formulation of general requirements to modelling methods is due to (v. Uthmann, 1999) with the formulation of their “Guidelines of Modelling” (GoM). There they postulate correctness, clarity, comparability, relevance, systematic design and economic efficiency as general requirements in order to achieve a high model quality. Therefore a method for modelling autonomous logistic processes should meet these guidelines.

Some of the requirements given in the following sections partly overlap with these guidelines or can be assigned to them. But, as they have a special meaning in the context considered, they will nevertheless be discussed here explicitly.

First of all it is necessary that a process expert, i. e. someone who is used to the processes to be modelled on a daily basis, should be able to use the method with no or only little learning effort. This calls for a graphical modelling method, based on a common and standardised notation. Examples of such notations

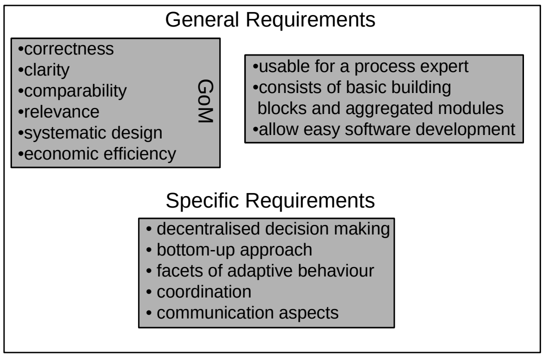

Fig. 3. Requirements to modelling methods.

are Event-driven Process Chains (EPC) or the Unified Modelling Language (UML). Furthermore in some cases it seems more adequate to pass on some generality of the modelling method in order to reduce complexity. In these cases focussing on the domain of logistics should be possible, though resulting in a loss of generality.

The modelling method should offer basic building blocks but also allow for aggregated modules on a higher level of abstraction. It should be possible to combine theses modules into libraries, easing re-use and thus reducing efforts of later modelling projects.

A further challenge is to ensure a good support for subsequent software development based on the model built of the process under consideration. On one hand support of logistic processes with the help of information technology plays an ever increasing role, so their implementation has to be considered during modelling and designing the processes. On the other hand, as already mentioned in chapter 2, realising autonomous logistic processes requires even further use of and support by information technology. Software implementation thus plays an even more important role there. In this regard it is important not to reduce understandability for process experts which would result from a modelling method that focuses too much on software development. In some sense the increasing importance of software implementation already is a requirement specific to modelling autonomous logistic processes.

4.2 Specific Requirements

Considering the above scenario of an autonomously controlled manufacturing system, several specific requirements to modelling can be derived.

In case of a machine breakdown for instance, logistic objects have to be able to decide on a further course of action. First of all for modelling this means that this decentralised decision making in heterarchical organizational structures, i. e. lacking central control, has to be representable. This proceeding suggests a bottom-up approach to modelling to allow to begin building a model, starting from the autonomous logistic objects available. This bears the danger of neglecting the global view on the processes which could lead to a model lacking consistency. Furthermore it becomes more difficult to design processes reaching global objectives this way. Thus the best way seems to be a combination of bottom-up- and top-down-approaches. The difficulty is to find the right balance.

Autonomous logistic objects adapt to a changing environment by themselves. So machine failure can be faced by reactively executing predetermined actions, like IF-THEN-rules. This means that in our exemplary scenario jobs have to have alternative ways of action based on the current state of damaged and alternative functioning machines and other relevant environmental influences. This corresponds to classic approaches to business process modelling.

Beyond this reactive action there are higher levels of decentralised decision making that would allow adaptive behaviour of jobs or other autonomous logistic objects. The logistic objects could adjust to a new state of their environment, e. g. machine breakdown, without using alternatives that are predetermined in detail. One possibility to obtain such behaviour would be the use of a planning method from artificial intelligence (Russel, Norvig, 2003). Other possibilities are learning on one hand and evolution on the other. Both cases rely on feedback of the consequences of actions executed. Learning requires an entity to be able to draw conclusions from the consequences of its own behaviour or the behaviour of other entities in response to its own actions. Again evolution means that current behaviour affects future generations, which can be seen as one kind of feedback, too. In both cases a modelling method has to support a way of representing these different kinds of feedback.

Furthermore one should be able to explicitly model knowledge required for decision making by decentralised autonomous units, maybe in the sense of a more cognitive modelling of mental states, decision processes and functions (Schmid and Kindsmüller, 1996). This local knowledge can be distinguished into knowledge the unit has about itself and the knowledge it has of its environment as well as connections between unit and environment. Knowledge about itself for instance means for a machine to know working operations possible on itself in conjunction with associated processing times, maintenance intervals or which parts it is able to process. Environmental knowledge e. g. consists of knowledge about other machines and times required to transport goods to them. In this case jobs know about their due dates and the production steps required to manufacture them. These examples describe mostly static knowledge. In addition there is dynamic knowledge, i. e. knowledge that is likely to change with time, for instance which jobs are currently scheduled to be processed on a machine.

