# Advances in Decision Sciences

Special Issue
Decision Making in Support of Manufacturing Enterprise Transformation

Guest Editors: Richard H. Weston, Albert T. Jones, Bernard Grabot, and Bernard Hon

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## Editorial Board

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Hindawi Publishing Corporation
Advances in Decision Sciences
Volume 2013, Article ID 326185, 2 pages
http://dx.doi.org/10.1155/2013/326185

*Editorial*

# Decision Making in Support of Manufacturing Enterprise Transformation

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Received 13 November 2012; Accepted 13 November 2012



To achieve the agility necessary to compete successfully in everchanging world markets, manufacturing enterprises of all sizes must exhibit a transformational leadership. Strategic, tactical, and operational decision making is an essential part of such leadership. The papers in this special issue seek to understand and characterize common transformational decision-making needs in manufacturing enterprises and the state of art in decision-making methods and technologies. Additionally, these papers identify gaps in those methods and technologies and propose research can fill those gaps.

In the paper titled "*The integrated use of enterprise and system dynamics modelling techniques in support of business decisions*" the authors use case studies to describe a new modelling methodology for analysing and managing dynamics and complexities in production systems. This methodology is based on a systematic transformation process that integrates enterprise, causal loop (CL), and system dynamics (SDs) modelling techniques. The methodology relies on the creation of CIMOSA process models, which are then converted to CL models. CL models are then structured and translated into equivalent SD models. The authors have used their methodology in a number of case study companies to (1) capture business processes, (2) model the dynamics impacting those processes, (3) analyse the impact of variations in customer demand on value realization, and (4) analyse the effect of constant sales orders on material supply, cost, and product realisation.

In the paper titled "*Performance assessment of product service system from system architecture perspectives*" the author focuses on a concept called Product Service System (PSS). The PSS enables the manufacturers of complex engineering products to incorporate support services into the entire product life cycle. However, the PSS design has imposed significant risks to the manufacturer not only in the manufacture of the product itself, but also in the provision of support services over a long period of time at a predetermined price. This paper analysed three case studies using case study research design approach and mapped the service elements of the case studies to the generic Complex Engineering Product Service System (CEPSS) model. By establishing the concept of capability distribution for a PSS enterprise, the capability of the CEPSS can be overlaid on the performance-based reward scheme so that decision makers evaluate options related to the business opportunities presented to them.

In the paper titled "*Evaluating ethical responsibility in inverse decision support" the author addresses an ethical dilemma in* "*Inverse Decision Support*." That dilemma arises whenever a decision support analyst (DSA) must evaluate the ethical responsibility in selecting a suboptimal alternative. This can happen, for example, when the actual decision maker requires the DSA's justification for a preconceived selection that does not correspond to the best option resulted from the professional resolution of the problem. To address this dilemma, the author proposed an extended application of the Analytic Hierarchy Process model. That extended application is consistent with the Inverse Decision Theory that is used extensively in medical decision making. The author conducted a survey of DSAs to assess their perspective of using the proposed extended application. The paper includes results from the survey. Those results show that (1) 80% of the respondents felt that the proposed extended application is useful and (2) 14% of them expanded the usability of the extended application to their academic courses.

In the paper titled "*Design of an integrated methodology for analytical design of complex supply chains*" the authors review modelling capabilities needed to advance industry best practice regarding the analytical design of supply chains. Those capabilities include (1) the graphical representation and explicit description of key structural properties of complex supply chains, (2) behavioural exploration of dynamic properties of existing complex supply chains, (3) prediction of possible future behaviours of complex supply chains when uncertainties arise, and (4) predictive quantification about relative performances of alternative complex supply chain configurations, including risk assessments, when they are subjected to uncertainty. They then reviewed alternative means of deploying state-of-the-art modelling techniques, including enterprise modelling (EM), causal loop diagramming (CLD), and simulation modelling (SM). Previously the literature had not reported methods of coherently applying EM, CLD, and SM techniques in support of the lifecycle engineering of complex supply chains. The authors then describe their efforts to specify and develop an integrated, model-driven method of modeling and engineering complex supply chains. This method has the potential to support collective and individual decision making of managers and engineers.

In the paper titled "*Multiobjective optimization of aircraft maintenance in thailand using goal programming: a decision-support model*" the authors develop a multiobjective optimization model in order to evaluate suppliers for aircraft maintenance tasks, using goal programming. The authors have developed a two-step process. Authors use the model as a decision support tool for managing demand, by using aircraft and flight schedules to evaluate and generate aircraft maintenance requirements, including spare part lists. In step two, they develop a multi-objective optimization model by minimizing cost, minimizing lead time, and maximizing the quality under various constraints in the model. Finally, they demonstrate the model in the actual airline case study.

In the paper "*Modelling framework to support decision making in manufacturing enterprises*" the authors describe a novel systematic framework for creating coherent sets of integrated models that facilitate production planning and control (PPC) strategies in future reconfigurable manufacturing enterprises (MEs). The framework is the enhanced integrated modelling framework (EIMF). EIMF supports the engineering of common types of strategic, tactical, and operational processes found in many MEs. The authors use the CIMOSA enterprise modelling approach to develop a structured, model-driven, integrated approach that can support various PPC decisions. This new approach can capture and represent both static and dynamic aspects of an organization. Finally, the authors provide example application cases that show benefits in terms of lead time and cost reductions.

In the paper "*Model driven integrated decision-making in manufacturing enterprises*" the authors summarize decision-making requirements and solutions from four world-class manufacturing enterprises (MEs). They include observations on deployed methods of complexity handling that facilitate multipurpose, distributed decision making. They also report on examples of partially deficient "integrated decision making" which stem from a poor understanding of the relationship between structure and behavior. As a way of improving this understanding, the authors propose a "reference model of ME decision- making" and a new model-driven approach, which can "underpin integrated ME decision- making." The authors include an ME case study to explain how their approach can improve the integration of previously distinct planning functions. The modelling approach is particularly innovative in respect to the way it structures the coherent creation and experimental reuse of "fit for purpose" discrete event (predictive) simulation models at the multiple levels of abstraction.

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Hindawi Publishing Corporation
Advances in Decision Sciences
Volume 2012, Article ID 640601, 19 pages
doi:10.1155/2012/640601

*Research Article*

# Performance Assessment of Product Service System from System Architecture Perspectives

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Received 7 January 2012; Accepted 20 August 2012

Academic Editor: Richard H. Weston



New business models in complex engineering products have favoured the integration of acquisition and sustainment phases in capability development. The product service system (PSS) concept enables manufacturers of complex engineering products to incorporate support services into the product's manufacturing and sustainment lifecycle. However, the PSS design has imposed significant risks to the manufacturer not only in the manufacture of the product itself, but also in the provision of support services over long period of time at a predetermined price. This paper analysed three case studies using case study research design approach and mapped the service elements of the case studies to the generic complex engineering product service system (CEPSS) model. By establishing the concept of capability distribution for a PSS enterprise, the capability of the CEPSS can be overlaid on the performance-based reward scheme so that decision makers evaluate options related to the business opportunities presented to them.

## 1. Introduction

Recent trend around the world among the owners of complex engineering systems such as aircraft or oil refinery is to include consideration for the sustainment of the system at the very early stages of system development. According to the Defence Materiel Organisation in Australia [1], the asset acquisition project is considered a continuum of four phases, which can be generalised as a capability systems lifecycle as shown in Figure 1. The goal is to ultimately attain desired capability levels that can be measured as a performance outcome of systems in-service.

There are two different contracting regimes in Figure 1.

(i) System acquisition agreements including functional and performance specification of the final system, that is, the tendering and contracting activities in the acquisition phase.

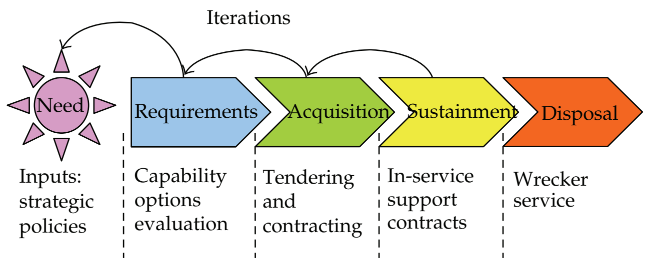


**Figure 1:** Capability systems lifecycle.

(ii) Sustainment agreements specifying outcomes and performance requirements for in-service support, that is, the in-service support contracts in the sustainment phase.

Although it is still early stage process development, the Australian Defence intends to adopt a more integrated approach by contracting for acquisition and sustainment simultaneously in some of their new system acquisitions.

Similarly, the Ministry of Defence [2] in UK is managing a general shift in defence acquisition away from the traditional pattern of designing and manufacturing successive generations of platforms. Instead, a new paradigm centred on support, sustainability, and the incremental enhancement of existing capabilities from technology insertions has evolved with the emphasis increasingly on through life capability management. The new approach to acquisition is built around the objective of achieving

(i) primacy of through life considerations;

(ii) coherence of defence spend across research;

(iii) development, procurement, and support,

(iv) successful management of acquisition at the departmental level.

From the industry's point of view, this shift in defence acquisition process means longer, more assured revenue streams based on long-term support and ongoing development instead of a series of big "must win" procurements [3]. Observation on other industry sectors shows similar changes in the manufacturing and sustainment of complex engineering products such as an oil refinery and mining machinery [4].

Traditionally, management of sustainment services is the responsibility of the asset owner, after the product is commissioned. Most asset owners simply take the recommended schedule of the manufacturer, either by in house service department or by a maintenance services contractor. The strategy is to minimise expenditure that should be spent on the asset [5]. Therefore, classical services and maintenance plans are designed on the principle that mean time between failures is a constant and hence the focus is to replace components before it fails. Typically, service activities including inspection, adjustment, and replacement are scheduled in fixed intervals [6]. Due to multifaceted relationship between operating context and characteristics inherent in the complex system, these intervals may not be optimised [7]. On the other hand, reliability-centred maintenance regime has been developed to plan actions in maintenance based on advanced understanding of the reliability of the system [8]. In addition, many other factors are also influencing the operations of the asset [9]. Many service decisions on assets are therefore made on rules of thumbs rather than using analysed system performance data. Many complex systems are left vulnerable with high risks of failure.

A new service business model known as "performance-based contracting" has emerged in recent years as one of the favourable choice of contracting mechanisms for the public sector and asset intensive industries [10]. Under performance-based contracting approach, a contractor offering systems support services needs to design an operation and support system that is sustainable, fits for the purpose, and demonstrates its value for money. The advantage of performance-based contracting is the sharing of benefits for both sides of the business. Efficiency gains are shared between the contractor and the owner of the business [11]. In this regards, original equipment manufacturers have significant advantage over other service providers because they know their product well. Many equipment suppliers have taken the opportunity to expand into offering after sales services to customers [12].

A manufacturer of complex engineering system entering into this kind of contract takes a lot of risks with the contract. For example, the new contracting framework by Defence Materiel Organisation [13] contains several elements of incentives and penalties. Application of these elements depends on the actual system performance results within four bands.

(i) *Performance Band I.* System performance result is below the required performance level. Contract payment is reduced proportionally to the actual performance outcomes as a disincentive.

(ii) *Performance Band II.* Result is poor but may be tolerable for short term only. Contract payment is significantly reduced proportionally to the actual performance outcomes with a more rapid reduction ratio until reaching zero.

(iii) *Performance Band III.* Result is totally unsatisfactory and represents an irrecoverable failure. No payment is made and other remedies may be applied.

(iv) *Performance Band IV.* Result of the achieved performance equals or exceeds the required performance level. An optional performance incentive may be paid in addition to the agreed value.

In this new service business model, risks exist throughout the whole of life of the product. How can the manufacturer know in advance what performance he/she can achieve at the conceptual design phase of the product life cycle? Which performance band is the system going to operate? There are many factors affecting system performance, for example, new deployment requirements, or change of software operating system, and so forth. The technology in the system is already very sophisticated. The model adds further complexities of sustainment and lifelong services in the commercial contract. These represent several layers of uncertainties in the commitment on the part of the service provider. A decision support methodology that can reduce such uncertainties in the life of the asset is required. This paper is motivated by the fact that new business paradigm emerging in the service sector has demanded a new set of principles and knowledge to assist the manufacturing industry. A new product and service enterprise architecture is proposed in this paper and verified by three past service systems design projects, with case study research design methodology. Based on the new architectural model, an assessment methodology that can be used for assisting decision makers to evaluate options available to them in regards to the business opportunities presented to them is proposed.

## 2. Product Service System

The shift of complex engineering products manufacture to service-oriented business environment has necessitated research in developing a new business model [14]. Abe [15] studied a service-oriented solution framework designed for Internet banking and described the new research as "service science". The concept of product service system (PSS) was initially developed around the optimization of sustainability criteria to operations, maintenance, and environmental related issues around the product [16]. The PSS concept extends, on the basis of an existing complex product, the provision of support services on that complex product when it is in operation. Bairnes et al. [17] presented a clinical style survey of contemporary practices in PSS and subsequently defined PSS as a special case of servitization. It is obvious that there are commercial benefits for companies to move into continuous services and support operations of the complex products they manufacture. In addition to the technical requirements of supporting a complex engineering system, a key feature of the new PSS model is the extension of product offering to service offering. A service system comprises people and technologies that adaptively adjust a system's value of knowledge while the system changes in its lifecycle [18].

One of the key questions emerged from this approach is the uniqueness of service requirements. Every complex engineering product is different and hence it is fair to say that each PSS is customised. Johansson and Olhager [19] examined the linkage between goods manufacturing and service operations and developed a framework for process choices that enable joint manufacturing and after-sale services operations. Study showed that moving into services-oriented business could have significant financial implications to the company [20]. In a performance-oriented service system, decisions for optimization can be quite different from maintenance oriented service concepts. For example, in order to reduce time of service to customers, Shen and Daskin [21] suggested that a relatively small incremental inventory cost would be necessary to achieve significant service improvements. Hence, to develop service systems that can handle this type of business requirements, companies should build common business functionalities as shared services so that they can be reused across lines of business as well as delivery channels [22].

When compared to traditional support arrangements, PSS concept changes a contractor's roles and responsibilities by shifting the support service to customer focus. Under service-oriented arrangements, the service provider is responsible for the full spectrum of support, including ownership, sustainment, and operation of assets. Furthermore, contracting arrangements will include incentives and penalties against levels of support service or delivery. The service provider will need to think differently and design the output solutions that deliver the desired outputs as well as generating profit. This is a different type of business with unfamiliar contractual metrics and risks. In PSS, the emphasis is on customisation of solution designs to meet service needs and create new values of use for the customer [23].

A performance-based contract in PSS will include incentives and penalties against levels of support service or delivery as discussed before. Hence, the service contractor should have a thorough understanding of how the system works and how the supporting systems around the asset provide the services to achieve the desirable performance [24]. Due to this highly individualised nature of service, no one performance-based contract is the same. The support system then becomes a one-off development which imposes significant system design issues to both asset owners and contractors.

A service contract often involves active interaction within the supply chain and with the customer. In a service environment, it is normal that a new separate enterprise is formed from several independent, collaborating enterprises. There are many risks in this strategy, for example, there are risks in collaboration, confidentiality, intellectual property, transfer of goods, conflicts, opportunity loss, product liability, and others. To minimise the risks for the new service enterprise, enterprise engineering researches provide an enterprise architecture framework as a common starting point. The study of enterprise architecture in the last decade has been on how enterprises can be designed and operated in an environment when the enterprise missions and objectives are clear. They assumed that one can follow the common engineering practice of well established sequences of steps: design, implementation, operation, and decommission phases [25]. The rationale to use enterprise engineering methodologies to guide these steps is to minimize enterprise design modifications and associated rework of the system governing information and material flows [26]. A PSS as discussed in this paper is a dynamic system. Any unplanned change to the enterprise is an impact of uncertainty to enterprise performances. The enterprise architecture (EA) approach provides a structured system to manage services activities, for example, promote planning, reduce risk, implement new standard operating procedures and controls, and rationalize manufacturing facilities [27]. Hence, this paper uses an EA approach to understand the enterprise under which the product and related services are managed and to assess the performance of the PSS.

