



This item was submitted to Loughborough's Institutional Repository (<https://dspace.lboro.ac.uk/>) by the author and is made available under the following Creative Commons Licence conditions.



**CC creative commons**  
COMMONS DEED

**Attribution-NonCommercial-NoDerivs 2.5**

**You are free:**

- to copy, distribute, display, and perform the work

**Under the following conditions:**

**BY:** **Attribution.** You must attribute the work in the manner specified by the author or licensor.

**Noncommercial.** You may not use this work for commercial purposes.

**No Derivative Works.** You may not alter, transform, or build upon this work.

- For any reuse or distribution, you must make clear to others the license terms of this work.
- Any of these conditions can be waived if you get permission from the copyright holder.

**Your fair use and other rights are in no way affected by the above.**

This is a human-readable summary of the [Legal Code \(the full license\)](#).

[Disclaimer](#) 

For the full text of this licence, please go to:  
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

# An integrated model driven approach in support of next generation reconfigurable manufacturing systems

T. Masood<sup>a,b</sup>, R.H. Weston<sup>a,b</sup>

<sup>a</sup> Manufacturing System Integration (MSI) Research Institute, Loughborough University, Leics, LE11 3TU, UK

<sup>b</sup> Centre of Excellence in Customised Assembly (CECA), Loughborough University, Leics, LE11 3TU, UK

---

## Abstract

Shortened product life cycles and globalization have induced dynamism and uncertainty into world markets. Hence manufacturing enterprises (MEs) can gain competitive advantage from being reconfigurable. But appropriate application of agile and lean Manufacturing philosophies must complement the application of reconfiguration techniques. However, choosing and applying the best philosophies and techniques are far from being well understood and well structured processes because most MEs deploy complex and unique configurations of processes and resource systems, and seek economies of scope and scale in respect of a number of distinctive product flows. It follows that systematic methods of achieving model driven configuration of component based manufacturing systems are required to design, engineer and change next generation MEs. This paper discusses research aimed at developing and prototyping a model-driven environment for the design, optimization and control of reconfigurable manufacturing enterprises with an embedded capability to handle various types of change. The developed environment supports the engineering of common types of strategic, tactical and operational process found in many MEs. Also reported are initial findings of manufacturing case study work in which coherent multi-perspective models of a specific ME have facilitated process reengineering and associated resource system configuration. The paper outlines key areas for future research including the need for research into unified modelling approaches and interoperation of partial models in support of complex organisation design and change (OD&C).

**Keywords:** Organisation design and change (OD&C), reconfigurability, enterprise modelling (EM), simulation modelling (SM).

---

## 1. Introduction

Significant change is ongoing in environments in which modern MEs must operate competitively. This has induced a need for faster, better and cheaper production. Quick and timely responses of various production system types are vital for MEs to remain competitive.

One key common response is for MEs to have a broadened product portfolio. But to compete they must

deploy an effective and change capable set of human and technical resource systems. Also because of falling product lifetimes and growing customisation requirements the deployment of these resource systems will increasingly need to give rise to economies of scope and mass customization [1]. For many companies around the world, staying in business necessitates:

- meeting specific customer requirements innovatively and effectively

- ❑ reducing the time-to-market of products
- ❑ manufacturing quality products at competitive cost.

The present day customer typically imposes constraints on MEs via their specific and changing quantity, quality, cost and delivery product and service demands. The implications of this customer focus are that; time to market is shortening, products are tailored to meet a breadth of customer needs, and demand is variable [2,3,4]. However, MEs cannot simply respond by deploying new processes and resources. Generally they need also to redeploy (i.e. re-configure and re-integrate) their use of existing processes and resources such that they can respond competitively to the ongoing business dynamic created by the specific and changing demands of their customer base.

The identification of methods by which manufacturing improvements can be achieved is ongoing and has led to a range of approaches in recent years including Lean and Agile Manufacturing. In addition, progressive improvements to information system capabilities continues to offer the belief that significantly improved support for effective decision making can be achieved [5,6].