To enable processing and completion of jobs it is necessary to connect the knowledge of several autonomous units and their coordination. To coordinate the behaviour of participating logistic objects a decentralised planning method should be used instead of centralised planning, allowing decentralized autonomous decision making.

To determine information that is not available locally, but required to execute decentralised distributed decision making as described in the exemplary scenario above, information exchange between autonomous logistic objects is necessary. Thus it should at least be possible to represent the following three aspects of communication; first of all which logistic objects are involved in the communication, second which information is exchanged and finally the temporal order of information exchange.

5. REQUIREMENTS ON EVALUATION SYSTEMS

In the CRC 637 fourteen subprojects are involved with different fields of investigation. Representatives from each subproject are joined together in a research group "scenarios". Within this research group CRC-wide scenarios will be developed in order to compare the different approaches to autonomous cooperating logistic processes. To evaluate these specific approaches an evaluation system valid for all CRC-subprojects is needed. The idea is to evaluate this with a mutual basis of various performance figures for logistic processes.

The intention of implementing autonomous processes in logistics systems is to increase logistic performance and to satisfy the new demands of logistic systems. The aim of a new or enlarged evaluation system for autonomous logistic processes is to cope with new demands due to autonomy. To measure the performance of logistic systems performance figures are needed to determine the target achievement. These specific logistic performance figures are combined in a performance measurement system. Due to new demands this performance measurement system has to be individually tailored to autonomous logistic processes and to conventionally managed processes as well. The specific system allocates the performance figures to a system of objectives. This performance measurement system is necessary to make a logistic system observable by increasing the transparency of the system. In figure 4 different levels of objectives are shown to specify the various logistic targets (Luczak *et al*. 2004). The arrows next to objectives indicate whether to increase or to decrease this value in order to get a *high logistic efficiency*. The objective *high logistic efficiency* describes the uppermost level of the system. In a second level this objective is divided into two further objectives. A *high logistic efficiency* is achieved by *high logistic performance* on the one hand and *low logistic costs* on the other hand. On the third level these targets are again divided into more detailed objectives. The logistic performance is divided in *high availability, high productivity, short throughput time* and *high delivery service* while the logistic costs are divided into *low inventory costs* and *low process costs*.

By implementing autonomous units with the ability to measure their current state at any time the specific characteristic values are determined near real-time.

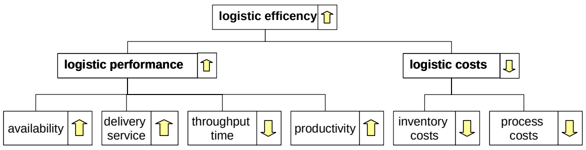

Fig. 4. Logistic objective system (Luczak *et al*. 2004)

Thus the transparency of the system will increase significantly. The intelligent objects (e.g. orders, machines, parts) are able to automatically perform a computer-aided production data acquisition, which is necessary for monitoring of the concerned system.

In the scenario described in chapter 3 different customer orders are manufactured in an exemplary production system. The customer order is defined by products and their structures, an amount of these products per order and a due date. In the following some exemplary performance figures are explained, which can be detected in this scenario. Depending on the product the order has to complete *n* operations on different machines. Thus the *total operation time* is defined as

$$t_{o,total} = \sum_{i=1}^{n} t_i \ , \qquad (1)$$

where t_i is the individual processing time for each operation on the different machines in the described scenario. The due date of each operation is appended to the order concerning these operations. At any time the order is comparing actual versus estimated times so that deviations are recognized in real-time and necessary actions like rescheduling can be performed. The appropriate performance figure in this case is defined as *current plan deviation*

$$PD = t_{act} - t_{est} \qquad (2)$$

with t_{act} as the actual time and t_{est} as the estimated time of the current stage of the order given by the order scheduling.

In the described scenario each order has to complete one manufacturing and one assembly stage before it is completed. All orders in the system have to coordinate their machine scheduling in order to get the best result for each order with regard to the due date. While competing for the limited resources (two manufacturing and two assembly stations in this scenario) it is possible to use priority rules to decide the sequence of order processing.

In case of a breakdown of one of the assembly stations the information about this breakdown is transmitted near real-time to the order in such a way as to enable the order to reschedule itself. At the same time the manufacturing and assembly stations adapt their capacity planning. While monitoring the performance measure *current plan deviation* (*PD*) the time lack between noticing a breakdown and reacting to this breakdown is minimised. The hope is to reduce the effects of unexpected events like a breakdown in comparison to conventionally controlled production systems.