## 3. Architectural Approach

An enterprise architecture defines methods and tools which are needed to identify and carry out change [28]. Enterprises need lifecycle architecture that describes the progression of an enterprise from the point of realisation that change is necessary through setting up a project for implementation of the change process. Denton et al. [29] specified an information technology route map that enabled rapid design of IT solutions to automate some business processes for service supply chains. Therefore, it is crucial to use a systematic design methodology that helps the management developing well-defined policy and process across the organisational boundaries and implements the changes in all enterprises of the service supply chain.

However, traditional enterprise architectures are based on top down approach. They emphasized on uniformity throughout the organization. As such, the structure is inflexible. Changing the structure in order to respond to fast changing dynamic issues for in service engineering systems will be too long to fix any problem [30]. Two issues in using standard enterprise architecture to model service and support systems are identified.

### *Inwards Modelling*

Existing enterprise architectures contain functions, data, staff, resources which are inwards looking and focus on internal company issues. There is very few, if any, modelling constructs for interaction with other systems.

### *Static, Snapshot View of Present and Future*

EA modelling methodology is based on the understanding that it is a snapshot of the enterprise at certain point in time. Service systems are dynamic organisations. There are frequent staff movements, external environment changes, customer changes, and change of use context. The static nature of existing EA is incapable of handling changes as anticipated in real service systems.

In order to support decisions on business opportunities by enterprise architectural approach, the PSS enterprise should have the following characteristics.

*Measurement of Performance and the Development of Metrics That Can Be Supported by Technology*

The PSS will be operated in parallel with the complex engineering system. Service is qualitatively different to the familiar product-based approach where hard artefacts are delivered to the asset owner. Service is a negotiated exchange with the asset owner (and operator) to provide intangible outputs that are usually produced together with the asset owner. A service is usually consumed at the time of production. Services cannot be transferred to other asset owners in the same way that products can. Hence, the development of appropriate performance metrics is essential and most of these are supported by advanced information and computational technologies.

*Use of Proven Enterprise Architecture That Incorporates Broad Range of Engineering Disciplines*

PSS incorporates system design knowledge that draws upon principles derived from a wide range of engineering disciplines including systems engineering, logistics engineering, project management, information systems, and many others. The knowledge helps the system support engineer to take into account as many constraints as possible during the system design phase. These constraints are imposed by the environment in which the complex system and the business are operating.

*Sustainability Capability That Manages Risks in the Support Contract*

The performance-based services are characterised by the need to create value for both asset owner and the service provider. As such both sides are treated as coinnovators in the design of the PSS. Many decisions are made based on incomplete data rather than fully analysed data set. There are a lot of risks, both from the point of view of data availability, as well as subjective human judgement and communication.

When customers want to outsource a service function, capturing the requirements is the real challenge for human intelligence and ability to manage what we know, what other people know, and what nobody knows [31]. A modelling construct that has more human interaction characteristics is required.

SHEL model has been developed from analysing and modelling human interaction with physical and project activities [32]. Chang and Yeh [33] applied the SHEL model to describe the structure of the air traffic control system and its interface to human operators. The research findings provided practical insights in managing human performance interfaces of the system due to changes in its operating environment. Felici et al. [34] applied the SHEL model to deal with the definition of the requirements for a new railways traffic control system. Lei and Le [35] evaluated risks of human factors in flight deck system. They used a SHEL model and found five most significant factors on the risks in the system.

Extending from traditional enterprise modelling methodology, Chattopadhyay and Mo [36] modelled a global engineering services company as a three-column progression process that was centred on human engineering effort. Chattopadhyay et al. [37] developed a business model for virtual manufacturing with particularly emphasis on the need for intense collaborative network for a variable-variety, variable-volume and manufacture to order situation with provisions for recycling and reverse logistics. The concept was further developed as an aggregated model resembling nature's atomic and molecular interaction after studying the supply chain in China [38]. These new attempts to incorporate human participation in modern global enterprises have highlighted the effect of new information and communication technologies in bringing the human dimension in enterprise architecture to a dominated position.

As seen from the literature, the SHEL model has particular focus on local, operational level of the enterprise. It does not have the support of engineering methodology to ensure repeatability and sustainability of the system. Likewise, traditional enterprise architecture methodology tends to ignore human interaction and becomes difficult to describe vibrant enterprises in the services sector. It is logical to develop a new enterprise model for services that combines traditional enterprise architecture with SHEL concept. We propose this new complex engineering product service system architecture as shown in Figure 2.

Figure 2 shows that a PSS for complex engineering products should be a four–dimensional system architecture: product, process, people, and environment. This is in contrast to conventional enterprise modelling methodologies that had significant influence to system development thinking in the 1990s. The new architecture covers the additional "changing" aspect of service system by integrating the concepts of product, process, people to changes in environment over time. The four dimensions are interlinked and affecting one another. The architecture provides a focus for consolidating existing knowledge of designing a service system as well as an instrument for projecting future requirements in a system so that new features can be developed in an orderly fashion.

## 4. Case Study Research Design

Case study research is particularly useful in identifying specific characteristics that affect system performances. Serra and Ferriera [39] identified four strategy pillars in five case studies of well-known multinational corporations. In supply chain case study research, Seuring [40] surveyed 68 papers related to supply chain sustainability and supply chain performance and concluded that more supply chain cases should be documented and reviewed. Lewis et al. [41] researched three case studies in the energy and maintenance management practices. They found that the link between different service requirements should be better understood when the teams worked together for service solutions.

However, extracting the theoretical essence of a PSS is not a trivial exercise from studying a wide variety of cases. For example, Holschbach and Hofmann [42] used case study evidence from eight manufacturing and eight service companies. They found that companies did not use quality management for externally sourced business services to its full potential. There were major difficulties in determining quality failures, standardization, and quantity of service. Zhang et al. [43] carried out a structured literature review on the influence of ICT in supply chain management. They found that despite inconsistency in reported findings in this field of research, there were general positive performance outcomes of supply chains due to ICT system development. Kucza and Gebauer [44] investigated the forms of servitization of products could help global manufacturing firms to develop new service-based and relationship-based value propositions for customers. Four such forms were identified: integrated and ethnocentric; integrated and polycentric; separated and polycentric; and separated and geocentric.

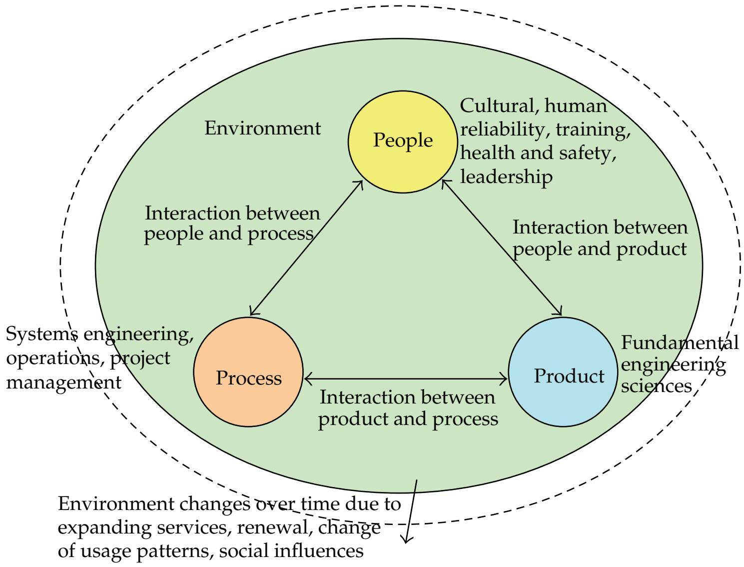


**Figure 2:** Complex engineering product service system (CEPSS) architecture.

One of the most difficult issues in the case study research is the definition of unit of analysis. Grünbaum [45] provided a useful elaboration of the concept by examples of generic case studies based on modifications of Yin's [46] case study design. Huang [47] interviewed top management of 40 SMEs in Taiwan on their perceptions of IT components in business and found five internal strategic factors inhibiting top management support in IT adoption. M. Bielli and A. Bielli [48] presented a conceptual model of a SMEs network in the European project CO-DESNET. The coordination of distributed and autonomous agents characteristics of the collaborative enterprise clusters was represented by suitable models such that global performances could be evaluated. The model was validated by a case study outlining a transition to the Net Economy of SMEs in Italy.

In this paper, three case studies are described and their key features are highlighted. The cases are earlier forms of PSS representing various degrees of success in creating new businesses for the equipment suppliers. The ad hoc systems established at the time of these cases provide good examples for benchmarking current thinking of the design and implementation of PSS. These cases are chosen because the parties in the cases have tried to apply a defined enterprise infrastructure that links different parts of the service system working in conjunction with the product. Subsequently, the service system has to be re-designed and tailored to characteristics of the product or the enterprise itself.

Data collection for this type of case study research depends on the relationship of the researchers and the parties in the cases. In all cases, the author of this paper has had varying levels of participation in the cases.

## 5. Case Studies

The products in the three cases are complex engineering systems. Case 1 is a computer controlled plasma cutting machine that can cut steel plates up to 50 mm thick. The machine has been sold over the world. Case 2 is a chemical plant that is designed and built by a

Japanese engineering company. In order to support the customer with minimum costs, the support system was designed to use the Internet, which was evolving at the time when the project was done. Case 3 is a defence case in which the ship builder formed a service consortium to continue its business after the ships were built. Evaluation and analysis of the cases will be based on the CEPSS model presented in Figure 2.

### *5.1. Case Study 1: Signal-Based Condition Monitoring System*

System health monitoring plays a critical role in preventative maintenance and product quality control of modern complex engineering products. The effectiveness of management can directly impact their efficiency and cost-effectiveness. A condition monitoring system monitors the products using various classical methods of signal analysis such as spectrum or state-space analyses [49]. Maintenance decisions are then made according to the prediction of system performance.

Using time-based signals available from normal machine sensing mechanisms, a CNC machine manufacturer in Australia developed a remote condition monitoring system for plasma CNC cutting systems with the aim of servicing the customer anywhere in the world via the Internet. Figure 3 shows the network structure of the system known as ROSDAM [50]. All ROSDAM-enabled machines were configured as servers that had functionality communicating with the global master server. Information about the operation of the machines was captured through individual companies' database. The significantly improved sources of information enabled the product manufacturer to decide the best option that supported operation and maintenance of the plasma cutting machine from a distance.

In this case study, new elements were required to be developed and integrated with the product, that is, the CNC plasma cutting machine. These elements are mapped to the CEPSS model as shown in Table 1.

### *5.2. Case Study 2: Global Operation Support Services*

Complex assets are normally built from a large number of components and involving a large number of engineers and contractors. In the past, customers as plant owners usually maintain their own service department. However, the increasing complexity of the plant and operating conditions such as environmental considerations require service personnel to have a higher level of analysis and judgment capability. Rathwell and Williams [51] used Flour Daniel as the study platform and validated the use of enterprise engineering methodology for creating services that support operations of chemical plant. The study showed that significant efficiency gain could be achieved in the design and implementation of the service system through systematic enterprise modelling analysis.

In managing the design and manufacture of a chemical plant for their customer, Kamio et al. [52] established a service virtual enterprise (SVE) with several partner companies around the world providing after-sales services to a customer (Figure 4).

Each partner in Figure 4 was an independent entity that was equipped with its own unique capabilities and competencies, assuming responsibility to perform the allocated work. The SVE was designed as a "hosting service" which had a broad range of services including plant monitoring, preventive maintenance, trouble-shooting, performance simulation and evaluation, operator training, knowledge management, and risk assessment. Participants of the virtual enterprise had well-defined roles and responsibilities.

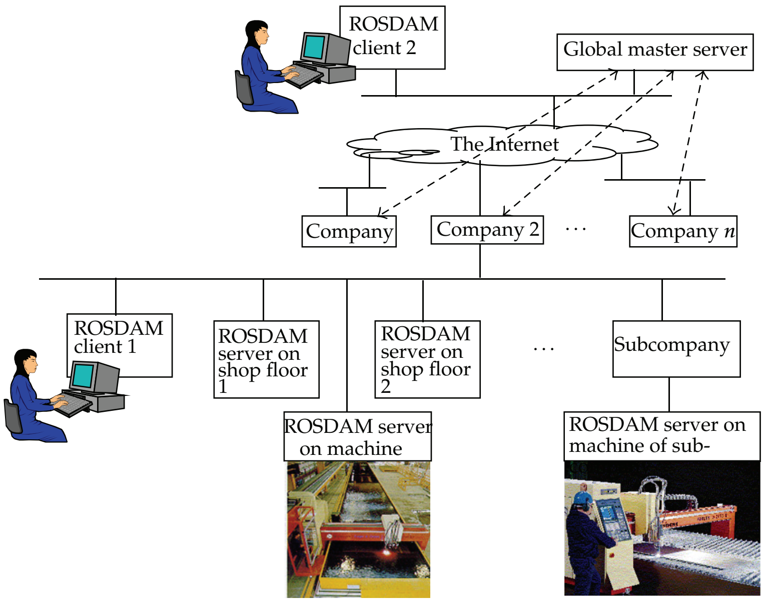


**Figure 3:** Signal-based condition monitoring service system network structure.

**Table 1:** Mapping of service elements in case 1 to CEPSS.

| Element | Description | Mapped to CEPSS |
|---|---|---|
| On machine signal-based diagnostics capability | A new diagnostics software module based on chaotic theory and digital signal processing was developed to assist identification of faults. | Product |
| Communication networks and IT systems based on client-server model | The controller of the machine was significantly changed from a normal standalone operating system to one that can act as a server in a network environment. | Product-People |
| Knowledge sharing—transform customer data to information to knowledge | New data processing algorithms were developed as software modules that were required to process data on machine to knowledge useful to enhance operational efficiency. | People |
| Engineering information integrated for supporting more effective customer service | Engineering information such as bill of material, machine configuration management, parts inventory, and resources planning were integrated from different sources including CAD, MRP, and various manufacturing sources to create seamless operation database for the machine. | Process |
| The new system design requires upgrade of field products | Field upgrade for machines that were already installed at customers' location was progressively rolled out according to contracted maintenance schedules. | Product-Environment |

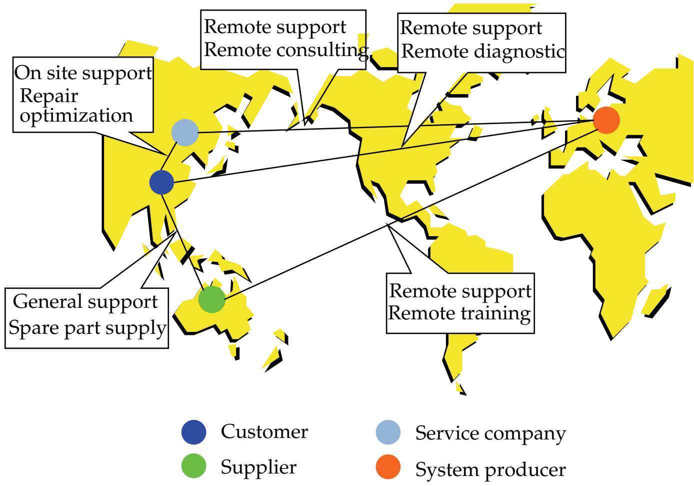


**Figure 4:** A global service virtual enterprise.

An essential element in the design of a service enterprise is to develop efficient system architecture and provide the right resources to the right service tasks. By synchronising organisational activities, sharing information and reciprocating one another's the technologies and tools, each partner in the service enterprise will be able to provide services that would have been impossible by individual effort. The PSS therefore requires properly designed components to support the use of technology in the provision of support services to customers.

In this case study, in order to operate the SVE, new service elements were developed. They are listed and mapped to CEPSS in Table 2.

It should be noted that the engineering product remained the same as it was designed initially. There was no noticeable engineering change required on the product itself in order to implement the support service offered by SVE.

