Information Fusion for Simulation Based Decision Support in Manufacturing

Leo J De Vin[1], Amos H C Ng[1], Jan Oscarsson[1], Sten F Andler[2]

1Centre for Intelligent Automation, 2Distributed Real-Time Systems Research Group
University of Skövde
Box 408, 541 28 Skövde, Sweden

ABSTRACT

Robust and informed decisions are important for the efficient and effective operation of installed production facilities. The paper discusses information fusion and situations for decision making, as well as the use of manufacturing resource simulation for design/configuration, operational planning & scheduling, and service & maintenance. A generic model for information fusion is presented, which is extended to incorporate modeling & simulation, and active databases.

1. INTRODUCTION

Key factors to remain competitive in the manufacturing business is the effective and efficient operation of installed manufacturing systems, as well as the ability to quickly and readily re-configure these systems, for instance in the case of new product introduction. Manufacturing systems usually consist of a number of people, machines and handling devices. These systems are sufficiently complex and sophisticated that (re)design, operational production planning, and machine service are intricate specialist tasks. As a result, these tasks increasingly require adequate decision support systems. These systems need to be able to support the decision maker with accurate information, based on historical data, actual status and expected trends/events. Simulation engineering is an enabling technology for life-cycle decision support. Previous and ongoing research of the group has highlighted the potential use of simulation in different manufacturing system life-cycle phases especially design and configuration but operational planning and service & maintenance as well [1-6].

The research reported on in this paper aims at developing a semi-autonomous decision support system for life-cycle management of manufacturing systems, and is an integral part of the recently started research program "information fusion from databases, sensors and simulations" at the University of Skövde. This research program aims at developing a generic theoretical framework for information fusion. It is envisaged that decision support systems for a relatively wide scope of applications and with fusion of information from a variety of source types be developed to support the theoretical research and to serve as a test-bed, manufacturing life-cycle support being one of the selected application areas. Other research in this area is often either limited in scope (e.g., related to defense tasks only) or limited in information sources (e.g., from sensors only). A key element in the proposed solution is the fusion of information [7] regarding the manufacturing system's history and previous operation (stored in databases), the actual status (obtained through monitoring), with information regarding the future (such as expected trends/events or explored through so-called "virtual scenarios" during simulation).

2. INFORMATION FUSION AND INFORMED DECSION MAKING

2.1. AN INTRODUCTION TO INFORMATION FUSION

Information Fusion (IF) encompasses the theory, techniques, and tools conceived and employed for exploiting the synergy in the information acquired from multiple sources (sensors, databases, information gathered by human, etc.) such that the resulting decision or action is in some sense better (qualitatively or quantitatively, in terms of accuracy, robustness, etc.) than would be possible if these sources were used individually without such synergy exploitation [7]. An example of IF in manufacturing is the fusion of information from multiple sensors [8]. In this paper, with IF we mean the fusion of information from the past operation of a manufacturing system (e.g., stored in databases), from the present (e.g., sensor signals, machine status), and from the future (in particular, predictions obtained through simulations).

In information fusion research and applications, the scope is often limited, for instance in application area (e.g., military applications only) or in sources (e.g., from sensors only). Whilst manufacturing in itself is such a relatively limited area, the research presented in this paper is an integral part of the recently started research program ‘information fusion from databases, sensors and simulations’ at the University of Skövde. This program aims at developing decision support systems for a relatively wide scope of applications and with fusion of information from a variety of source types. Through cross-disciplinary research across the university and with its industrial partners, the theoretical framework for the work presented in this paper is more generic than many other models.