By knowing all specific logistic metrics, orders are able to determine their own performance figures like the *operation time slice* (*OTS*) which is defined as

$$OTS = \frac{t_{o,total}}{t_{through}} \tag{3}$$

with $t_{through}$ as the throughput time of the specific order. In terms of the level of autonomy it has to be pointed out that some of the logistic metrics have to be divided into conventionally managed parts and autonomously controlled parts. With regard to the throughput time this value is given as

$$t_{through} = t_{through,a} + t_{through,c} \tag{4}$$

while $t_{through,a}$ is the time slice of autonomously controlled operations and $t_{through,c}$ the one for conventionally managed. These performance figures which are divided into conventionally managed and autonomous processes will allow specifying effects by changes of the system. The effects by these specific changes will thereby be assigned to autonomously and conventionally managed subsystems. To detect the border of autonomy a criteria catalogue for autonomous processes will be developed within the CRC 637. By means of this catalogue autonomous processes will be identified for different types of manufacturing systems, so that it will be possible to identify t_a and t_c.

By implementing intelligent objects (e.g. intelligent orders) with the capability to measure their specific indicators at any time these performance figures will no longer be determined at a fixed time or in a fixed period of time but will be determined continuously. By finishing an order the performance figure *delivery date reliability* (*DR*) for the entire system is updated automatically by the order. It is defined by the ratio of outgoing products delivered in time $n_{out,it}$ by the total number of outgoing products n_{out}

$$DR = \frac{n_{out,it}}{n_{out}}. \tag{5}$$

Thus the system transparency is always up to date because of meaningful performance figures. Beside these exemplary performance figures the new evaluation system is able to provide a wide range of different performance figures specifying the level of logistic efficiency.

Logistic systems with intelligent objects and autonomous cooperating processes also generate new requirements to performance measurement systems because of their dynamic target system. While in conventionally managed processes the system objectives are clearly defined, this is different in the case of autonomous systems. A customer's order for example may have the objective *high delivery reliability* while suborders like the manufacturing order of the different parts may have the objective *short throughput time*. The other objects in this system have different objectives, like the machines trying to increase their utilisation ratio or the buffers trying to minimize their stock. In fact the different types of objects may have different logistic objectives like the ones shown in figure 4. Changes in the different logistic objectives over the time, which will also lead to a dynamic objective system, are possible as well. A set of different objectives with different priorities is also possible. The new performance measurement system has to cope with emergent behaviour of autonomous subsystems, which means that a global behaviour of the whole system is not explainable with its subsystems. A positive effect of emergence obviously is a faster and higher achievement of the global objectives.

As the intelligent objects know their current state and are able to communicate at any time the evaluation system has to manage this amount of different information from different types of objects like machines, orders, parts etc. The task is to filter this large amount of information and generate meaningful performance figures. These significant performance figures must be available for the concerned objects in order to support their decision making process for the next steps. In addition to the preparation of information the performance measurement system has to evaluate the subsystems as well as the overall production system. Thus it has to measure the performance of different autonomous subsystems and maybe different conventionally managed subsystems on the one hand and has to reach a conclusion of the global objective achievement on the other hand. Conventional performance measurement systems are so far not able to cope with these requirements so that there is a need of new concepts of evaluation systems and performance figures, which will be developed in the CRC 637.

6. CONCLUSION AND FUTURE OF RESEARCH

The upper mentioned CRC 637: "Autonomous Cooperating Logistic Processes - A Paradigm Shift and its Limitations" at the University of Bremen, with its several sub-projects, is for example strongly motivated by the still existing broad range of lacks and unfulfilled requirements concerning the systems' analysis and design of such a new process paradigm. Some very interesting fundamental ideas of autonomy and self-control, originating from natural (e.g. biology, physics) or cognitive science, up to now just cannot be expressed satisfactorily with some of the common notation for business process modelling like UML or EPC. These new ideas of autonomy will lead to emergent behaviour of the global system which cannot be evaluated by conventional performance measurement systems so far and thus new or extended ones have to be developed to close this gap.

Therefore concerning for example the future application and dissemination of agent technology as industrial-strength autonomous controlling entities, it will be of major importance to provide these more comprehensible modelling methods respectively some generally extended foundations (e.g. basic building blocks). They must clearly address the actual problems of the business processes in order to derive the needed services as skills or functions provided by the software agent. Up to now the available methods are clearly developer driven, and basically the aspect of system integration (e.g. RFID, PDA, Legacy Systems) is often not considered.

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