### 5.3. *Case Study 3: Ship Service System*

The ANZAC Ship Alliance (ASA) could be thought of as a virtual company with shareholders comprising the Australian government and two commercial companies, one of which was the ship builder. The primary goal was to create best value for money [53]. The primary goal of ASA was to manage all changes and upgrades to the ANZAC Ships [54]. The Alliance was a "solution focused" company where the staff of the ANZAC Ship Alliance Management Office would develop change solutions but the detailed design is undertaken by the "shareholders" drawing upon their existing and substantial knowledge of the ANZAC Class.

Prior to the development of ASA, Hall [55] developed a highly integrated documentation and configuration management system that served the on-going need of ten ANZAC class frigates. Over the life time of the asset (30 years), changes due to new technologies, people and defence requirements are inevitable. The organisation structure of ASA can be described as shown in Figure 5.

In this case study, the enterprise was not set up as a legal entity. There was no formal binding agreement among the partners in ASA. In the language of virtual enterprise, the

**Table 2:** Mapping of service elements in SVE to CEPSS.

| Element | Description | Mapped to CEPSS |
|---|---|---|
| Intercompany communication networks and IT systems | New IT and communication systems were installed to enable intercompany exchange of information as well as personal interaction. | Process-People |
| Work items synchronized within the project across companies | Work items were analysed individually so that the link from individual level to group level can be streamlined ensuring minimum duplication of work and conflicts. | Process |
| Change of human organisation role | The relationship within a SVE was definitely different from a totally authoritative company structure. A much more flexible human organisation structure was established. | People |
| Global access by customer | The SVE was implemented on the Internet. At the time of the development of this PSS, the Internet was still not entirely effective in some parts of the world, and this environmental constraint imposed significant challenges on the SVE development. | Process-Environment |

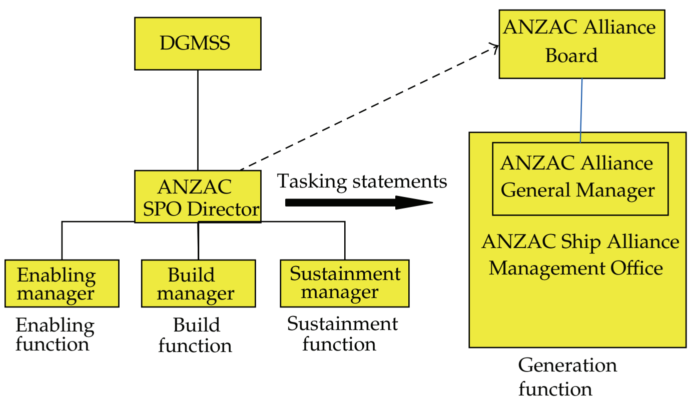


**Figure 5:** Organisation structure of ANZAC Ship Alliance.

partners were loosely linked organisations such that everything done in the ASA is based on trust. The new service elements that were developed on this premise were listed in Table 3.

From the point of view of the ship builder company, the ASA was an unprecedent business environment that no one knew exactly how to operate. There were some upgrade projects as continuous support initially. After several years of operation, the ASA entered into a new material support program focusing on supplies and shore facilities.

**Table 3:** Mapping of service elements in ASA to CEPSS.

| Element | Description | Mapped to CEPSS |
|---|---|---|
| New procedures and legal processes | All parties joined the ASA with the understanding of a set of business rules.<br>(i) All parties win or all parties lose<br>(ii) Collective responsibility, equitable sharing of risk and reward<br>(iii) All decisions based on "best for project" philosophy<br>(iv) Access to resources, skills, and expertise of all parties<br>(v) All financial transactions are fully open book<br>(vi) Encouragement of innovative thinking—outstanding outcomes<br>These nontraditional business rules imposed challenges on the ASA as the service system of the ships. | Process |
| Ownership of product-related services rested with ASA | The enterprise was a joint development of several companies and hence the ownership of the product-related services had to be resolved. This issue settled at the end but as all participants were in the defence business environment, and the customer was a partner of ASA, the "company" structure at the right hand side of Figure 5 was able to provide sufficient background understanding for the people to rely on. | Process-Product |
| Secondment of staff from the three partner organisations | As the "company" status was eventually accepted, the need to develop a set of processes that is acceptable to all staff (who were all seconded from the partner organisations) became urgent. A lot of time was spent in synchronising practices and culture originating from individual companies. There was confusion in the first year among the staff of the participating organization about the nature of ASA. This issue was resolved through a number of ASA workshops. | People-Environment |

## 6. Performance-Capability Assessment

From the foregoing case studies, the subsystems and interactions between the subsystems of the CEPSS model are represented by specific elements in the cases. Table 4 summarises the relevance of the cases in a matrix.

When a PSS enterprise is created by three interdependent subsystems under the CEPSS model, the ability of the total PSS in meeting the performance expectation of the customer will depend on how the capability of each of the subsystems is designed and the effect of the environment on the execution of these subsystem capabilities. Theoretically, for each of the subsystems in a CEPSS enterprise, it is possible to devise some measures of enterprise capability in relation to the outcomes that can be produced by the capability. These methods include survey, interviews, system audit, comparative analysis, human resources

**Table 4:** Applicability of cases to elements and interactions of CEPSS.

| | Product | People | Process |
|---|---|---|---|
| Product | Case 1 | | |
| People | Cases 1 and 2 | Cases 1, 2, 3 | |
| Process | Case 3 | Case 2 | Cases 1, 2, 3 |

records, and so forth. This type of capability assessments are bound to have certain degree of uncertainty. In addition, the enterprise capability will change over time due to changes in people, process, and product.

Likewise, by way of aggregation of subsystem capabilities, the capability of the PSS can be benchmarked against the theoretical capabilities required to achieve expected performance, an assessment of the potential achievement can be made at the outset, when the PSS enterprise is established. Due to the uncertainties as explained above, the probability of the PSS enterprise's achievement can be expressed in terms of the frequency of success of this capability meeting specified performance metrics.

Using case 1 as an example, assuming all other capabilities are able to deliver to the required performance standards, the improved service elements can be assessed using a 5-point scale of 1 to 5 where 5 represents most certain and 1 represents rarely meeting expectation as shown in Table 5.

The ratings in Table 5 are for illustration only. Since most ratings are above average, the PSS in case 1 is assessed as likely to meet customer expectation. With an assessment of the capability against expectation outcomes, the probability of the service contract being successful can then be determined from the contractual terms.

As an illustration, if the Defence Materiel Organisation four-band performance incentive/penalty scheme is used, the capability distribution can be overlaid on the achieved performance axis as shown in Figure 6. The capability distribution (in dotted curve) represents the probability density of the enterprise achieving a performance level on the $x$-axis. Different risks and probabilities of a PSS contract can then be identified as shown in Figure 6.

Several decisions can be made using this assessment outcome. For this discussion, the CEPSS contractor is the prime contractor who is a major engineering company working with the client on a new complex engineering system within the capability systems lifecycle shown in Figure 1. Using the performance-capability assessment methodology, the CEPSS contractor has visibility on what risks are likely to incur in its current proposal.

First, based on this information, the CEPSS contractor can decide whether to go ahead with the enterprise capabilities he/she has. This is a go and no-go decision scenario. The contractor will have to decide in conjunction with other concurrent opportunities, which may be assessed by the same PSS opportunity assessment methodology or other means.

Second, if the risk level is too high, the CEPSS contractor can increase his/her enterprise capabilities by raising the contract price to cover the costs, or by implementing organisational improvements such as lean and six sigma. In the latter case, the time factor of the CEPSS will be brought in to map the change of capability over time.

Third, the CEPSS contractor can identify the shortfall capability areas and collaborate with other prime suppliers in the industry. The performance capability assessment is then modified as the overall performance capability of the combined CEPSS consortium. The contractual detail of the coalition arrangement is outside the scope of this paper [56].

**Table** 5

| CEPSS | Element | Customer expectation | Assessed capability | Rating |
|---|---|---|---|---|
| Product | On machine signal-based diagnostics capability | Diagnose the causes for all (100%) of reported problems. | The new signal diagnostics capability only provides high level fault analysis. | 3 |
| Product-People | Communication networks and IT systems based on client-server model | Obtain online support information at any time. | Connection to the master server depends on the Internet | 5 |
| People | Knowledge sharing—transform customer data to information to knowledge | Receive correct advice all the time. | Fault trees based on past records sometimes contain conflicting cases | 4 |
| Process | Engineering information integrated for supporting more effective customer service | Identify suitable machine configuration and spare parts. | Support system is integrated with product design database which requires minor interface development. | 4 |
| Product-Environment | The new system design requires upgrade of field products | Upgrade as minimum cost and within reasonable time. | Establish a separate group within the company responsible for upgrade requests. | 5 |

A mapping of potential changes over time in capabilities of other parties should also be considered, as highlighted by the CEPSS model.

Fourth, the CEPSS contractor can consider boosting its core capabilities by mergers and acquisition with other companies. This case is more complicated since consideration of which companies to acquire depends on strategic alignment requirements. However, this option will represent an immediate shift of the capability distribution to the right. The only concern is whether the new organisation can be restructured and operated effectively and quickly enough for executing the PSS contract [57].

## 7. Conclusion

New business models in delivering capabilities from the operations of complex engineering products such as aircraft, ships, and refineries have favoured the integration of acquisition and sustainment phases of the products. The product service system (PSS) concept enables manufacturers of these complex engineering products to incorporate support services into the product's system capability lifecycle. These services are substantially more complex than routine, reliability-based maintenance or spare parts support. Unfortunately, in the past decade, researches in the development of support systems have been fragmented. There is no unified body of knowledge specifying the methodologies that can naturally lead to the design of a support solution for any scenario. This situation prompted this study.

The new type of service business model, which is represented by performance-based contracts, focuses on the performance of the complex engineering product during operations in terms of timeliness, availability, maintainability, and sustainability costs in the product's complete lifecycle from conception, design, manufacture to disposal. Ultimately, the service

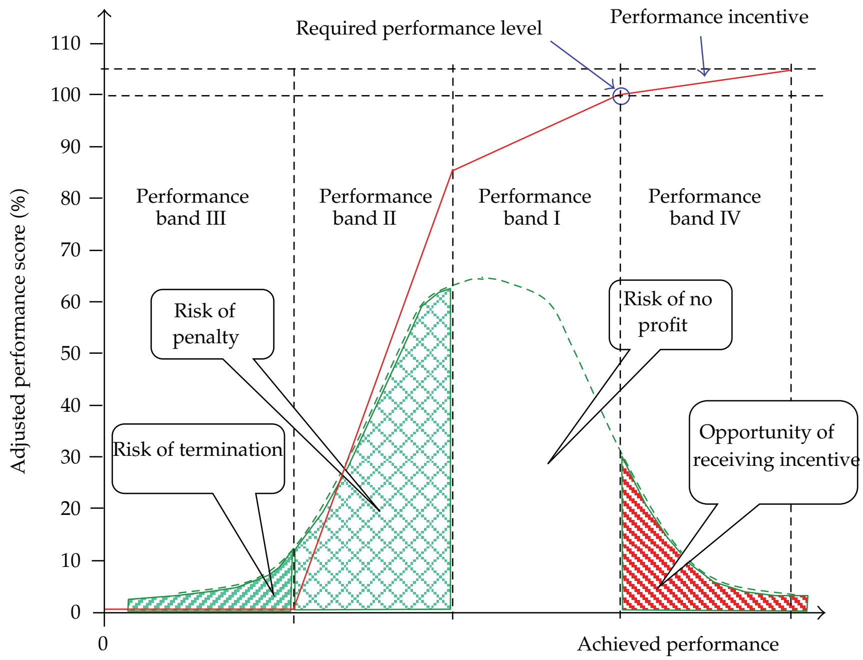


**Figure 6:** Performance band and risks in the PSS contract.

business model is expected to provide long-term benefits to both contractor and customer due to efficiency gains. However, the PSS itself has imposed significant risks to the contractor not only in the manufacture of the product, but also in the provision of support services over long period of time at a fixed reward scheme with a lot of unknowns. A successful PSS enterprise requires an analysis methodology that can assist the contractor to estimate the performance outcomes of the PSS.

In this paper, three case studies are analysed using case study research design approach to investigate a new complex engineering product service system (CEPSS). CEPSS combines the conceptual elements in the SHEL model with the systematic enterprise architecture modelling approach. Service elements of the three case studies have been mapped to CEPSS. Through this mapping, the CEPSS can be broken down into subsystems. Capabilities of the subsystems are readily assessed against customer expectation using qualitative methods such as opinion surveys. Once the capabilities are known, they can be overlaid on the performance-based incentive/penalty scheme so that different risk levels can be assessed as a decision support tool. Decision makers can then use this information to select options related to the business opportunities presented to them.

This paper is a preliminary investigation of the fundamental question: what service elements should be developed in the new PSS environment? Investigation using case study approach so far seems to show that the capability of the PSS can be assessed by an aggregated evaluation of these service elements and hence the expected performance of the service system can be estimated. However, the complexity of the system cannot be ignored. Further research is required to create a consistent scoring framework that can be applied across different risks and engineering systems. Naturally, more case studies on a broad range of engineer products would be necessary, while validating of the CEPSS using a more quantitative, evidence-based approach against these cases is vital to the development of a quantitative consistent scoring framework.

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Hindawi Publishing Corporation
Advances in Decision Sciences
Volume 2012, Article ID 873710, 15 pages
doi:10.1155/2012/873710

*Research Article*

# Evaluating Ethical Responsibility in Inverse Decision Support

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Received 5 April 2012; Accepted 16 July 2012

Academic Editor: Richard H. Weston



Decision makers have considerable autonomy on how they make decisions and what type of support they receive. This situation places the DSS analyst in a different relationship with the client than his colleagues who support regular MIS applications. This paper addresses an ethical dilemma in "Inverse Decision Support," when the analyst supports a decision maker who requires justification for a preconceived selection that does not correspond to the best option that resulted from the professional resolution of the problem. An extended application of the AHP model is proposed for evaluating the ethical responsibility in selecting a suboptimal alternative. The extended application is consistent with the Inverse Decision Theory that is used extensively in medical decision making. A survey of decision analysts is used to assess their perspective of using the proposed extended application. The results show that 80% of the respondents felt that the proposed extended application is useful in business practices. 14% of them expanded the usability of the extended application to academic teaching of the ethics theory. The extended application is considered more usable in a country with a higher Transparency International Corruption Perceptions Index (TICPI) than in a country with a lower one.

## 1. Introduction

The ethical dilemma addressed in this paper is represented by a simple case. After his graduation, the first job of a decision analyst was the head of a decision support unit in a governmental agency of a developing country. The most important task he started with was to support the top decision maker of the agency in selecting the best one among several IT companies participating in a tender of a large-scale project. Using the Analytical Hierarchy Process (AHP) of Saaty [1] and considering specialists' judgment on the relative importance of detailed selection criteria, the analyst prepared a report recommending a specific company X that had the best offer. Upon receiving the report and listening to the professional presentation given by the analyst, the decision maker commented: “it is a good work; however, you have to rewrite the report to show that company Y is the most suitable for this project.” The problem was defined by the analyst at this moment as “developing criteria for a preselected decision” or “Inverse Decision Support.”

There were two notions conflicting in the back of analyst’s mind. The first was the notion of “support, not replace decision maker” as recommended by all known DSS textbooks [2–4]. In this notion, the decision maker is the owner of the decision and the decision should reflect her/his preferences and values [5]. The second was the professional responsibility as mentioned in the ACM [6], IEEE [7], and AIS [8], Codes of Ethics and Professional Conduct. Article 2.1 of ACM’s Code says explicitly “Strive to achieve the highest quality, effectiveness, and dignity in both the process and products of professional work.” [6, page 1]. Resolving this conflict was another decision the analyst had to make.

After a couple of days, the analyst came up with a new report entitled: “The cost of selecting company Y points for negotiation.” The report explained the details of loss or gain on each selection criterion in case of selecting the suboptimal company Y rather than the optimal company X. The report also defined some points for negotiation with company Y to substitute such losses and increase gains through other services or products to be provided by the company. This report was considered a proactive type of “Inverse Decision Support.”