One model for IF is the JDL model [9, 10]. This model describes the stepwise refinement of information. However, the model does not describe how this refinement takes place and furthermore, the model is specific for military applications. It is the result of work performed under the Joint Directors of Laboratories (JDL) of the Department of Defense of the United States of America. The model comprises four levels, which form a hierarchy of processing. On Level 1, "object refinement" is performed. This is an iterative process of fusing data to determine the identity and other attributes of entities (objects) and also to build tracks to represent their behavior. The result from this level is called the situation picture. That is, Level 1 tries to determine what it is (i.e. identification) and where it is and when (i.e. tracking). On Level 2, "situation refinement" is performed. This is an iterative process of fusing the spatial and temporal relationships between entities to group them together and form an abstracted interpretation of the patterns in the order of battle data. The result from this level is called the situation assessment. On Level 3, "threat refinement" is performed. This is an iterative process of fusing the combined activity and capability of enemy forces to infer their intentions and assess the threat that they pose. The result from this level is called the threat assessment. Level 4 performs "process refinement", which is an ongoing monitoring and assessment of the fusion process to refine the process itself, including optimization of data acquisition. There are, however some problems in applying the JDL model [9]. For instance, in many cases, analogies with Levels 2 and 3 may be absent. Furthermore, acquiring data from external sources (e.g., geographical databases as provided by commercial companies) means that optimization of data acquisition is hampered.

Another military-specific model is the OODA loop [10, 11], where OODA stands for “Observe, Orient, Decide and Act”. However, in this model, the only military-specific term is “Orient”. If we replace this term with the more generic expression “Interpret” as in Figure 1, then the model becomes suitably generic. The whole loop is part of the IF process, even although intuitively, the “Interpret” phase is a phase in which a large part of the IF takes place. However, observing, i.e. gathering certain information, implies that certain information is going to be fused, which is the result of deciding and acting (namely, deciding which information is needed and the execution of that decision).The IF process does not just import and fuse information, it interacts with databases, external processes and simulation models in various ways (Figure 1). For instance, results from the IF process can be used to control processes or to improve simulations by tuning parameters in the simulation model. Furthermore, the IF process can result in the design of a new set of simulation experiments, to be carried out with the use of the simulation model.

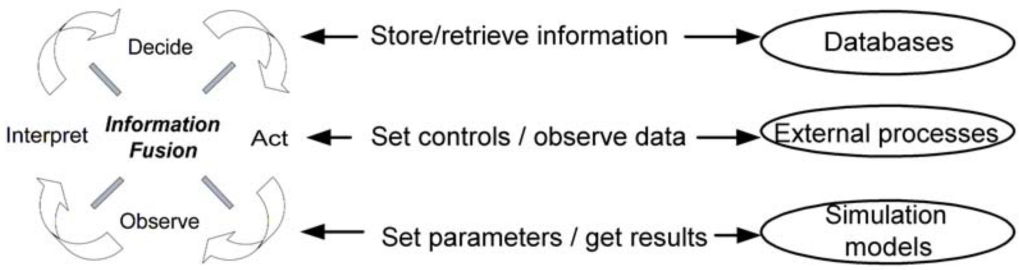

Figure 1: IF process and interaction of IF with databases, external processes and simulations

2.2. INFORMED DECISION MAKING

With “informed decision making”, we mean the making of decision based on correct information. This information can pertain to the actual situation/conditions at the time of decision making, but it can also be related to the consequences of certain decisions, including so called “what if” scenarios. “What if” scenarios address uncertainties regarding for instance customer and competitor behavior, such as orders that may be placed or not. In general, informed decisions are better than decisions based on gut-feeling or guesswork. For instance, if the consequences of alternative decisions in a number of “what if” scenarios can be explored thoroughly, a decision that is relatively insensitive to variations in customer behavior may be selected, rather than making a decision that is good in one case only. Decisions that are less sensitive to variations or uncertainties are called “robust decisions”.

Better decisions, and especially more robust decisions, reduce the need for corrective actions. Poor decisions may give rise to a chain of corrective actions when unexpected situations/events occur, thus creating a relatively chaotic environment with a high entropy level. Robust decisions reduce the need for corrective actions, and thus result in a lower entropy level, which contributes to the sustainability of a company’s operations. An additional advantage of informed decisions is that it is easier for decision makers to motivate their decisions, which normally results in more internal support for the decision.