Hence it has been observed that modern manufacturing systems must be; flexible/agile, reactive, integrated, and cost efficient [3]. It also follows that ME personnel must have (individual and collective) in-depth understandings about specific processes and resource systems and that these processes must be flexible enough to change whenever the need rises. The complexity of manufacturing systems is reaching that of many natural (e.g. economic and political) systems, thus ongoing re-design and re-engineering of such systems require the use of systematic approaches which deploy various types of system model to understand current and possible future behaviours and to inform systems engineering decision making.

## **2. Need for reconfigurable model driven manufacturing systems**

Business process analyses, aided by the use of Enterprise Modelling and Integration (EM&I) techniques, has potential to reduce the risks and increase chances of realising successful business process operation and interoperation. It also has potential to enable organisations to capitalise knowledge and react to change effectively and efficiently. Systematic decomposition and analysis of

complex systems is possible with the aid of supporting EM & I architectures, approaches and tools.

However realising the potential of EM & I technologies gives rise to far from trivial problems. The skill with which EM & I technologies are used in conjunction with other modelling technologies such as Simulation Modelling (SM) and IT systems engineering technologies, will determine the extent to which benefits of improved ME systems design and interoperation can in practice be realised. For example the models developed using these various technologies need themselves to be reconfigurable and interoperable in order to synchronise their development and deployment within targeted change-capable environments.

There have been recent advancements to extend the coverage of public domain open systems architectures and to bridge the gap between static modelling and dynamic or simulation modelling. Such enhancements include Rahimifard and Weston's enhanced use of EM and SM techniques [7], Chatha's E-MPM [8], and Monfared's approach [9] which has been developed at MSI Research Institute. It is noted that Computer Integrated Manufacturing Open Systems Architecture (CIMOSA) [4] has been central to most of the developments referenced here. A natural focus of these modelling efforts has been to make the models 'live' and responsive to the upcoming rapid changes. Here the idea is to have modelled and real elements of complex and changing sets of processes (and their underlying resource systems) interoperate in a readily integrated and change capable manner which satisfies specific dynamic requirements of the business environment in which the processes are used.

During recent times technological innovation has induced very significant change in industry. It has also impacted significantly on the way that manufacturing enterprises (MEs) operate and compete with each other. In general MEs are very complex entities: designed, managed and changed by people and their designed systems; to realise people and system requirements; by deploying technological resources in systematic, timely and innovative ways that generate competitive behaviours. Because typically MEs have multi purposes and stakeholders it is difficult to decide how best to develop the technological systems they deploy and it is difficult to change them rapidly and in ways that enhance overall ME competitive behaviours. Whereas comparatively it will be simpler, easier and faster to design and realise change in systems with a single well defined purpose and small set of

stakeholders. Hence there is a great need to seek to deploy decomposition principles aimed at breaking down complex systems into readily understood and reusable technical building blocks; which can be used as interoperating 'components' (or modules) of wider scope and complex MEs that can be reconfigured as requirements change.

Globalisation is one outcome from technological innovation within MEs. With sufficient resources, many entrepreneurs can now physically or virtually relocate themselves and their products (knowledge, experience, ideas and artefacts) to various locations around the globe. This has enabled knowledge sharing on a worldwide basis and globalisation of technical systems. Hence many MEs now take the form of an appropriate configuration of less complex entities with a global reach as a result.

The research reported in this paper builds upon previous research in MSI Research Institute to achieve an enhanced and synergistic use of enterprise modelling, simulation modelling, causal loop modelling and workflow modelling in support of the ongoing configuration and interoperation of manufacturing systems. These techniques come from different origins and potentially can support the creation and use of different types of model. However there is little reported in the literature on (1) their complementary capabilities, and (2) their collective use so as to provide semantically rich models that can support numerous aspects of ME design and change. Hence in recent years the present authors and their research colleagues have conceived, incrementally developed and case study tested a set of unifying concepts and methods.