Decision makers, especially in developing countries, have considerable autonomy on how they make decisions and what type of support they receive. This places the DSS analyst in a different relationship with the client than their colleagues who support regular MIS. In the case of “Inverse Decision Support,” the result is fixed in advance by a decision maker, and the role of the decision analyst is to alter the “process” by which the decision is “arrived at” to fit the preconceived result.

The nature of support provided by DSSs can be characterized according to a continuum of passive through to normative support [9]. Passive decision support tends to place the emphasis more on the decision maker to control the decision process, while normative support imposes a structure and process on the decision makers regardless of their preferences or normal style of work [4, 9]. Most DSSs, however, tend to sit somewhere in the middle, offering more structured support whilst respecting the autonomy of the decision maker to control the process. Such systems are labeled by Keen and Morton [4] as “active” DSSs. Active DSSs expose both the decision maker and decision analyst to a range of ethical issues.

This paper addresses an ethical dilemma in “Inverse Decision Support”, where the analyst supports a decision maker who has a tendency toward a suboptimal alternative. An extended application of the AHP is proposed for evaluating the ethical responsibility of selecting a suboptimal alternative rather than the optimal one. The extended application is consistent with the Inverse Decision Theory (IDT) that used extensively in medical decision making [10, 11]. The validity of the extended application is checked by measuring decision analysts’ perception on its usability.

DSS includes personal support systems, group support systems, executive information systems, online analytical processing systems, data warehousing, and business intelligence applications [2, 12]. This paper focuses on personal decision support system, that is, a system designed to support an individual decision maker with a single specific decision task.

The paper consists of six sections. Section 2 reviews the available literature on the ethical issues in supporting decision making. In Sections 3 and 4, a proposed extended application of AHP for evaluating the ethical responsibility of selecting a suboptimal alternative and an illustrative example are presented. Section 5 demonstrates the measurement of decision analysts’ perception on the usability of the proposed extended application. Finally, the conclusion, contributions, and limitations are provided in Section 6.

## 2. Ethical Perspectives on Supporting Decision Making

Several cases of biased decision making are mentioned in the literature [13–16]. Bias includes the situation where the decision maker has predetermined the decision based upon her/his own prejudices [17]. In this case, the decision maker asks the decision analyst to develop justification for her/his predetermined decision rather than to help her/him reaching the optimal one. Such case is defined in this paper as “Inverse Decision Support.”

However, the ethics of decision making as a specific topic has received very little attention in comparison to the issues of privacy and other general IT ethics issues [18]. Based upon detailed statistics of the literature, Meredith and Arnott concluded that “indeed, there is a major gap in the literature on this topic” [18, page 1566].

Ferrell and Gresham [19] believe that there is no such thing as an ”ethically neutral” decision making. All decisions are based on a set of values, which are representative of an ethical viewpoint. The most commonly used moral philosophy seen in research is that of utilitarianism [20, 21]. Utilitarianism believes that a useful decision is by definition a good decision. Therefore, the determining considerations of right conduct should be the usefulness of its consequences. On the other side, we may consider the level of ethical responsibility of suboptimal selection as a function of the total losses due to this selection on all criteria.

According to the issue-contingent model provided by Jones [22], the ethical decision-making process begins with the environmental factors outside the organization such as social influences, cultural expectations, or economic conditions. These environmental factors often invoke an ethical dilemma and provide a context for making the ethical decision. The second step of the model is the recognition of a moral issue that deserves further ethical evaluation, which entitled the ”moral intensity” of the issue. Jones [22] identifies six characteristics of the issues that define moral intensity, which are the magnitude of consequences, social consensus, probability of effect, temporal immediacy, proximity, and concentration of effect. The third step is the ethical judgment based upon the cognitive moral development, moral philosophies, or the ethical value system of the individual [23–25]. Carlson et al. [26] provide an extension to Jone’s model, which considers the potential contribution of DSS within the ethical model in such a way that a decision maker’s engagement in a certain behavior is moderated by her/his use of DSS.

Johnson and Mulvey [27] address the issue of responsibility for outcomes resulting from decisions made based, in part, on advice provided by a DSS. They believe that the decision analysts should have similar responsibilities as any other professional or expert who is hired for her/his advice. That is, decision analysts should bear responsibility for the quality of the advice their DSS provide. They should also establish standards and norms for the ethical use of their systems.

Chae et al. [28] raise the issue of analyst’s responsibility to check whether or not the correct decision is being supported. They point out that ignoring the stakeholders value positions in a decision problem can lead to the wrong problem being supported.

Fox [29] addresses the ethical issue in expert systems. Expert systems have a significant level of autonomy to make decisions and undertake corresponding actions. If an ethically questionable decision is made, the moral responsibility potentially resides with the system designer.

Meredith and Arnott [18] believe that the framework for ethical medical DSS [30] is useful for DSS in general. The framework includes four bioethical principles, which are beneficence, nonmaleficence, autonomy, and justice. Beneficence means an act of commission and nonmaleficence means the omission, both aimed at ensuring that, in the medical setting, the "good" for the patient is maximized and the "bad" is minimized. Beauchamp [31] derives four directives from the first two principles, which are not to inflict evil or harm (nonmaleficence), to prevent evil or harm (beneficence), to remove evil or harm (beneficence), and to do or promote good (beneficence). The aim of DSS analysts is to support decision makers positively within the context of a decision problem. As professionals, they should avoid introducing negative factors, which exacerbate the cognitive biases of the decision maker [17]. Analysts must be aware of the full consequences of their actions in satisfying the principles of beneficence and nonmaleficence [31].

Oliver and Twery [32] believe that human nature ensures biases including biases in decision making. Since bias will always exist, it is important for both the decision maker and the analyst to understand the possible influences this bias may have on decision making. Danielson [33] presents a computational representation and evaluation of imperfect, imprecise user statements in decision analysis.

Keeney [34] goes to great lengths to make sure that an analyst gets the right objectives before starting decision analysis. He recommends that the right objectives measure what the decision maker really cares about. The case when a decision analyst discovers that a decision maker really cares about an unethical hidden criterion has not been discussed.

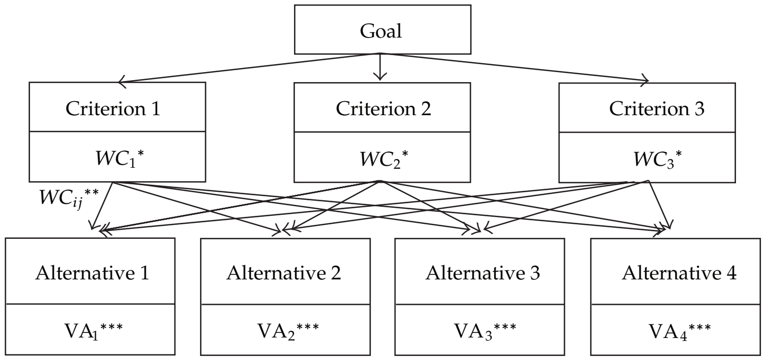
The concept of utility loss due to inefficient decision making dates back to the work of Barron [35]. Typically the concept has been used to measure the quality of the decision and not an ethical dilemma [36].

IDT is used mainly in medical decision making when there is a widely accepted treatment strategy, to determine the space of losses associated with such strategy [10]. In the IDT, a Bayesian approach is used to estimate the probabilities associated with the diagnostic tests and make inferences about the region in loss space where these medical procedures are optimal [11].

Reviewing the available literature shows the importance of considering ethical issues in supporting decision making. Supporting the selection of suboptimal alternative in decision making is considered mainly a quality issue rather than an ethical issue. Models that discuss ethical issues in supporting decision making are descriptive in nature. The magnitude of bias consequences is different for each suboptimal alternative of the same decision problem. However, measuring the magnitude of bias consequences for each suboptimal alternative has not been addressed explicitly in any of the available literature. This paper attempts to contribute to filling this gap.

## 3. A Proposed Extended Application of the AHP for Evaluating Ethical Responsibility

The AHP is a comprehensive framework designed to cope with both the rational and the irrational when decision makers make multiobjective multicriterion decisions about any number of alternatives considering both qualitative and quantitative aspects [37]. The AHP approach systematically solves complex problems by decomposing the structure of a problem




* $WC_j$, $j = 1, n$ is the local priority of criterion $j$ where $j$ from 1 to $n$.
** $W_{ij}$, $i = 1, m$, $j = 1, n$ is the local priority of alternative $i$ on criterion $j$ where $i$ from 1 to $m$.
*** $VA_i$ is the total priority of alternative $i = \sum_j W_{ij} * WC_j$, for all values of $i$.

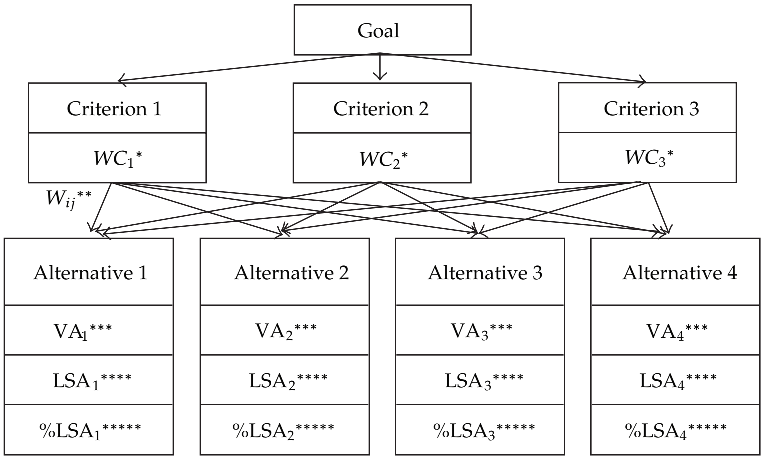
**Figure 1:** The conventional AHP decision model.

into hierarchies and the users then make pairwise comparison judgments of importance or preference to develop priorities in each hierarchy [1, 38].

The use of AHP has been extended and integrated with several other methodologies. Li and Ma [39] and Ahmad et al. [40] integrate the AHP and the data envelopment analysis (DEA) for improving the efficiency of solution. Nieto-Morote and Ruz-Vila [41] and Thomaidis et al. [42] present methodologies of embodying techniques of fuzzy sets theory into the classical multicriteria decision analysis to handle the subjectiveness that often characterizes expert judgments on a decision problem. Kabil and Kabeil [43] and Onesime et al. [44] integrate the AHP with the quality function deployment (QFD) methodology. However, these methodologies are mainly used for improving the process of decision making rather than dealing with an ethical dilemma.

The original AHP decision model is constructed in three steps [1]. The first is to structure a decision making problem in a hierarchy of goal, criterion, subcriterion (if needed), and alternative levels. The second is to pairwise compare the criteria/subcriteria for assigning their local priorities and for every criterion/subcriterion, pairwise compare the alternatives to obtain a series of local priority matrices. A ratio of relative preference is assigned to each paired comparison according to linear nine-point scale from 1 to 9 and their reciprocal, where 1 means "equally preferred pair" up to 9, which means one element of a pair is "extremely preferred" over the other element. The third step is to synthesize the comparisons by multiplying local priorities ($W_{ij}$, $i = 1$ to $m$ alternative, $j = 1$ to $n$ criterion) times the local priority of the respective criterion ($WC_j$, $j = 1$ to $n$ criterion) and the results are summed up to produce the total priority or ranking of each alternative ($VA_i$, $i = 1$ to m alternative) as depicted in Figure 1.

Then, the model selects the alternative with the highest total priority (rank) as the best or optimal alternative to the goal. Sensitivity analysis may be conducted to test the impact of any change in the local priorities on the resulted decision [45]. However, the conventional model does not directly show the local loss or gain on each criterion or subcriterion due to selecting a suboptimal alternative. Even though the value of such local loss or gain and hence




* $WC_j$, $j = 1, n$ is the local priority of criterion $j$ where $j$ from 1 to $n$.

** $W_{ij}$, $i = 1, m$, $j = 1, n$ is the local priority of alternative $i$ on criterion $j$ where $i$ from 1 to $m$.

*** $VA_i$ is the total priority of alternative $i = \sum_j W_{ij} * WC_j$, for all values of $i$.

**** LSAi is the total loss due to selecting alternative $i = \sum_1 (W_{bj} - W_{ij}) * W_{bj}$, where $W_{bj}$ is the local priority of the best alternative on criterion $j$.

*****%$LSA_i$ is the percentage of loss due to selecting alternative $i = (LSA_i / VA_b) * 100$, where $VA_b$ is the total priority of the optimal alternative.

**Figure 2:** The proposed extended application of the AHP decision model.

the magnitude of consequences on each criterion or subcriterion can vary significantly from one suboptimal alternative to another.

The proposed extended application of the model represents a mechanism for evaluating the ethical responsibility based upon calculating the local loss or gain on each criterion/subcriterion and the total losses due to selecting a suboptimal alternative rather than selecting the one with the highest total priority (optimal alternative) as depicted in Figure 2. The total losses are also calculated as percentages of the optimal alternative's total priority.

The total loss due to selecting a suboptimal alternative is calculated as the summation of the difference between the local priority of optimal alternative and local priority of suboptimal alternative on each criterion times the weight of the criterion. The percentage of loss due to selecting a suboptimal alternative is calculated as the total loss divided by the total priority of the optimal alternative times 100. In the new structure, two rows are added to alternatives level with the total loss and the percentage of loss.

As shown in the proposed extended application of AHP decision model, having a lower local priority of a suboptimal alternative does not mean that it has lower local priority on all criteria. Despite the total priority of all suboptimal alternatives are less than the total priority of the optimal one, some local priorities of suboptimal alternatives on a criterion may be larger than the local priorities of the optimal alternative on that criterion as shown in the following illustrative example for companies 1, 3, and 4 on the price criterion and company 3 on the performance criterion. In other words, the suboptimal companies 1, 3, and 4 are better than the optimal company 2 on the price criterion and the suboptimal company 3 is better than the optimal company 2 on the performance criterion. The proposed extended application is illustrated by the following numerical example.

**Table 1:** Local and total priorities of alternatives.

| | Price $WC_1 = 0.2$ | Performance $WC_2 = 0.5$ | Services $WC_3 = 0.3$ | Total priority |
|---|---|---|---|---|
| Company 1 | 0.33 | 0.19 | 0.11 | 0.194 |
| Company 2 (optimal) | [0.11] | [0.29] | [0.47] | [0.308] |
| Company 3 | 0.26 | 0.43 | 0.05 | 0.282 |
| Company 4 | 0.30 | 0.09 | 0.37 | 0.216 |

## 4. Illustrative Example

*Four Companies Participate in a Tender*

The author's assumed criteria for selecting the tender winner are price, Performance, and Services. The corresponding relative preferences of the criteria based upon pairwise comparisons are 0.2, 0.5, and 0.3. On the price criterion, the local priorities of the four companies are 0.33, 0.11, 0.26, and 0.30, respectively. In such context of preferences, a lower price will have higher priority than a higher price, so, the "Price" criterion actually means "Price Justification". On the performance criterion, the local priorities of the four companies are 0.19, 0.29, 0.43, and 0.09, respectively. On the services criterion, the local priorities of the four companies are 0.11, 0.47, 0.05, and 0.37, respectively.

So, the total priority of company 1 is calculated as 0.33 * 0.2 + 0.19 * 0.5 + 0.11 * 0.3 = 0.194. The same process is carried out for calculating the total priority of company 2 as 0.308, of company 3 as 0.282, and of company 4 as 0.216.

Table 1 represents the lower part of a hierarchy similar to the hierarchy depicted in Figure 2. As shown in Table 1, the optimal company to execute the project is the company with the highest total priority which is company 2.

In case of choosing for the project execution a suboptimal company (i) rather than the optimal company (b), which is company 2 in this example, the total losses would be assessed as

$$\sum_{j} \left(Wb_j - W_{ij}\right) * \ WC_j, j = 1 \text{ to } n \text{ criterion } \& \ i = 1 \text{ to } m \text{ alternative}, \tag{4.1}$$

where $Wb_j$ is the local priority of the optimal company $(Wb)$ on Criterion $(j)$, $W_{ij}$ is the local priority of suboptimal company $(i)$ on Criterion $(j)$, and $WC_j$ is the local priority of Criterion $(j)$. This expression gives for each company the total losses on all criteria.