In order to be able to take informed decisions, the information must be present and accessible. Furthermore, the user or system that needs that information also needs to know that it is available, as well as where, in which format, and how to access it. In many cases, information is missing or not readily available (for instance, tacit knowledge about a particular machine, stored in the head of the operator). In principle, three situations in decision making for product realization can be distinguished regarding information availability [13, 14]: (1) Information about the environment and the objectives is complete; (2) Information about the objectives is complete, but information about the environment is incomplete; (3) Information about the objectives and about the environment is incomplete. Situations (2) and (3) give rise to the need for emergent synthesis [13], however one should always try to strive after arriving in situation (1) [14]. The importance of information fusion and simulation in this respect is that these activities can retrieve information regarding the environment from a variety of sources, and present a concise view of the environment to the decision maker, thus arriving at (or approaching) a situation (1) information availability.

3. SIMULATION BASED MANUFACTURING SYSTEM LIFE-CYCLE SUPPORT – AN OVERVIEW

3.1. MANUFACTURING SYSTEM LIFE-CYCLE PHASES

In a manufacturing system’s life-cycle, a number of phases can be distinguished. In this paper, we adopt the GERA model [15], as this model provides a good overview of the various phases (Figure 2). Furthermore, it is easy to see how other theories/models can be incorporated in the GERA model. For instance, for the design phase, the theory developed by Pahl & Beitz [16] may be adopted, which means that some of the phases in the GERA model will be replaced by the phases functional design – conceptual design – embodiment design – detailed design (and engineering analysis). Likewise, Suh’s axiomatic design method [17] with mapping from the customer’s domain to the process domain via the functional domain and physical domain may be adopted. The GERA model shows the whole development cycle, from the identification of needs to decommissioning. The model also shows that the operation phase is not an uninterrupted phase, but that continuous improvement and minor redesign changes may take place along the way, as may major enterprise reengineering projects. The GERA model does not break down the operation phase into tasks (as this would be beyond the scope of the model), but it will be obvious that operational planning and service & maintenance are important tasks in this phase.

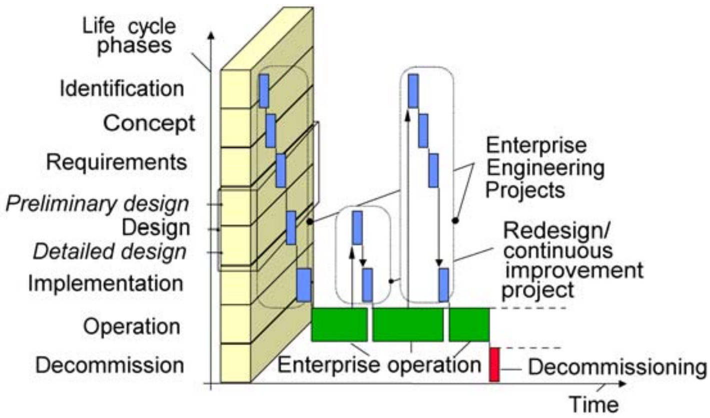

Figure 2: GERA life cycle phases

Whilst the various phases provide interesting research topics in their own right, there is a need to address these issues in an integrated manner. For instance, machine maintenance must be taken into account during operational planning, and regular failure to meet planning objectives may prompt reconfiguration or changes in service and maintenance schedules and routines.

3.2. Virtual Manufacturing (VM) – Resource Simulation

The product realization process can be divided into three domains: Product domain, Process domain and the Resource domain. In simulation, this is sometimes referred to as the "PPR hub". Virtual manufacturing (simulation) stretches over the process and resource domains, although important interactions with the product domain exist (e.g., for manufacturability analysis of new products). This paper focuses on resource simulation. The resource simulation tools considered in this paper are Discrete Event Simulation (DES, or DEVS) and Computer Aided Robotics (CAR), Figure 3. DES tools are normally used to study production flow, although their use can be extended to other areas such as healthcare [18]. CAR tools are normally used to study movements of industrial robots and so on, with collision avoidance and off-line programming as important applications. Ergonomic simulation, for instance posture analysis for workplace design, is a technology related to CAR.