The new approach to creating configurable and interoperable manufacturing systems assumes a need for process oriented thinking when designing present day configurable organisations and that various modelling technologies are required in support of organisation design and enactment. Hence, an overall research aim is to develop a model-based unified environment, which lends structure to and supports multi-perspective decision making involved in organisation design and enactment. The scope of research found to be necessary to satisfy this need encompassed:

- Understanding the nature and role of processes in manufacturing organisations;

- Achieving semantically rich process modelling within the broader context of enterprise modelling decomposition principles;
- Unification of a number of state of the art modelling techniques.

On completion of this research the following main deliverables are being delivered and case study tested on a progressively comprehensive and improved basis:

(1) a methodology including modelling stages, concepts and methods for capturing relevant aspects of organisations, and techniques and tools that can be deployed to develop unified models of processes, work flows and their needed resource system;

(2) a unified modelling framework and modelling concepts that describes those aspects of an enterprise that need to be understood and captured while modelling processes so that various models of these aspects can interoperate in respect of current and possible future ME compositions.

### **3. A model-driven approach in support of reconfigurable manufacturing systems**

The modelling approaches have significant roles to play in enabling decision making in dynamic manufacturing organisations. Analysis of business processes aided by Enterprise Modelling and Integration (EM&I) can reduce risks and increase chances of implementing successful business processes. Business process thinking can also enable organisations to capitalise knowledge so that they can react by changing operations in an effective, efficient and timely manner. Systematic decomposition and analysis of complex systems is possible with the aid of supporting architectures and by using complementary modelling techniques which can include Enterprise Modelling (EM), Causal Loop Modelling (CLM), Simulation Modelling (SM) and Work Flow Modelling (WfM) [10]. The models of ME processes, resource systems and workflows created need themselves to be reconfigurable and interoperable in order to synchronise between virtual and real elements of processes and systems that need to interoperate within dynamic (often uncertain) environments [11]. In principle, by achieving a unification of different modelling approaches new opportunities will arise to make the models live and responsive to upcoming but 'yet to be determined' rapid changes [11].

This paper describes a systematic approach to creating coherent sets of unified models that can interoperate to replicate and predict changing organisational behaviours in support of reconfigurable manufacturing systems. The modelling approach used

to support reconfigurable manufacturing systems is illustrated in Fig. 1.

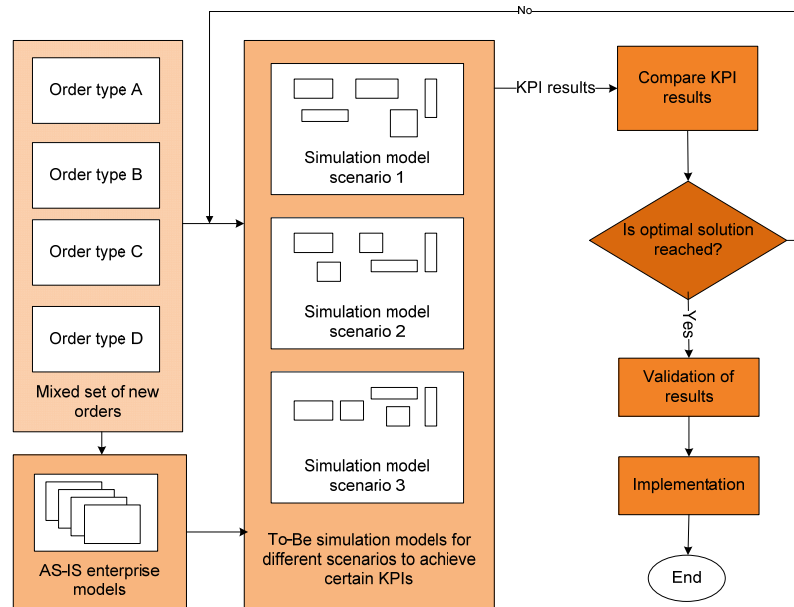


Fig. 1. A model driven approach in support of reconfigurable manufacturing systems

The purpose of this section is to describe how a simulation modelling methodology was developed to computer execute models of manufacturing systems under different configurations. This methodology is centred on simulation modelling but uses a combination of enterprise and simulation modelling techniques to create a coherent set of models that can structure and inform:

- Understanding of the problem domain;
- Development of conceptual model in relation to problem domain;
- Information and data collection;
- AS-IS model building for present configuration;
- TO-BE model building for different configurations;
- Verification and validation of models;
- Experimental work and analysis based upon key performance indicators (KPIs) leading to system selection.