So, the total loss due to selecting company 1 instead of company 2 is ($LSA_1$) = (0.11–0.33) $*$ 0.2 + (0.29–0.19) $*$ 0.5 + (0.47–0.11) $*$ 0.3 = 0.114. And, the percentage of loss due to selecting company 1 instead of company 2 is ($\%LSA_1$) = (0.114/0.308) $*$ 100 = 37.01%.

The same process is carried out for calculating the total loss and percentage of loss due to selecting company 3 instead of company 2 as 0.026 and 8.44%. It is also carried out for calculating the total loss and percentage of loss due to selecting company 4 instead of company 2 as 0.092 and 29.87%.

The extended application proposed in this paper shows the different levels of loss for suboptimal alternatives. It is clear from Tables 2 and 3, that selecting the suboptimal company 3 for the project execution is less harmful than selecting the suboptimal company 1. The level of losses which reflects the magnitude of decision consequences is a key factor

**Table 2:** Loss on each criterion due to selecting a suboptimal company.

| | Price $WC_1 = 0.2$ | Performance $WC_2 = 0.5$ | Services $WC_3 = 0.3$ | LSA | % LSA |
|---|---|---|---|---|---|
| Company 1 | −0.22* | 0.10 | 0.36 | 0.114 | 37.01% |
| Company 2 (optimal) | 0 | 0 | 0 | 0 | 0.00% |
| Company 3 | −0.15* | −0.14* | 0.42 | 0.026 | 8.44% |
| Company 4 | −0.19* | 0.20 | 0.10 | 0.092 | 29.87% |

*Negative loss means a gain on this criterion.

**Table 3:** The proposed priority-loss matrix.

| | Price $WC_1 = 0.2$ | Performance $WC_2 = 0.5$ | Services $WC_3 = 0.3$ | Total priority | LSA | % LSA |
|---|---|---|---|---|---|---|
| Company 1 | (0.33)* | 0.19 | 0.11 | 0.194 | 0.114 | 37.01% |
| Company 2 (optimal) | [0.11] | [0.29] | [0.47] | [0.308] | 0 | 0.00% |
| Company 3 | (0.26)* | (0.43)* | 0.05 | 0.282 | 0.026 | 8.44% |
| Company 4 | (0.30)* | 0.09 | 0.37 | 0.216 | 0.092 | 29.87% |

*Local priority of suboptimal alternative is higher than the local priority of the optimal alternative.

in determining the ethical responsibility of the decision maker according to Jones's model discussed in Section 2.

The proposed application of AHP decision model, illustrated above, can be used for several purposes.

(1) determining the total loss due to the selection of a suboptimal alternative rather than the optimal alternative (the one with the highest total priority);

(2) determining the local loss or gain on each criterion due to the selection of a suboptimal alternative rather than the optimal one;

(3) raising points for negotiation with the preselected suboptimal alternative to be acceptable for winning the tender; The negotiation points are based upon the local loss or gain on each criterion due to the selection of this suboptimal alternative rather than the optimal one;

(4) indicating the differences in the magnitude of consequences that determine the level of responsibility in cases of taking each one of the suboptimal decisions rather than the optimal one.

However, the practical usability of the proposed extended application is based upon the perception of decision analysts on decision support ethics. The measurement of the analyst's perception is the subject of next section.

## 5. Perception of Decision Analysts on Model Usability

The main ethical issues that affect the usability of the proposed extended application were built in a test case scenario. Each participant was asked to describe the ethical dilemmas faced in the test case from her/his moral agent's point of view [46]. Then, the proposed extended application was introduced to the test subjects and used to make further analysis on the test case. After using the extended application, the test subjects reassessed their original choices and were asked if they would change their decision. The perception of decision analysts on the usability of the proposed extended application was concluded.

### 5.1. The Test Case

Each participant of the test case was presented with the following scenario. Last year a governmental agency was having a new tender for building a national IT backbone network. Four large companies (X, Y, Z, and W) submitted different bids for the design and implementation of the system. You work for this governmental agency as a decision support analyst.

The head of agency formed a team of three decision support analysts (W, F, and R) for surveying and selecting the candidate executer of the national IT backbone network project. The team collected data from all available related sources. The team defined all relevant criteria and relative preferences of all types of users including the head of agency. After reviewing all proposals, the team arrived consensually to a conclusion that company X is the best candidate for the project. The report with findings was presented to the head of the agency.

However, the head of the agency did not accept the report and asked the team to reinvestigate the issue because he believed that company Y is the most suitable for this project. The only justification he gave was his own feelings.

All the team members agreed on the subjectivity of the head of agency but they could not reach an agreement on what their further course of action should be. Their alternatives ranged from quitting the team, to following the new decision of the head, to pursuing corrective measures.

Member W asked to withdraw from the team because he could not cooperate with a biased decision maker (as he believed) and at the same time he could not afford fighting him. Member F asked to follow the selection of the head since he was the owner of the decision and he was the responsible for the decision consequences. Member R asked for more analysis on the cost of selecting company Y rather than the company with the best offer (company X) and to pursue corrective measures.

The test subjects were asked to describe the ethical dilemma in the three different reactions of the decision analysts in the test case and choose the reaction, that is, the most close to her/him. The HARPS methodology [47] explains that the case will be perceived differently because each person approaches a situation from her/his own perspective. When a participant was asked to describe the ethical dilemma faced in the test case, in fact, she/he was asked to describe the case from the moral agent's point of view and this view changed from a participant to another [46]. Accordingly, it was expected that the usability of the proposed extended application would be perceived differently.

### 5.2. The Test Group

The test group consists of 44 decision analysts from two countries with different Transparency International Corruption Perceptions Index (TICPI) [48]. The first country has a high TICPI (6.3) and the second one has a low TICPI (3.1). According to the 2010 index, the TICPI is ranging from 9.3 (the least corrupted country) to 1.1 (the highly corrupted country), where 5.0 is the borderline distinguishing countries that do and do not have serious corruption problems.

In addition to the environment, the context of the test subjects' personality may have also an influence on the persons' moral decisions. Therefore, the participants' gender, age, education, work experience, religious doctrines, ethnic background, and whether they perceive themselves to be ethically minded or not were recorded. Thirty-five (80%) of the test subjects perceive themselves to be ethically minded.

Since the presented case was business oriented, the duration of employment was found to be a crucial factor. Those who had less than 1 year or no work experience and were unfamiliar with the business environment approached the situation differently. Subjects with more work experience were more sensitive to issues at the business environment and their solutions. They were capable of taking more factors into account than those without that degree of professional experience. The educational background of the subjects included 16 undergraduates (senior MIS students), 19 holding a Bachelor's degree (MBA students), and 9 holding a post graduate degree (MBA students). Most of the test subjects (66%) had no background in ethics theory. The other factors including gender did not indicate any or at least not any clear correlations to the decisions made. The test variables and values are listed in Table 4.

### *5.3. The Test Results*

The four responses that answered "Not Clear" on the "Case Information" question are excluded. A paired-samples $t$-test was conducted to compare the perception of ethical dilemma before and after using the tool. There was a significant difference in perception of the Ethical Dilemma before using the proposed extended application ($M = 1.65$, $SD = 0.7$) and after using it ($M = 2.28$, $SD = 0.91$), and at 95% confidence interval of the difference, the Sig. (2-tailed) value $P = 0.004$. The Pearson correlation coefficient between the analyst's perception on the usefulness of proposed extended application and the difference in perception of Ethical Dilemma is 0.63.

A paired-samples $t$-test was also conducted to compare the analyst's decision before and after using the tool. There was a significant difference in Analyst's Decision before using the proposed extended application ($M = 1.65$, $SD = 0.7$) and after using it ($M = 2.57$, $SD = 0.87$), and at 95% confidence interval of the difference, the Sig. (2-tailed) value $P = 0.000$ (less than the decimal places shown). The Pearson correlation coefficient between the analyst's perception on usefulness of proposed extended application and the difference in Analyst's Decision is 0.67.

About 80% of participated analysts considered the proposed extended application useful. After using the proposed extended application, 73% of participated analysts changed their decision and 78% of them changed their perception of the Ethical Dilemma. These results suggest that using the proposed extended application does have significant impact on changing the perception of the Ethical Dilemma and Analyst's Decision. Specifically, the results suggest that the respondents consider the proposed extended application useful.

The results also show that the responses of the test subjects were different from one environment (country) to another, which indicates that the environment has a significant impact on the ethical choices of individuals and consequently on the usability of the extended application. In the country with higher TICPI, almost 84% of the test subjects considered the proposed extended application useful and in the country with lower TICPI, only 73% of the test subjects considered the proposed extended application useful. Despite some responses consider the proposed extended application not useful, the values of their answers were positively changed by using the model.

**Table 4:** Test variables and values (44 subjects).

| SN | Variable | Variable description | Scale | Scale description | Values |
|---|---|---|---|---|---|
| 1 | Env | Ethical environment | 1 | Country with TICPI 6.3 | 26 |
| | | | 0 | Country with TICPI 3.1 | 18 |
| 2 | Gen | Gender | 1 | Male | 28 |
| | | | 0 | Female | 16 |
| 3 | Age | Age group | 1 | From 20 to <30 | 19 |
| | | | 2 | From 30 to <40 | 15 |
| | | | 3 | From 40 to 50 | 10 |
| 4 | Edu | Education level | 1 | Undergraduate student | 16 |
| | | | 2 | Bachelor degree | 19 |
| | | | 3 | Postgraduate degree | 09 |
| 5 | Exp | Work experience | 1 | Less than 1 year | 10 |
| | | | 2 | From 1 to <5 years | 20 |
| | | | 3 | From 5 to <10 years | 09 |
| | | | 4 | More than10 years | 05 |
| 6 | Rel | Perceived as religious believer | 1 | Conservative believer | 16 |
| | | | 2 | Moderate believer | 22 |
| | | | 3 | Liberal | 6 |
| 5 | Eth | Ethical background | 1 | Has ethical background | 15 |
| | | | 0 | Has no ethical background | 29 |
| 8 | EthM | Perceived as ethically minded | 1 | Perceives herself/himself as ethically minded | 35 |
| | | | 0 | Does not perceive herself/himself as ethically minded | 09 |
| 9 | DelB | Ethical dilemma before using the model | 1 | Supporting the decision maker versus replacing her/him | 23 |
| | | | 2 | Supporting only the right decisions versus supporting all decision maker's queries (truth versus loyalty) | 16 |
| | | | 3 | Defending your selection versus withdrawing from the process | 05 |
| | | | 4 | Other | 00 |
| 10 | DecB | Subject's decision before using the model | 1 | Follow the selection of the decision maker | 23 |
| | | | 2 | Withdraw from the team | 16 |
| | | | 3 | Calculate the cost of selecting suboptimal alternative and pursue corrective measures. | 05 |
| | | | 4 | Other | 00 |
| Reinvestigate the test case after using the proposed extended application | | | | | |
| 11 | DelA | Ethical dilemma after using the model | 1 | Supporting the decision maker versus replacing her/him | 13 |
| | | | 2 | Supporting only the right decisions versus supporting all decision maker's queries (truth versus loyalty) | 14 |
| | | | 3 | Defending your selection versus withdrawing from the process | 14 |
| | | | 4 | Others: local versus global optimization | 03 |

**Table 4:** Continued.

| SN | Variable | Variable description | Scale | Scale description | Values |
|---|---|---|---|---|---|
| 12 | DecA | Subject's decision after using the model | 1 | Follow the selection of the decision maker | 11 |
| | | | 2 | Withdraw from the team | 06 |
| | | | 3 | Calculate the cost of selecting suboptimal alternative and pursue corrective measures | 24 |
| | | | 4 | Others: contacting a higher authority, contacting public media, and negotiating with company Y to improve its bid. | 03 |
| 13 | Mod | Model usefulness | 1 | Useful | 32 |
| | | | 0 | Not useful | 12 |
| | | | — | Cannot evaluate it | 00 |
| 14 | Case | Case information | 1 | Clear | 40 |
| | | | 0 | Not Clear | 04 |

Interestingly, the subjects who perceived themselves not ethically minded had the same attitude toward the proposed extended application in both countries. The same portion (almost 75%) of this category considered the proposed extended application not useful, which implies that the environment has no significant impact on subjects who perceived themselves not ethically minded.

When asked to frame the problem, 56% of the test subjects identified "supporting the decision maker versus replacing her/him" as the ethical problem. A smaller part of the test subjects (40%) framed the problem as "Truth versus Loyalty" with solutions that ranged from following the decision maker to withdrawing from the system. The majority of the test subjects (91%) pointed out that the test case presented enough information to be framed correctly. However, some of them (20%) considered the proposed extended application not useful.

More than half of the participants started with a decision to follow the selection of the decision maker (57.5%). One of the interesting comments of test subjects was that "the experience and intuition of the head of the agency may allow her/him to make a better decision than the decision of the analyst which was based purely on the analysis of quantitative indicators." However, almost half of them changed their decision after using the extended application. This portion of the test population is viewed as those who have gained a positive outcome from using the proposed extended application. The subjects who changed their decision after using the extended application could be divided into two groups. The first one (86%) changed their decision to calculate the cost of selecting suboptimal alternative on each criterion and pursue corrective measures. The second group (14%) changed their decision to other decisions such as contacting the higher authority, contacting public media, and negotiating with Company Y to improve its bid.

In general, 80% of the participants considered the proposed extended application useful in business practices. Moreover, the extended application could be used in academic teaching. Some of the comments on the usefulness of the extended application suggested using it in academic teaching of the Ethics Theory.

## 6. Conclusion

The paper addresses an ethical dilemma in "Inverse Decision Support," when the analyst supports a decision maker who requires justification for a preconceived selection that does not correspond to the best option resulted from the professional resolution of the problem. An extended application of the AHP model is proposed for evaluating the ethical responsibility in selecting a suboptimal alternative. A survey of decision analysts is used to assess their perspective of using the proposed extended application.

According to the results, 80% of the participants considered the proposed extended application useful in business practices. Some participants expanded the usability of the extended application to academic teaching of ethics theory. The extended application was considered more usable in a country with a higher TICPI than a country with a lower one.

There are three contributions in this paper. First, the notion of "Inverse Decision Support" is addressed as a new concept of dealing with detailed consequences and negotiation options of predetermined decisions. Second, the paper proposes an extended application of the AHP that enables the analyst to calculate the utility losses due to selecting a suboptimal alternative rather than the optimal one and the associated local loss or gain on each criterion. The third contribution is the measuring of decision analysts' perception on the usability of the proposed extended application in determining the ethical responsibility of suboptimal selection.

The main limitations of the paper are the narrow scope of both the extended application usability and perception measurement. The proposed extended application is limited to active decision support with focusing on single decision maker. It needs more study on sharing ethical responsibility of suboptimal selection among members of group decision making. The sample used for measuring decision analysts' perception on the proposed extended application is small and limited to only two environments with different levels of TICPI.

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Hindawi Publishing Corporation
Advances in Decision Sciences
Volume 2012, Article ID 128346, 17 pages
doi:10.1155/2012/128346

*Research Article*

# Multiobjective Optimization of Aircraft Maintenance in Thailand Using Goal Programming: A Decision-Support Model

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Received 3 April 2012; Revised 6 June 2012; Accepted 15 July 2012

Academic Editor: Richard H. Weston



The purpose of this paper is to develop the multiobjective optimization model in order to evaluate suppliers for aircraft maintenance tasks, using goal programming. The authors have developed a two-step process. The model will firstly be used as a decision-support tool for managing demand, by using aircraft and flight schedules to evaluate and generate aircraft-maintenance requirements, including spare-part lists. Secondly, they develop a multiobjective optimization model by minimizing cost, minimizing lead time, and maximizing the quality under various constraints in the model. Finally, the model is implemented in the actual airline's case.