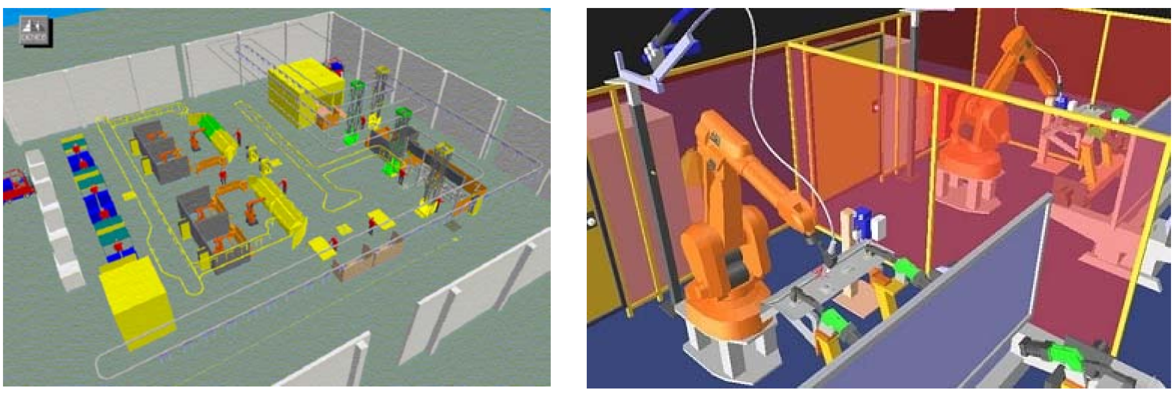

Figure 3: Snapshots from DES and CAR.

Resource simulation tools such as DES and CAR do not always provide sufficiently accurate estimates of cycle times, even when modules such as RRS (Realistic Robot Simulation) are used, at least not for certain monitoring and diagnostics tasks. Furthermore, in practice, cycle times tend to vary. Since a cycle usually consists of a number of operations, relatively large aberrations in one operation may only have a minor influence on the overall cycle time, and may therefore remain undetected. In order to remedy this problem, artificial intelligence will be implemented in the diagnostic function of MSSS, in the form of an artificial neural network (ANN). The ANN serves to distinguish between normal and abnormal variations in cycle times or times for individual operations. For the simulation model to generate accurate nominal machine behavior, ANNs are also used for the non-linear system identification of the machine dynamics.

3.3. VM FOR MANUFACTURING SYSTEM DESIGN

The VIR-ENG project [1, 2] has highlighted the potential role of virtual engineering in machine system design. The main objective of the project was to develop highly integrated design, simulation and distributed control environments for building agile modular manufacturing machine systems which offer the inherent capacity to allow rapid response to for instance product model changes. In the project, a component based paradigm was adopted for both hardware and software development. In essence, machine systems including their control system are developed in a virtual environment and subsequently implemented as a physical system.

The main environments developed in the VIR-ENG project as shown in Figure 4 are the highly integrated Modular Machine Design Environment (MMDE), Control System Design Environment (CSDE) and Distributed Run-time Environment (DRE). An Infrastructure and Integration Services (IIS) environment based on the component object-based computing platform provides all the 'pipes and plumbing' for the information integration within the VIR-ENG environment. The integration services are applied not only to the VIR-ENG environment but also support enterprise wide information integration.

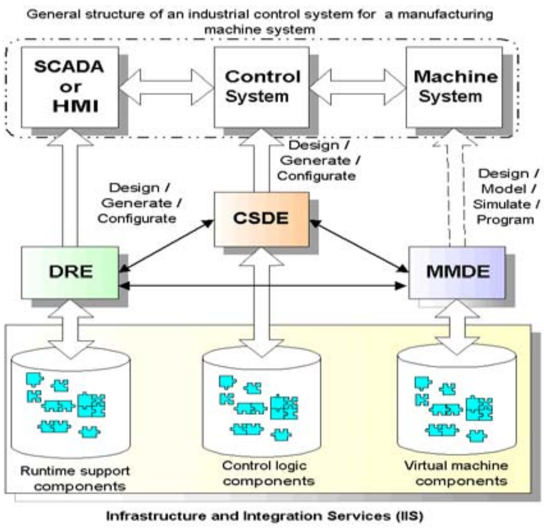

Figure 4: VIR-ENG environments

3.4. VM FOR SERVICE AND MAINTENANCE

Service and maintenance is an intricate specialist task and machine builders often have to provide service at short notice. Machine builders would benefit enormously from extended possibilities to monitor and diagnose equipment operating at distant locations – both for condition-based preventive maintenance and for diagnostic purposes before flying in qualified maintenance personnel and spare parts. Even within a single plant, the possibility to monitor manufacturing equipment from a central service and maintenance office has obvious benefits.