A set of computer and manual simulation technologies and systems are used to simulate the problem scenarios and provide suitable interface to

users. The subscript packages were used for simulation purposes:

- SIMUL8®
- Plant Simulation ®
- iThink®
- MS Visio®
- CIMOSA Diagramming Templates
- Causal Loops

The interfaces enables the user to:

- Capture requirements data;
- Input data into the model;
- Reconfigure a simulation model to meet various specified needs;
- Conduct various experiments based upon different scenarios;
- Collect results and
- Conduct analysis of results.

#### 4. Case Study

The case study company (referred to as ABC onwards) is a furniture manufacturing SME with 50

employees. It operates primarily within the UK but has European suppliers of raw material. It manufactures over 300 different furniture products from pine wood; including a range of tables, cabinets, beds, wardrobes and other furniture items that are designed for house hold and business users. The application of a number of different reconfiguration concepts is being investigated at ABC. A coherent set of enterprise and simulation models were created to explicitly represent and computer execute behaviours of ABC's business processes, (human and technical) resource systems and dynamic patterns of multi-product workflows.

Reduction in lead time (and in effect throughput time) is one of the key performance indicators in engineering of a reconfigurable manufacturing system. The current system was analysed for future implementation of a hybrid Make-To-Stock (MTS) / Assemble-To-Order (ATO) system. When populated order behaviours are available, the predictability of orders is better achievable using forecasting methods. Such a MTS/ATO system is practicable in environments where standard parts are available to assemble using postponement approach. With product (re)design, it is achievable to make standard parts which are partially driven by MTS strategy and partly by ATO strategy. Implementation of a hybrid MTS/ATO system needs better product and process (re)design, availability of stock, availability of Bill of Material (BOM) data, availability of forecasted orders, commonality of parts (standardisation of parts or modularisation) and better supplier relationships.

Provided these supports are available, reduction in lead time is achievable which leads to customer satisfaction and then may result in an increased frequency of orders. All above-mentioned factors enhance the chances of success rate of implementation of hybrid MTS/ATO system.

Enterprise and simulation models were developed in order to enable decision making about ME possible selection of an improved PPC strategy which could make this assembly process segment (and its underlying resource systems) become more configurable and interoperable. Fig. 1 shows ME modelling approach (based on using enterprise and simulation models) which was adopted in order to enable improved decision making in ABC. The case study and exemplary models have been presented in further detail in [12] for an example of PPC strategy realisation.

It was noted that the combined use of EM and SM techniques helped to gain in depth understanding about the ABC's production methods, their shortcomings and possible ways of improvements. Such reconfiguration decision making supports OD&C process. There is a need to develop methods and technologies for unified modelling and interoperation of partial models in support of complex OD&C. The future research also relate to the use and updating of enterprise and simulation models. Table 1 summarizes key existing ABC approaches, authors' observations and proposed strategies related to reconfiguration.

Table 1  
Summary of observations and proposed reconfiguration strategies in ABC

Production Strategies	Existing ABC Scenario	Observations	Proposed strategies
PPC Hierarchy	<input type="checkbox"/> No aggregate planning based on forecasting	<input type="checkbox"/> No visibility of order behaviour <input type="checkbox"/> Slow to react	<input type="checkbox"/> Needs forecasting <input type="checkbox"/> Historical data analysis
Customer Order Decoupling	<input type="checkbox"/> Make to Order (MTO)	<input type="checkbox"/> Majority of production starts with order arrival	<input type="checkbox"/> Assemble to order <input type="checkbox"/> Inclusion of Postponement theory
Push vs. Pull System	<input type="checkbox"/> Push system	<input type="checkbox"/> Longer lead time	<input type="checkbox"/> Pull system where possible <input type="checkbox"/> Production based upon commonality of parts <input type="checkbox"/> Parts standardisation
Production Scheduling	<input type="checkbox"/> Accumulated order list due to logistic constraints	<input type="checkbox"/> High variety induced in system bottleneck	<input type="checkbox"/> Break up of job list by removing the constraint
Production Sequencing	<input type="checkbox"/> First In First Out (FIFO) <input type="checkbox"/> Minimum set up time	<input type="checkbox"/> Does not reflect global objectives <input type="checkbox"/> Does not take into account overall lead time performance across Assembly Shop and ABC	<input type="checkbox"/> Adoption of dynamic sequencing rules ○ Minimum number of remaining operations ○ Minimum remaining process time