## 1. Introduction

With severe competition and under the current global uncertainty, airlines have to generate new strategies in order to enhance their competitive advantages in the current marketplace [1–4]. Currently, an individual airline mainly focuses on its existing business function, while impacts from supply chain efficiency have been neglected. Consequently, the aviation supply chain management is not well understood and effectively implemented like other industries for example, automobiles, electronics, and so forth [5]. Thus, the effective management of the aviation supply chain must be considered [6]. Major findings show that there is information about new trends in the aviation supply chain that correlate with existing problems [7]. The supply chain in aircraft maintenance includes the flow of materials or services from many suppliers through airline maintenance [8]. The airline must fulfill air travelling demand as committed to in their flight schedule.

The supply chain in Thai Aviation starts from the aircraft owner requesting services to commercial maintenance centers or internal maintenance department. The maintenance manager buys the materials or outsources services from overseas suppliers. There are more than 1,000 aircraft in Thailand, which are operated by commercial airlines, government, commercial flying training schools, and private owners [9].

Government agencies fly their aircraft under a self-quality assurance system with support from manufacturers. The Royal Thai Air Force, Royal Thai Navy, Royal Thai Army, Ministry of Agriculture, and the Ministry of Natural Resources are operating aircraft fleets under different maintenance systems. They usually buy spare parts overseas. Most of them believe that aircraft parts which are manufactured or repaired by the OEM (original equipment manufacturer) are top-quality products, Federal Aviation Administration (FAA) or European Aviation Safety Agency (EASA) is the second-class quality aircraft parts. These government agencies prefer the OEM's parts. However, prices and lead times are other trade-off issues in decision-making. They frequently find long lead time problems in purchasing and repairing. Sometimes, the repair in the US has an 18-month lead time. The operator must cannibalize aircraft parts from other unserviceable aircraft. This uses double manpower and is risky for unexpected malfunctions during removing. Moreover, some aircraft must stop flying and wait for the spare parts. This problem results in cancelling some government missions.

On the other hand, commercial airlines and commercial flying training schools are operating in Thailand under the Department of Civil Aviation (DCA) regulations [10]. They prefer the lowest costs with minimum quality required by DCA regulation. The lead time is also an important factor for the airline, especially the highly utilized airline such as Thai Air Asia. They lose a lot of income for each day of unserviceable aircraft. Moreover, they have other extra expenses for example, parking fees, recovering costs, and so forth.

The privately owned aircraft in Thailand are operated under DCA regulations. They mostly fly for leisure and seek the cheapest aircraft maintenance cost. Since they are not in a hurry to fly, they can wait for a long lead time purchase in return of lower material price.

The supply chain of aircraft operators in Thailand is different than airlines in the USA. In the USA, several suppliers and repair shops are located near airlines. Buying and repairing lead time is shorter and also costs are lower. The procurement lead time in Thailand is longer. Also, manpower costs in Thailand are lower.

This paper reviews important factors which impact aircraft maintenance performance. Later, this research formulates the multioptimization model to minimize cost and lead time, and maximize quality of aircraft maintenance, which benefits aircraft maintenance managers in making decisions for material procurement. Moreover, this research presents the actual airline case in Thailand and outlines the empirical results of the method.

## 2. Literature Review

There are several studies in performance measurement methods in the aviation supply chain [8, 11]. Most of them used a single factor to measure their systems. However, in a practical environment, the system composes several important factors, which relate to an enterprise's success. The authors specify key factors in aircraft maintenance to be cost, time, quality, reliability, maintainability, availability, and flexibility or replace ability.

### *2.1. Cost*

The cost is the primary factor of firms, especially in a highly competitive industry. Researchers mention unsatisfactory global sourcing costs [12]. Airline operations directly affect the costs of the products or services and their purchase price. These costs are generated directly or indirectly from the supply chain. Consequently, higher costs and prices decrease airline competitiveness [13]. Choy et al. studied the costs of aircraft parts and developed a performance measurement system to monitor the effectiveness of the logistics flow in handling various components for rework, maintenance or replacement, and benchmark with the best-in-class practice [8].

However, the process analysis or cost-reduction strategy provides insights into the inefficiencies which exist within current processes and place more emphasis on demand pull-type processes which require forecasting operational schedules [14].

Nevertheless, aircraft fuel is the most important issue to airlines cash flow. It is the highest operating cost portion (26.5%) of the total cost [3]. Airlines separately manage fuel cost and maintenance. Aircraft climb technique results in a 5 per cent fuel saving [15]. Thai Airways International tries to manage high fuel price risk by hedging, but they are not successful [16]. Other airlines in Thailand face a fuel crisis and share the risk with passengers under a fuel surcharge.

### *2.2. Times*

Time refers to maintenance time and material procurement lead time. Maintenance time is the job-processing time since the service was requested by a customer up to completely fulfilling that requirement [11, 17]. Procurement lead time begins from an order issued until the part's arrival at the promised location [18]. Lead times include transport time, custom clearance time, and other unexpected delays. Moreover, the supplier relationship possibly affects procurement lead time [19].

Chen studied the minimization of completion time, subject to maintenance and the proposed integer linear programming model [20]. This model only applies to jobs performed in a serial fashion, but in aircraft maintenance, practical operations are continuously performed in both parallel and serial fashions.

### *2.3. Quality*

Aircraft parts must be manufactured by factories, which are officially approved by the civil aviation organization of the state. Also, inspection, repair, altering, or overhauls of aircraft parts must performed by an approved factory [21]. The worldwide-accredited auditors are the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA). The Department of Civil Aviation (DCA) of Thailand is also an approved auditor for repairing factories, which are located in Thailand [22]. On the other hand, the quality of aircraft maintenance is related to approval organization. Airlines trust FAA/EASA-certified repair stations as top quality and DCA-certified repair station as lower quality. However, both FAA/EASA and DCA are acceptable as explained in ICAO annex 6 [23].

### *2.4. Reliability*

Langford explained the meaning of reliability as "*the probability that a system will perform its intended function for a specified interval under stated conditions*" [11] and expressed as an equation as follows:

$$R_t = e^{-\lambda t}, \tag{$i$}$$

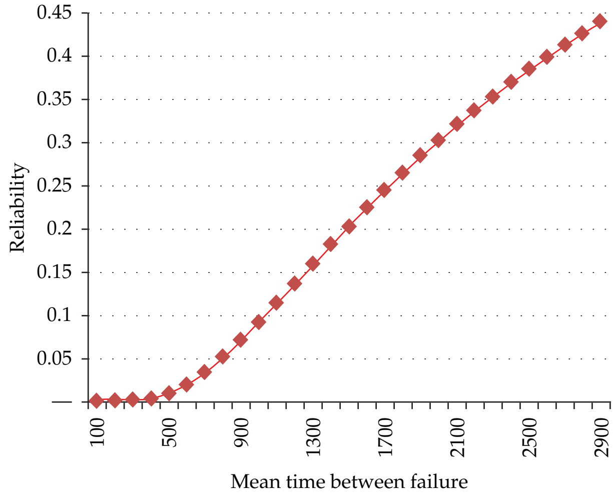


**Figure 1:** The relationship between MTBF and reliability [11].

where $R_t$ = probability that the system will successfully preform as required over the interval of time $t$. $\lambda$ (failure rate) = 1/mean time between failures (MTBF), $t$ = specified operation interval. $e = 2.7182818$.

Figure 1, the longer mean time between failures (MTBF) results in higher reliability. In order to increase aircraft reliability, maintenance managers must reduce aircraft downtime due to maintenance, which is related to aircraft-part-procurement lead time and repairing time [11].

The failure rate dictates the frequency of unscheduled corrective maintenance (or repair) of a system affected by random malfunction. Low reliability indicates frequent failures, which trigger more frequent corrective maintenance. Consequently, the reliability can be improved by enhancing maintenance support in forms of facilities, skilled technicians, tools, and supporting stocks of spare components, and repair parts [24]. Increased system reliability based on high-quality components can greatly extend the intervals of operation between failures and eliminate or minimize corrective maintenance support requirements [25].

### *2.5. Maintainability*

The maintainability measures ability of a system to be restored to a specified level of operational readiness within defined intervals with the use of the aforementioned facility, and equipment resources [11, 26]. The maintainability, (ii), is related to scheduled and unscheduled maintenance. The minimization of related factors (time, procurement lead time, corrective/preventive time) results in maximization of maintainability.

$$\overline{M} = \frac{\lambda \cdot \overline{M}_{\text{ct}} + f_{\text{pt}} \cdot \overline{M}_{\text{pt}}}{\lambda + f_{\text{pt}}}, \tag{ii}$$

where $\overline{M}$ = mean active maintenance time, $\lambda$ = corrective maintenance frequency, $\overline{M}_{ct}$ = mean time between corrective maintenance, $f_{pt}$ = schedule maintenance frequency, and $\overline{M}_{pt}$ = mean preventive maintenance time.

*Maintainability* refers to ease and speed at which any maintenance activity can be carried out on any equipment. Maintenance can be measured by mean time to repair (MTTR) [27]. It is a function of equipment design, and maintenance task design including use of appropriate tools, jigs, work platforms, and so forth [28]. Once a piece of equipment has failed, it must be possible to get it back into an operating condition as soon as possible [11].

### *2.6. Availability*

*Availability* measures the readiness of a system to fulfill its assigned function [29]. Airlines try to obtain high utilization to maximize their income. The aircraft must be available before next scheduled flight; otherwise, the flight delay may be costly [30]. Maintenance managers must predict unforeseen troubles and preplan materials, skilled technicians, and facilities [31]. They seek possible solutions for minimizing aircraft-maintenance times which results in maximized availability [32]. Thus, aircraft availability relates to flight hours per period. Higher flight hours (lower ground time) results in higher availability.

### *2.7. Flexibility/Replace Ability*

Operation managers frequently experience problems of material shortage or malfunction of equipment. Flexibility is an ability of production plant or service provider by which he switches the planned operation to another process or solution to meet the customer expectation [33].

Supply chain flexibility is an ability to reconfigure the supply chain and alter the supply of product in line with customer demand [34]. It is composed of two dimensions: (1) resource flexibility refers to a resource that can be applied to a range of alternative uses with low costs and low difficulties are associated with the switching from one resource to another as well as a short time is required for the switch [35], (2) coordination flexibility is a flexibility of process that redefines product strategies in reconfiguring the chain of resources to produce the product, and re-deploy those resources needed to produce the product [36, 37].

In this research, the three factors of aircraft maintenance cost, aircraft downtime, and quality are considered, since the reliability, maintainability, and availability relate to aircraft downtimes in an adverse direction. On the other hand, flexibility, and replace ability relate to the choice of alteration, material sources, or outsource maintenance centers. In the next section, the authors formulate an optimization aircraft maintenance model by using these three factors.

## 3. Multiobjective Optimization Model

In order to formulate the model, an aircraft supply chain is first explained. The supply chain of an aircraft can be illustrated as Figure 2. The suppliers deliver materials or maintenance services to an airline. Later, the airline delivers services to passengers, tour agencies, and

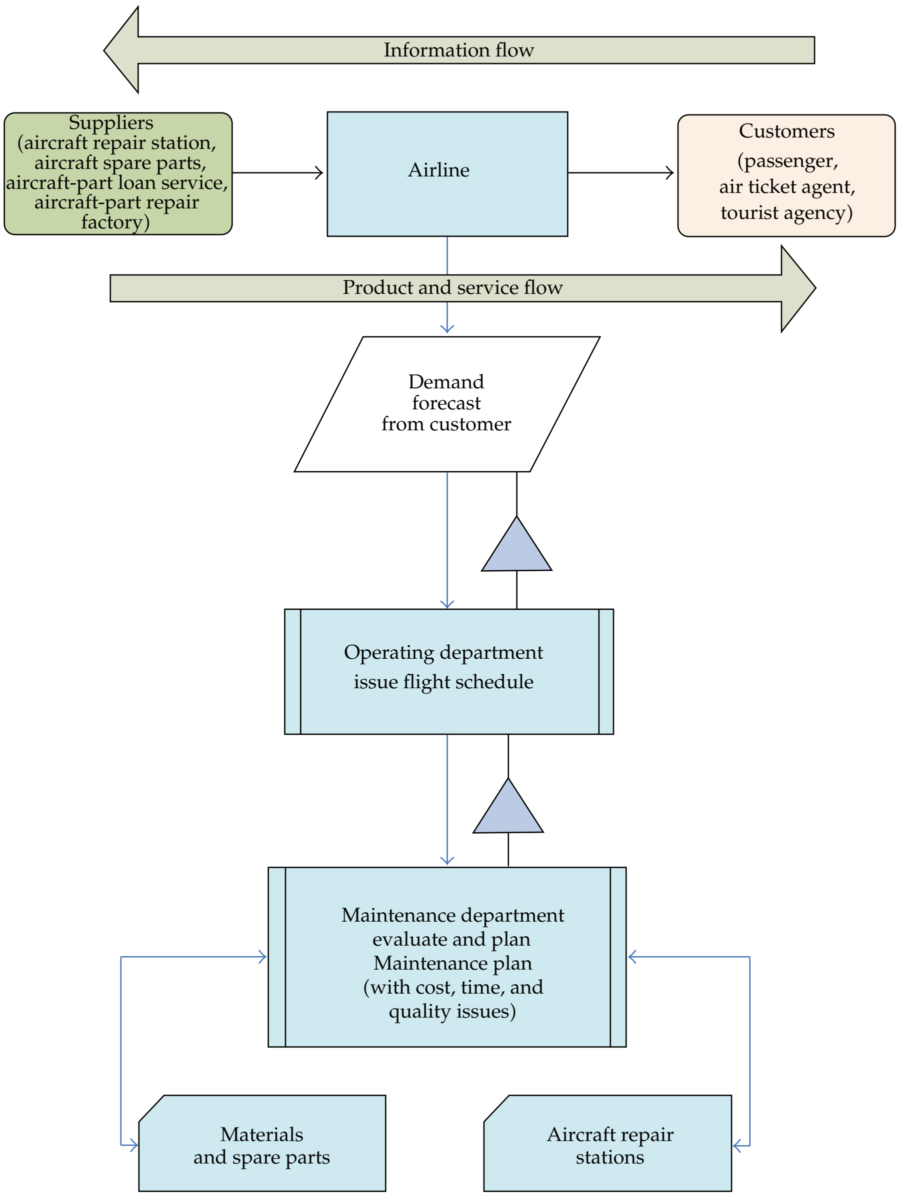


**Figure 2:** Supply chain of airline with maintenance support.

air cargo agencies with a promised quantity and specified time. The airline must prepare its aircraft with effective and efficient maintenance [38]. Back office has to plan future maintenances, which conform to a flight plan. The manager must make a decision whether to insource or outsource maintenance services as well as material suppliers in advance.