Most condition monitoring applications in manufacturing are limited to sensor information fusion for applications such as tool-wear monitoring [8, 19] or spindle bearing monitoring [20, 21]. Examples of sensor information are vibrations and oil contamination [22], temperatures and electric currents. Whilst this approach is extremely useful for preventive service and maintenance, it is limited to some features of individual machines rather than being applicable to machines as part of a machine system.

The approach proposed in this paper builds upon the tools and techniques from the VIR-ENG project and continued research. A key element in this approach is the seamless integration between simulation model (which is a hybrid DES/CAR model) and physical equipment. An example of networked connections between the real process and the simulation model is shown in Figure 5. This integration makes it possible for instance to:

- Study failure modes and their effects during machine system design through simulations in which certain disturbances/faults are emulated.
- Monitor the operation of the machinery system on-line, which facilitates not only supervision by humans but also automatic data-acquisition.
- In the case of breakdowns, retrieve control code execution, sensor information from a temporal database and carry out a 'replay' of the machinery systems recent history in the simulation model.
- Develop, test and upload temporary control code in the case of temporary reconfiguration due to machine service activities (either preventive or corrective maintenance).

Within MASSIVE, these concepts are being realized through an integrated software environment called MSSS (Machine Service Support System), as an extension of the VIR-ENG machine design and control environments. The system architecture that defines various components of MSSS and their interactions is illustrated in Figure 5. MSSS is essentially a remote data acquisition and analysis system. Therefore, an advanced data acquisition, pre-processing and management framework is the foundation for all other functions. The data acquisition system can be remotely configured so that specified parameters, machine process variables, discrete-event signals can be acquired in prescribed time intervals and sampling rates. Configurations for routine periodic data logging can also be selected for day-to-day monitoring. All configurations to the data acquisition components are done through the Web methods provided by the XML Web services using the user interface functions provided by Scenario Manager.