## 5. Conclusions

This paper discusses research aimed at developing and prototyping a model-driven environment for the design, optimization and control of enterprises with an embedded capability to handle various types of change in different production configurations. The developed environment supports the engineering of common types of strategic, tactical and operational process found in many MEs. Also reported are initial findings of manufacturing case study work in which coherent multi-perspective models of a specific ME have facilitated process reengineering and associated resource system configuration and interoperation. It follows that systematic methods of achieving model driven configuration and interoperation of component based manufacturing systems are required to design, engineer and change next generation MEs. The basis of a systematic approach to creating coherent sets of unified models that facilitate the engineering of reconfigurable system is described. A summary of observations and proposed configuration strategies have been presented in the paper which supported model-driven reconfiguration of manufacturing systems. The paper has identified key areas for future research which relates to the use and updating of enterprise and simulation models.

## References

- [1] Vernadat, F.B., *Enterprise Modelling and Integration (EMI): Current Status and Research Perspectives*. Annual Reviews in Control, 2002. 26: p. 15-25.
- [2] Suri, R., *QRM and POLCA: A Winning Combination for Manufacturing Enterprises in the 21st Century, Technical Report*. 2003, Centre for Quick Response Manufacturing, <http://www.engr.wisc.edu/centers/cqrm/pub/qrm21st.htm>.
- [3] Ladet, P. and F.B.E. Vernadat, *The Dimension of Integrated Systems Engineering*, in *Integrated Manufacturing Systems Engineering*. 1995, Chapman & Hall: London. p. 3-9.
- [4] Vernadat, F.B., *Enterprise Modelling and Integration: Principles and Applications*. 1st ed. 1996, London, UK: Chapman & Hall. 513.
- [5] Maropoulos, P.G., *Digital enterprise technology – defining perspectives and research priorities*. International Journal of Computer Integrated Manufacturing, 2003. 16(7-8): p. 467-478
- [6] Young, R., *Informing Decision Makers in Product Design and Manufacture*. International Journal of Computer Integrated Manufacturing, 2003. 16(6): p. 428-438.
- [7] Rahimifard, A. and R.H. Weston, *The enhanced use of enterprise and simulation modelling techniques to support factory changeability*. International Journal of Computer Integrated Manufacturing, 2007. Vol. 20(No. 4): p. 307-328.
- [8] Chatha, K.A., *Multi-Process Modelling Approach to Complex Organisation Design. Thesis (PhD)*, in *Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University*. 2004: Loughborough, UK. p. 294.
- [9] Monfared, R.P., *A Component-Based Approach to Design and Construction of Change Capable Manufacturing Cell Control Systems. Thesis (PhD)*. in *MSI Research Institute*. 2000, Loughborough University: Loughborough, UK. p. 266.
- [10] Weston, R.H., et al. *Simulation Model Interoperability in support of complex organisation design and change*. in *European Simulation and Modelling (ESM) Conference*. 2006. Toulouse, France.
- [11] Weston, R.H., et al. *Simulating Dynamic Behaviours in Manufacturing Organisations*. in *International Conference on Industrial Engineering and Systems Management (IESM 2007)*. 2007. Beijing, China.
- [12] Masood, T. and R.H. Weston, *Integrated modelling approach in support of change-capable PPC strategy realisation*, in *The 4<sup>th</sup> International Conference on Innovative Production Machines and Systems (IPROMS 2008)*. 2008. The Internet.