These activities need powerful and impacting decision tools for aircraft maintenance and relevant supply chain. The planner has to survey aircraft flying requirements and

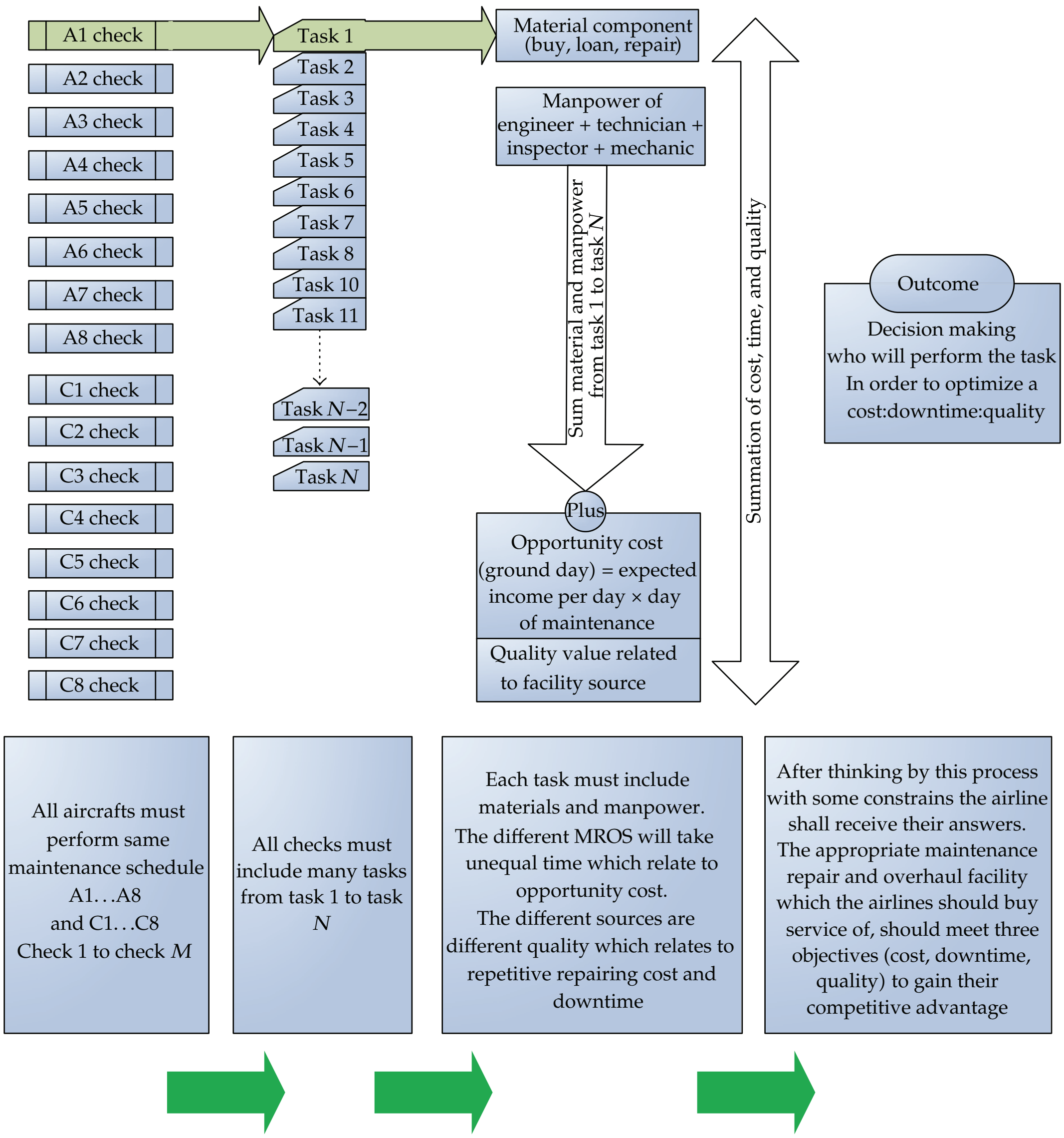


**Figure 3:** Aircraft maintenance planning process.

transform them to a flight plan, which indicates exactly the aircraft registration number and flight schedule. Then, the planner reviews the aircraft maintenance planning data along with the aircraft use. The results provide the maintenance scope of works and an individual maintenance schedule.

The next process is the resource preparation for future inspection. There are different types of inspection for example, A-check (aircraft inspection 600 flight hours interval) and C-Check (aircraft inspection 6000 flight hours interval). The aircraft maintenance plan can be depicted in Figure 3.

The quality of aircraft parts must be high realized, which conform to an aviation organization's certificate. In this research, quality is classified as follows:

(i) the value of OEM (original equipment manufacturer) equals 4;

(ii) FAA (Federal Aviation Administration) or EASA (European Aviation Safety Agency) equals 3;

(iii) Thai DCA (Department of Civil Aviation) equals 2;

(iv) other state aviation organizations approval equal 1;

(v) the Bogus part (no accepted document) or cannibalized part equal 0.

The Airlines should accept at least Thai DCA approval quality.

The mathematical model is formulated for maintenance planning decision support in preparation of the material sources. Figure 3 illustrates an Aircraft Maintenance Planning Document (APMD) issued by an aircraft manufacturer. The manual declares inspection, service, and repair procedures in several intervals related to flight hours. The airline must perform A-check every 600 flight hours and C-Check in every 6,000 flight hours (the different aircraft models may have different intervals). Each check includes several task cards, which indicate manpower, tools, materials, and procedures. The maintenance manager must prepare internal capability economically. The airline hires external services for any checks that are cheaper than investing their own capability. The aircraft material procurement process is separated from man powers and tools. The manager surveys material suppliers and approves them. The aircraft part procurement criteria are prices, lead time, and quality. The mathematical model of multiobjective optimization can be formulated as follows:

*Indices*

$i \in \{1, \ldots, I\}$,

$I$ = Number of jobs (A-check, C-Check),

$j \in \{1, \ldots, J\}$,

$J$ = Number of tasks (inspection task card or service task card).

The index $i$ represents the $i$th job. There are $I$ jobs such as A1-check, A2-check, and so forth. On each job, there are $J$ tasks. The index $j$ represents the $j$th task.

*Decision Variables*

$$X_{ij} = \begin{cases} 1 & \text{if a manager chooses to buy the material for check } i, \text{ job task } j \\ 0 & \text{otherwise} \end{cases}$$
$$Y_{ij} = \begin{cases} 1 & \text{if a manager chooses to loan the material for check } i, \text{ job task } j \\ 0 & \text{otherwise} \end{cases}$$
$$Z_{ij} = \begin{cases} 1 & \text{if a manager chooses to repair the material for check } i, \text{ job task } j \\ 0 & \text{otherwise.} \end{cases} \tag{3.1}$$

There are three binary decision variables which are valued 0 and 1. The $X_{ij}$ represent a decision of buying the material. It equals "1" when the manager chooses buy and "0" otherwise. The $Y_{ij}$ represents a decision of loaning the material. It equals "1" when the manager chooses loan and "0" otherwise. The $Z_{ij}$ represents a decision of repairing the material. It equals "1" when the manager chooses repair and "0" otherwise.

*Parameters*

$a_{ij}$ = material selling price (United State dollars),
$b_{ij}$ = material loan price (United State dollars),
$c_{ij}$ = material repair price (United State dollars),
$d_{ij}$ = lead time of buying material (days),
$e_{ij}$ = lead time of loaning material (days),
$f_{ij}$ = lead time of repairing material (days),
$p_{ij}$ = quality value of buying material (0, 1, 2, 3, and 4),
$q_{ij}$ = quality value of loaning material (0, 1, 2, 3, and 4),
$r_{ij}$ = quality value of repairing material (0, 1, 2, 3, and 4).

The $a_{ij}$, $b_{ij}$, and $c_{ij}$ represent a sell price, loan price, and repair price of material respectively. The $d_{ij}$, $e_{ij}$, and $f_{ij}$ represent a lead time of buying material, a lead time of loan material, and a lead time of repairing material consecutively. The $p_{ij}$, $q_{ij}$, and $r_{ij}$ represent a quality value of buying material, a quality value of loan material, and quality value of repairing material. The values of material's qualities are scored by referring to the certificate of approval of the factory issued by an aviation organization as follows: (1) the Bogus part (no certificate) = 0; (2) the other state aviation organization approval = 1; (3) the Thai DCA = 2, FAA or EASA = 3; the OEM = 4).

*Objective Function*

$$\text{Minimize } z_1 = \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}X_{ij} + b_{ij}Y_{ij} + c_{ij}Z_{ij}. \tag{3.2}$$

Equation (3.2) is objective function 1: minimize total cost

$$\text{Minimize } z_2 = \sum_{i=1}^{m}\sum_{j=1}^{n} d_{ij}X_{ij} + e_{ij}Y_{ij} + f_{ij}Z_{ij}. \tag{3.3}$$

Equation (3.3) is objective function 2: minimize total lead time

$$\text{Maximize } z_3 = \sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}X_{ij} + q_{ij}Y_{ij} + r_{ij}Z_{ij}. \tag{3.4}$$

Equation (3.4) is objective function 3: maximize total quality.

*Constraints*

$$X_{ij} + Y_{ij} + Z_{ij} \geq 1 \tag{3.5}$$

$$Y_{ij} - Z_{ij} \leq 0 \quad \forall(i,j), \tag{3.6}$$

$$c_{ij} \cdot Z_{ij} \leq 0.85X_{ij} \quad \forall(i,j), \tag{3.7}$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}X_{ij} \geq \sum_{i=1}^{m}\sum_{j=1}^{n} q_{ij}Y_{ij}, \tag{3.8}$$

$$d_{ij}X_{ij} - 30 \leq e_{ij}Y_{ij} + f_{ij}Z_{ij} \quad \forall(i,j), \tag{3.9}$$

$$X_{ij} \in \{0,1\} \quad \forall(i,j), \tag{3.10}$$

$$Y_{ij} \in \{0,1\} \quad \forall(i,j), \tag{3.11}$$

$$Z_{ij} \in \{0,1\} \quad \forall(i,j), \tag{3.12}$$

$$a_{ij}, b_{ij}, c_{ij}, d_{ij}, e_{ij}, f_{ij}, p_{ij}, q_{ij}, r_{ij} \geq 0 \quad \forall(i,j). \tag{3.13}$$

Constraint (3.5) ensures that each task card chooses at least one choice. If the system chooses loan, it must choose a repair (constraint (3.6)). In normal repair, repair price of the item should not higher 85% of current buying price. If it is higher than 85%, maintenance manager mostly chooses buying (constraint (3.7)). Technically, the quality of purchasing items should be higher than repairing in overall (constraint (3.8)). Flexible and replaceable channels of material sources are loan and repair but it should receive spare parts at least thirty days faster (constraint (3.9)). Decision variables are binary (Constraints (3.10)–(3.12)). Constraint (3.13) ensures that parameters are not negative.

## 4. Solution Algorithm

In this research, goal programming is used to solve multiobjective optimization. The problem will be solved by generating decision variables as follows:

*Decision Variables*

$d_1^-$ = underachievement deviation from the minimum total cost,
$d_1^+$ = overachievement deviation from the minimum total cost,
$d_2^-$ = underachievement deviation from the minimum total lead time,
$d_1^+$ = overachievement deviation from the minimum total lead time,
$d_3^-$ = underachievement deviation from the minimum total quality,
$d_3^+$ = overachievement deviation from the minimum total quality.

There are six decision variables which are: (1) an underachievement deviation from the minimum total cost; (2) an overachievement deviation from the minimum total cost; (3) an underachievement deviation from the minimum total lead time; (4) an overachievement deviation from the minimum total lead time; (5) an underachievement deviation from the minimum total quality; (6) an overachievement deviation from the minimum total quality.

*Variables*

TC = total cost of a single minimized object 1

TLT = total lead time of a single minimized object 2

TQ = total quality of a single maximized object 3

$$\text{Minimize } z_1 = \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}X_{ij} + b_{ij}Y_{ij} + c_{ij}Z_{ij}. \tag{4.1}$$

The equation (4.1) is a single-objective optimization from a previous problem. After solving (4.1) using the X-press program of cost optimization, total cost is 58,418,000 US dollars.

$$\text{Minimize } z_2 = \sum_{i=1}^{m}\sum_{j=1}^{n} d_{ij}X_{ij} + e_{ij}Y_{ij} + f_{ij}Z_{ij}. \tag{4.2}$$

The equation (4.2) is a single-objective optimization from a previous problem. Solving (4.2) using the X-press program of time optimization, total lead time is 151,000 days.

$$\text{Maximize } z_3 = \sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}X_{ij} + q_{ij}Y_{ij} + r_{ij}Z_{ij}. \tag{4.3}$$

The equation (4.3) is a single-objective optimization from a previous problem. Solving (4.3) using the X-press program of quality optimization, the total quality is 57,670 points.

This problem can be formulated as a linear goal programming model. The new objective function minimizes the sum of undesirable deviations. In goal programming, a specific numeric goal is established for each goal function (constraint), and then a solution is derived that minimizes the weighted sum of deviations of these goal functions from their respective goals.

*Objective Function*

$$\text{Minimize Q} = d_1^+ + d_2^+ + d_3^-, \tag{4.4}$$

where, $d_1^+$, $d_2^+$, and $d_3^-$ are the overachievement and underachievement deviations from the goals.

*Constraints*

$$\begin{gathered}
\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}X_{ij} + b_{ij}Y_{ij} + c_{ij}Z_{ij} + d_1^- - d_1^+ \le \text{TC}, \\
\sum_{i=1}^{m}\sum_{j=1}^{n} d_{ij}X_{ij} + e_{ij}Y_{ij} + f_{ij}Z_{ij} + d_2^- - d_2^+ \le \text{TLT}, \\
\sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}X_{ij} + q_{ij}Y_{ij} + r_{ij}Z_{ij} + d_3^- - d_3^+ = \text{TQ}, \\
Y_{ij} - Z_{ij} \le 0 \quad \forall (i,j), \\
c_{ij} \times Z_{ij} \le 0.85 \times X_{ij} \quad \forall (i,j), \\
\sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}X_{ij} \ge \sum_{i=1}^{m}\sum_{j=1}^{n} q_{ij}Y_{ij}, \\
d_{ij}X_{ij} - 30 \le e_{ij}Y_{ij} + f_{ij}Z_{ij} \quad \forall (i,j), \\
X_{ij} \in \{0,1\} \quad \forall (i,j), \\
Y_{ij} \in \{0,1\} \quad \forall (i,j), \\
Z_{ij} \in \{0,1\} \quad \forall (i,j), \\
a_{ij}, b_{ij}, c_{ij}, d_{ij}, e_{ij}, f_{ij}, p_{ij}, q_{ij}, r_{ij} \ge 0 \quad \forall (i,j), \\
d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+ \ge 0.
\end{gathered} \tag{4.5}$$

## 5. Case Study

The AAA airline in Thailand flies from Bangkok to Chiang Mai, Phuket, Udon Thani, and other airports, which are two-hour flights. The AAA airline maintenance manager plans five years' maintenance of 15 aircraft with 10,000 spare-part requirements. He must indicate the upcoming aircraft scheduled maintenance with service centers and suppliers. The mathematical algorithms are used in AAA airline's case. The different lead time deviations and different quality deviations are used on each solving. The results are cost deviations. Each solution is shown in each row of Tables 1, 2, and 3.

The minimum-cost solutions do not meet the minimum lead time and the maximum quality. Then, the authors apply +154,500 deviations to the total time and −25,000 deviations to quality. Therefore, the solution is 107,810 higher costs as shown in Table 1 Row 1. The first solutions are 58,525,810 total material costs, 154,500 total waiting days, and 32,671 total quality points. For the second row, the total lead time is changed to +3,400 deviate days and −25,000 deviate qualities. The result is a higher total cost than row 1′s solution. The testing changes several lead time deviations. This table illustrates fifteen different parameter sets which result in different cost deviations. Then, it is concluded that the shorter lead time produces higher cost at the same quality level.

**Table 1:** Quality average = 2.83 ($d_3^- \le 25000$).

| $d_1^-$ | $d_1^+$ | $d_2^-$ | $d_2^+$ | $d_3^-$ | $d_3^+$ | TT cost | TT LT | TT Q | Qavg |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 107,810.00 | 0 | 3500 | 24999 | 0 | 58,525,810 | 154,500 | 32,671 | 2.83 |
| 0 | 120,810.00 | 0 | 3400 | 24999 | 0 | 58,538,810 | 154,400 | 32,671 | 2.83 |
| 0 | 134,950.00 | 0 | 3300 | 24999 | 0 | 58,552,950 | 154,300 | 32,671 | 2.83 |
| 0 | 149,950.00 | 0 | 3200 | 24999 | 0 | 58,567,950 | 154,200 | 32,671 | 2.83 |
| 0 | 164,950.00 | 0 | 3100 | 24999 | 0 | 58,582,950 | 154,100 | 32,671 | 2.83 |
| 0 | 179,950.00 | 0 | 3000 | 24999 | 0 | 58,597,950 | 154,000 | 32,671 | 2.83 |
| 0 | 200,005.00 | 0 | 2900 | 24999 | 0 | 58,618,005 | 153,900 | 32,671 | 2.83 |
| 0 | 246,505.00 | 0 | 2800 | 24999 | 0 | 58,664,505 | 153,800 | 32,671 | 2.83 |
| 0 | 293,860.00 | 0 | 2700 | 24999 | 0 | 58,711,860 | 153,700 | 32,671 | 2.83 |
| 0 | 341,860.00 | 0 | 2600 | 24999 | 0 | 58,759,860 | 153,600 | 32,671 | 2.83 |
| 0 | 389,860.00 | 0 | 2500 | 24999 | 0 | 58,807,860 | 153,500 | 32,671 | 2.83 |
| 0 | 437,860.00 | 0 | 2400 | 24999 | 0 | 58,855,860 | 153,400 | 32,671 | 2.83 |
| 0 | 626,520.00 | 0 | 2300 | 24999 | 0 | 59,044,520 | 153,300 | 32,670 | 2.82 |
| 0 | 950,520.00 | 0 | 2200 | 25000 | 0 | 59,341,320 | 153,200 | 32,670 | 2.82 |
| 0 | 1,220,120.00 | 0 | 2100 | 25000 | 0 | 59,638,120 | 153,100 | 32,670 | 2.81 |

Note: TT cost: total material cost, TT LT: total lead time (in procurement), TT Q: total quality, and Qavg: average quality.