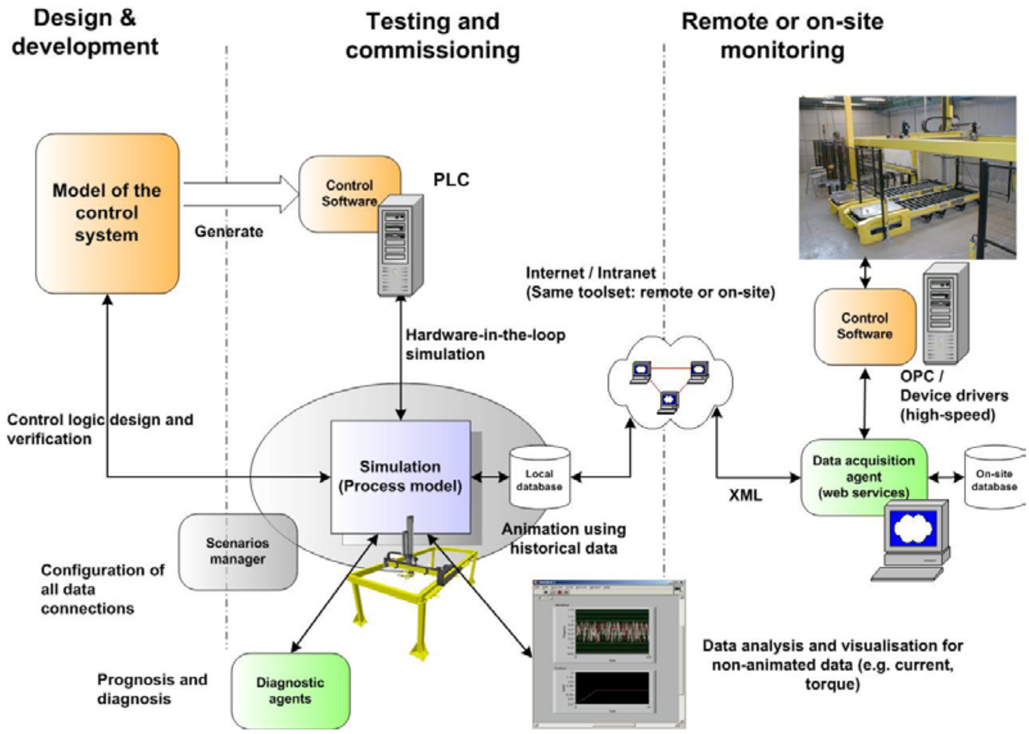

Figure 5: System architecture for a machine service support system

For continuous visual monitoring or in the case of a machine failure (breakdown), MSSS users can use the data saved in the database to carry out "replays" to investigate the recent history of the machine system using the corresponding simulation models. In these cases, animations are driven by recent historical data, but simultaneously, the reference process models generate the nominal dynamic response of the system using data based on long-term history. The outputs can be visualized and compared using various data analysis and residual analysis techniques. The data visualization features accomplish the 3-D animation for presenting useful “non-animated” data like electric current and voltage produced both from the simulator and the collected data as an additional means for assisting any monitoring and diagnostic tasks. Fault alarms can be generated by the diagnostic agents, for instance, if a residual signal is evaluated to exceed a certain threshold; but more advanced fault detection algorithms can easily be incorporated into MSSS.

Whilst MSSS enables real-time on-line monitoring, this can be a tedious and error-prone activity. Furthermore, in case of a well-functioning manufacturing system it is not very meaningful and a waste of resources. To remedy this, the diagnostic agent in MSSS uses an active database (ADB). An ADB does not just store data (in this case, temporal), but can also identify certain trends or events (such as a certain parameter exceeding a threshold value). Such an event can be propagated to decision level, or can be used to alert service and maintenance experts that the manufacturing system’s operation is showing some anomalies and that closer monitoring would be appropriate.

3.5. VM FOR OPERATIONAL PLANNING

Operational production planning is another specialist task. Typically, the planning horizon is about a week but the planning activity must be executed several times per week or even daily, due to disturbances, changes in production orders and so on. Although most ERP/MRP systems incorporate planning algorithms, the possibility to address dynamic effects due to disturbances, rush orders and so on is often limited. In contrast, a simulation-based approach allows online monitoring of the status of the production facility, such as buffer levels, machine status and so on, and information exchange with ERP/MRP systems. In this way, the following can be achieved:

- The starting point of the planning is the actual status of the production facility, based on so-called ‘snapshot information’. This also facilitates rescheduling in case of breakdowns or rush orders.
- Snapshot information can be fused with information about the previous operation of the production facility. This means that parameters can be made dynamic instead of static.
- Different planning solutions can be tested and compared during simulation, and different scenarios can be simulated. This allows for selecting a good and robust planning solution.
- The (often very powerful) visualization possibilities of the DES tools, makes them very suitable for training purposes, with the online connection providing realistic training conditions.

At the University of Skövde, such a simulation based system is currently under development within the SimPlan project [4, 5]. The system design contains the following components: a model of the production system implemented in DES, a database, a middleware to act both as the actual configuration tool, the user interface and as the gateway between the DES tool, the production monitoring system and the ERP-systems. The middleware is implemented in C# utilizing the Microsoft .NET technology. Furthermore, the middleware features a component design in order to be generic and flexible. This design offers the possibility to replace various components such as DES tool or database. This design makes the system adaptable and the actual implementation has been tested under laboratory conditions and later on, two test cases will be conducted in different production contexts.

The communication from the middleware to the external systems is handled via standard interfaces. The integration with Quest is handled via a socket server that is running as a component in the middleware. Data is passed to the server via a socket data stream and then further processed in the middleware. The ERP-integration is handled via ODBC and via SOAP/XML. Finally, the communication with the production system is handled via OPC, which is the de facto standard when interacting with Windows applications. OPC communication is usually done via an OPC-client or by a programming API. The SimPlan implementation uses a C# API, supplied by OPC-labs. This design choice further sustains the concept of the architecture being generic and flexible.

A production planner facing the task of making a production schedule for the week ahead could face the following issues: What is the current status of the production line? Which orders have to be processed? Which rush orders could come in during the week? What's the expected capacity of the line, taking into account breakdowns and scheduled maintenance? In other words, the production planner needs "situation awareness" as it is called in military jargon. Obviously, snapshot information, order information and information from the MSSS are important information packets. These can be used as a starting point for simulations with dynamic parameters, which are based on long-term data logging (incorporating trends and real-life statistical distributions). Typically, scheduling is a "man in the loop" task which allows for different scenarios to be explored through simulation. This results in a better situation awareness which in its turn provides a better support for informed decisions.

4. THE INFORMATION FUSION MODEL REVISITED

The generic IF model as presented in Section 2 can be combined with the modeling and simulation model as per Robinson [23]. The latter model is not very specific regarding data exchange between the real world system and the simulation model. This, however, is not an omission but makes the model more generic. The exchange of data and information (data in its context) can be achieved in many ways and therefore, it is not possible to address details of data exchange (e.g., which and how) in a generic model. The generic IF model as presented before describes the data and information exchange in more detail without being unnecessary restrictive regarding specific solutions/methods for information fusion. This IF model, extended with the Robinson model is presented below (Figure 6), where what is called “real world” in the Robinson model is referred to as “external process” in an IF context. Furthermore, one more connection is added. This connection is specific for the use of active databases in for instance service and maintenance support as discussed in Section 4, and represents the propagation of abnormal conditions or events from the active database (that detects such anomalies) to decision/IF level.

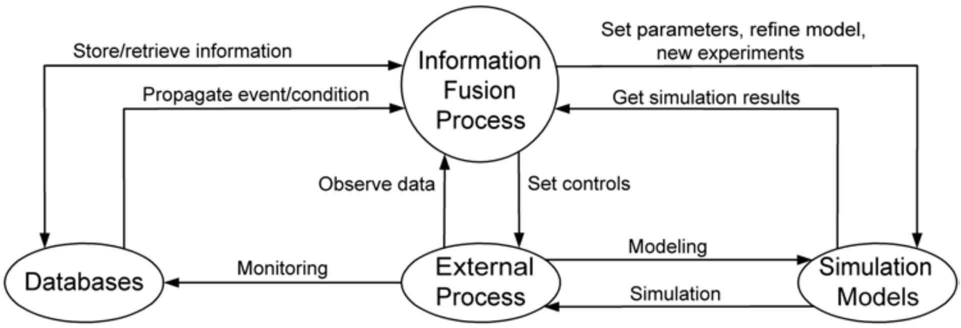

Figure 6: Extended IF model for service and maintenance support

5. CONCLUSIONS

Resource simulation and information fusion are potentially powerful tools for decision support in manufacturing. However, simulation is often used as a stand-alone tool for design and configuration of production facilities, or for off-line programming. Without playing down the importance of this, simulation tools offer even more benefits and better decision support when connected to the production facility on-line. Examples for scheduling and service & maintenance have been given. In decision making, three levels of information regarding objectives and environment may exist, and simulation helps to reduce the level of uncertainty. Information fusion is often application-specific, or limited in information source types. Simulation and information fusion are a powerful combination for decision support, and a generic framework for information fusion has been presented, as well as a modified framework for decision support in manufacturing, based on both information fusion and resource simulation with on-line monitoring facilities. Even the role of active databases has been discussed and incorporated in this framework.

REFERENCES

[1] *Adolfsson, J.K., Ng, A.H.C, & Moore, P.R., Modular Machine System Design Using Graphical Simulation. 33rd CIRP International Seminar on Manufacturing Systems KTH, Stockholm, Sweden, pp335-340, 2000.*

[2] *Olofsgård, P., Ng, A., Moore, P., Pu, J., Wong, C.B. & De Vin, L.J., Distributed Virtual Manufacturing for Development of Modular Machine Systems. Journal of Advanced Manufacturing Systems, Vol 1 No 2, pp141-158, 2002*

[3] *Karlsson, T., Rogstrand, V. & De Vin, L.J., Verifying Manufacturing Requirements Using Tools for Digital Plant Technology. 37th CIRP International Seminar on Manufacturing Systems, Budapest, Hungary, pp291-296, 2004*

[4] *Nilsson, M, Solding, P &, De Vin, L.J., A System Architecture for Integrated Simulation-Based Production Planning and Scheduling, Mechatronics 2004, Ankara, Turkey, pp815-824, 2004*

[5] *Solding, P., Nilsson, M., Eriksson, P. &, De Vin, L.J., Structure for Data Management in Simulation Based Planning Activities. 37th CIRP International Seminar on Manufacturing Systems, Budapest, Hungary, pp193-198, 2004*

[6] *De Vin, L.J., Ng, A.H.C. & Oscarsson, J., Simulation Based Decision Support for Manufacturing System Life Cycle*

Management, Jrnl of Advanced Manufacturing Systems, Vol 3 No 2, pp115-128, 2004

[7] *Dasarathy, B.V., Information Fusion – What, Where, Why, When, and How?. Information Fusion, 2, pp75-76, 2001*

[8] *Dasarathy, B.V., Information Fusion as a Tool in Condition Monitoring. Information Fusion, 4, pp71-73, 2003*

[9] *http://www.data-fusion.org/article.php?sid=70 (visited December 8, 2004)*

[10] *Llinas, L., Bowman, C., Rogova, G., Steinberg, A., Waltz, E. & White, F., Revisiting the JDL Data Fusion Model II. Fusion2004, Stockholm, Sweden, pp1218-1230, 2004*

[11] *Bass, T., Intrusion detection systems and multisensor data fusion. Communications of the ACM, ACM Press, New York, USA, Volume 43 , Issue 4, pp99-105, 2000*

[12] *Warston, H. & Persson, H., Ground surveillance and fusion of ground target sensor data in a network based defense. Fusion2004, Stockholm, Sweden, pp1195-1201, 2004*

[13] *Ueda, K., Markus, A., Monostori, L., Kals, H.J.J. & Arai, T., Emergent Synthesis Methodologies for Manufacturing. Annals of the CIRP, 50/2, pp535-551, 2001*

[14] *Sohlenius, G., Fagerström, J. & Kjellberg, A., The Innovation Process and the Principle Importance of Axiomatic Design. 2nd ICAD, MIT, Cambridge, USA, 2002*

[15] *IFIP-IPAC Task Force, GERAM Generalised Enterprise Reference Architecture and Methodology. Version 1.6.1, 1998*

[16] *Pahl, G., & Beitz, W., Konstruktionslehre, 2.Auflage. Berlin, Germany, 1986*

[17] *Suh N.P., Applications of Axiomatic Design. 1999 CIRP Intnl Design Seminar, Enschede, The Netherlands, pp1-46, 1999*

[18] *Urenda Moris, M., Eriksson, P.T. & De Vin, L.J., 2004, Introducing Discrete Event Simulation for Decision Support in the Swedish Health Care System. WMC2004, San Diego, USA, pp48-53, 2004*

[19] *Kandilli, I., Ertucc, H.M. & Cakir, B., Real-Time Tool Wear Monitoring Using Neural Networks. Mechatronics 2002, Univ. Twente, The Netherlands, pp1018-1027, 2002*

[20] *Salvan, S.M.E., Parkin, R.M., Coy, J., Jackson, M. & Li, W., Condition Monitoring and Location of Multiple Roller Bearings Using Three Sensors. Mechatronics 2002, Univ. Twente, The Netherlands, pp998-1007, 2002*

[21] *Li, B., Chow, M.-Y., Tipsuwan, Y. & Hung, J.C., Neural-Network Based Motor Rolling Bearing Fault Diagnosis. IEEE Transact. on Ind. Electr., 47/5, pp1060-1069, 2000*

[22] *Carnero, M.C., Selection of Diagnostic Techniques and Instrumentation in a Predictive Maintenance Program. A Case Study, Decision Support Systems, in press.*

[23] *Robinson, S., Three Sources of Simulation Inaccuracy (and How to Overcome Them). 1999 Winter Simulation Conference, Phoenix AZ, USA, pp1701-1708, 1999*