**Table 2:** Quality average = 2.84 ($d_3^- \le 22000$).

| $d_1^-$ | $d_1^+$ | $d_2^-$ | $d_2^+$ | $d_3^-$ | $d_3^+$ | TT cost | TT LT | TT Q | Qavg |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 235,250.00 | 0 | 5300 | 21999 | 0 | 58,653,250 | 156,300 | 35,671 | 2.84 |
| 0 | 240,250.00 | 0 | 5200 | 21999 | 0 | 58,658,250 | 156,200 | 35,671 | 2.84 |
| 0 | 245,250.00 | 0 | 5100 | 21999 | 0 | 58,663,250 | 156,100 | 35,671 | 2.84 |
| 0 | 250,250.00 | 0 | 5000 | 21999 | 0 | 58,668,250 | 156,000 | 35,671 | 2.84 |
| 0 | 263,440.00 | 0 | 4900 | 21999 | 0 | 58,681,440 | 155,900 | 35,671 | 2.84 |
| 0 | 305,440.00 | 0 | 4800 | 21999 | 0 | 58,723,440 | 155,800 | 35,671 | 2.84 |
| 0 | 347,440.00 | 0 | 4700 | 21999 | 0 | 58,765,440 | 155,700 | 35,671 | 2.84 |
| 0 | 389,440.00 | 0 | 4600 | 21999 | 0 | 58,807,440 | 155,600 | 35,671 | 2.84 |
| 0 | 432,010.00 | 0 | 4500 | 21999 | 0 | 58,850,010 | 155,500 | 35,671 | 2.84 |
| 0 | 475,010.00 | 0 | 4400 | 21999 | 0 | 58,893,010 | 155,400 | 35,671 | 2.84 |
| 0 | 519,150.00 | 0 | 4300 | 21999 | 0 | 58,937,150 | 155,300 | 35,671 | 2.84 |
| 0 | 564,150.00 | 0 | 4200 | 21999 | 0 | 58,982,150 | 155,200 | 35,671 | 2.84 |
| 0 | 776,700.00 | 0 | 4100 | 21999 | 0 | 59,194,700 | 155,100 | 35,670 | 2.84 |

**Table 3:** Quality average = 2.85 with $d_3^- \le 20000$.

| $d_1^-$ | $d_1^+$ | $d_2^-$ | $d_2^+$ | $d_3^-$ | $d_3^+$ | TT cost | TT LT | TT Q | Qavg |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 380,200.00 | 0 | 6200 | 19998 | 0 | 58,798,200 | 157,200 | 37,672 | 2.85 |
| 0 | 410,200.00 | 0 | 6100 | 19998 | 0 | 58,828,200 | 157,100 | 37,672 | 2.85 |
| 0 | 441,400.00 | 0 | 6000 | 19998 | 0 | 58,859,400 | 157,000 | 37,672 | 2.85 |
| 0 | 476,400.00 | 0 | 5900 | 19998 | 0 | 58,894,400 | 156,900 | 37,672 | 2.85 |
| 0 | 511,400.00 | 0 | 5800 | 19998 | 0 | 58,929,400 | 156,800 | 37,672 | 2.85 |
| 0 | 546,400.00 | 0 | 5700 | 19998 | 0 | 58,964,400 | 156,700 | 37,672 | 2.85 |
| 0 | 583,080.00 | 0 | 5600 | 19998 | 0 | 59,001,080 | 156,600 | 37,672 | 2.85 |
| 0 | 625,080.00 | 0 | 5500 | 19998 | 0 | 59,043,080 | 156,500 | 37,672 | 2.85 |
| 0 | 1,261,700.00 | 0 | 5400 | 19998 | 0 | 59,679,700 | 156,400 | 37,670 | 2.84 |

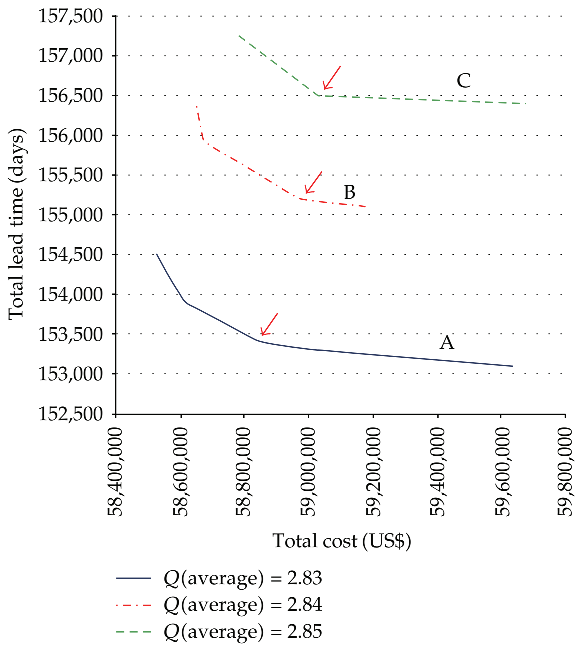


**Figure 4:** Total cost and total lead time of three different qualities.

The maintenance manager may tradeoff between reducing the waiting time and higher material expenses. In practical exercise, the AAA airline generates average income at US$33,000 per day. Thus, the maintenance manager can make technical decisions to overpay aircraft recovery up to US$16,500 (50% from income) to reduce a single AOG (Aircraft on ground) day.

Table 2 shows the results as an average 2.84 quality points and different lead time periods. This table illustrates thirteen different parameter sets which result in different cost deviations. However, the trend of data is similar to Table 1. It is only different in longer lead time at equal prices. Thus, the maintenance manager can use the data from two tables for making decisions among expected quality, lead time, and increasing/decreasing prices. In Table 2, if the maintenance manager aims to increase material's average quality, he must pay higher material costs. Furthermore, if he wants shorter procurement lead time, it will result in higher material expenses, which indicate in Table 2.

Table 3 shows the results under a higher average quality and different lead time periods (compare with Table 2). This table illustrates nine different parameter sets which result in different cost deviations. The AAA airline maintenance manager confirms that these results are valid by reviewing empirical results with their operational records. Therefore, the data from Tables 1, 2, and 3 are created in a single chart, which is used for comparisons between total cost, total lead time, and average quality.

Figure 4 shows a graphical comparison of Tables 1, 2, and 3. The high total cost at an early stage produces shorter lead time with a high negative slope. Each point on the three curves explains three objective dimensions: cost, lead time, and quality. Line B represents when airlines increase average quality, they pay a higher cost for the same lead time in order to buy, repair, or loan higher-quality aircraft parts. The arrow position points are the limit points to increase costs for a shorter time. It is not worth to pay a higher price for a small reduction of time beyond the arrows.

The solutions of the multiobjective optimization are not only three factors beneficial but also reliability, availability, and maintainability. Meanwhile, the material lead time is shorter, it reduces the aircraft downtime, which results in a shorter mean time to repair (higher maintainability), the longer MTBF (higher reliability), and the higher availability of the aircraft. The solutions are beneficial to the airlines that aim to fulfill travelling demand. The cost minimization results in lower airfare. Hence, the airlines gain a higher competitive advantage. The time minimization results in a higher flight time. Then, there are higher available flight hours of the airlines in responding to the market demand. Thus, this model is beneficial to the airlines on competitive advantage.

## 6. Conclusions

A multiobjective optimization using goal programming is particularly useful to aircraft maintenance organizations in simultaneous reduction of cost and aircraft downtime, as well as for increasing quality. Also, it is valuable to the improvement of supplier flexibility/replace ability, aircraft availability, and aircraft reliability. For airlines in Thailand, the results of the model with AAA airline's data are used as a decision-support strategy of multi-factors in aircraft maintenance, which generates the best solution among $7.8 \times 10^5$ possible solutions.

There are six contributions in this paper. First, the mathematic model supports the commercial aviation industry or the military aircraft fleet in survival under limited cost or certain budgets in Thailand by developing the supply chain. Second, this research illustrates the critical factors to aviation performance measurement. Third, the model assists the aircraft maintenance manager in decision support of resources selection. Fourth, the airline maintenance manager could develop the mathematical algorithm in their maintenance to optimize relative benchmarking and continue their best operation to enhance their competitive advantage. Fifth, the outcome of this research can be applied in aircraft operational risk management. Finally, it is beneficial to future research in performance analysis of other industries for example, ship, train, truck, and so forth.

However, aircraft fuel price is a vital factor that is related to operating costs and this needs to be carefully watched, thus future research may review and add the fuel cost factor into the optimization model.

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Hindawi Publishing Corporation
Advances in Decision Sciences
Volume 2012, Article ID 328349, 29 pages
doi:10.1155/2012/328349

*Research Article*

# Model Driven Integrated Decision-Making in Manufacturing Enterprises

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Received 7 February 2012; Accepted 30 April 2012

Academic Editor: Albert T. Jones



Decision making requirements and solutions are observed in four world class Manufacturing Enterprises (MEs). Observations made focus on deployed methods of complexity handling that facilitate multi-purpose, distributed decision making. Also observed are examples of partially deficient "integrated decision making" which stem from lack of understanding about how ME structural relations enable and/or constrain reachable ME behaviours. To begin to address this deficiency the paper outlines the use of a "*reference model of ME decision making*" which can inform the structural design of decision making systems in MEs. Also outlined is a "*systematic model driven approach to modelling ME systems*" which can particularise the reference model in specific case enterprises and thereby can "*underpin integrated ME decision making*". Coherent decomposition and representational mechanisms have been incorporated into the model driven approach to systemise complexity handling. The paper also describes in outline an application of the modelling method in a case study ME and explains how its use has improved the integration of previously distinct planning functions. The modelling approach is particularly innovative in respect to the way it structures the coherent creation and experimental re-use of "*fit for purpose*" discrete event (predictive) simulation models at the multiple levels of abstraction.

## 1. Decision Making Concepts and Frameworks and Their Relevance to MEs

Seminal studies of decision making and problem solving by Simon [1] have been widely referenced. Notable among these commentaries are reviews by Augier [2] and Karni [3] that report Simon as saying that "*the work of managers, of scientists, of engineers, of lawyers—the work that steers the course of society and its economic and governmental organizations—is largely work of making decisions and solving problems. It is work of choosing issues that require attention, setting goals, finding or designing suitable courses of action, and evaluating and choosing among alternative* *actions. The first three of these activities Simon called problem solving; the last he referred to as decision making. Nothing is more important for the well-being of society, such as at the level of business organizations (product improvement, efficiency of production, choice of investments), and at the level of our individual lives (choosing a career or a school)." The abilities and skills that determine the quality of our decisions and problem solutions are stored not only in more than multimillion human heads, but also in tools and machines, and especially today in computers. This fund of brains and its attendant machines form the basis of ingenuity*.

Augier [2] also points out that central to knowledge about decision making has been the theory of subjective expected utility (SEU), a sophisticated mathematical model of choice that lies at the foundation of most contemporary economics, theoretical statistics, and foundation operations research [4]. However, Karni [3] states that prescriptive theories of choice such as SEU are complemented by fruits of empirical research that show how people actually make decisions; which demonstrate how people solve problems such as via selective, heuristic search through large problem spaces and large data bases. The expert systems that are now being produced by research on artificial intelligence are arguably out growths of these research findings on human problem solving [5].

Essentially therefore decision making theories show how people cut problems down to size: how they apply approximation ideas to handle complexity that cannot be handled exactly. Operations research and artificial intelligence can provide powerful computational tools, but, at the same time, a new body of mathematical theory is evolving around the topic of computational complexity [3]. For example, the area of economics is now paying a great deal of attention to uncertainty and incomplete information [6] *which takes account of the institutional framework within which decisions are made;* to game theory, which seeks to deal with *inter individual and intergroup processes in which there is partial conflict of interest*, Augier [2]. Economists and political scientists are also increasingly buttressing the empirical foundations of their field by studying consequences of individual choice by studying behaviour in experimentally constructed markets and simulated political structures, Augier [2].

A number of decision making frameworks are reported in the literatures that seek to define typical decision making processes. For example, Payne [7] describes the so called three lenses for decision making; that are claimed to integrate ethical and economic considerations into business decisions. The three lenses proposed are based on three dimensions of "responsible decisions," namely, contribution to purpose; consistency with guiding principles; impact on people. However, this and other published decision making frameworks do not provide a decision rule or a "right" solution to complex business decisions. The Payne framework can help provide a view of some problem perspectives, by facilitating an examination of necessary tradeoffs that lead to responsible decisions. The Payne framework is only useful, however, when decision makers have the authority and ability to implement it and take responsibility for the action. In related work, Nash [8] poses 12 questions to help managers address ethical dilemmas. Also Johnson [9] proposed another approach to "Ethics & Policy Decision Making" based on nine decision making elements, namely, identify the desired result; describe the conditions or criteria to be met for satisfactory outcomes; identify all stakeholders; search for all reasonably promising results; evaluate all the alternatives; compare the alternatives and choose between them; carry the choice forward; reflect on the processes and consequences.

Much of our existing knowledge about problem solving, decision making, and complexity handling has been put into practice in the various functional areas of manufacturing enterprises (MEs) operating around the globe [5, 6, 10–13]. This is not at all surprising because MEs are essentially manmade "elements or building blocks of society" and our

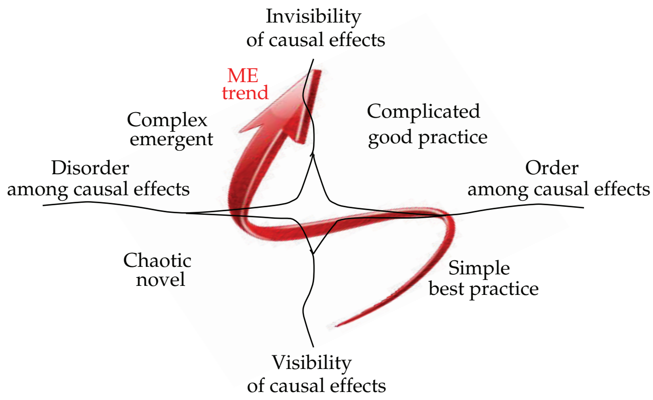


**Figure 1:** An interpretation of causality in MEs (after [14]).

ingenuity can be profitably directed towards strategic, tactical, and operational decision making about them. However, as discussed by Snowden [14] and illustrated in Figure 1, MEs are essentially a complex system of systems that interacts with external systems (e.g., political, financial, and technological systems) within their environment via difficult to understand and predict causal and temporal relationships. Some of these relationships may be well ordered and visible, others maybe disordered and invisible to the problem solver/ decision maker.

Some common examples of external variables that impinge on MEs are illustrated in Figure 2; consequently there is a need for business, engineering, and production systems deployed by MEs to handle that causality and complexity. As discussed in Section 2, the nature of decision making in MEs can vary significantly. This variability and complexity of decision making processes mitigates against any “holy grail” of finding a “one decision making process or decision making system fits all MEs.” Indeed by definition, MEs compete by being distinctive so that they respond and thrive in their environment better than competitor MEs [11, 13]. Further in general the inherent complexity and variability of interactions within and external to any ME generally results in MEs applying numerous decision making processes, frameworks, and systems in ad hoc rather than systematic ways [11–13]; commonly (as also discussed in Section 2) deploying very distinctive problem and decision making approaches on different time frames, in different ME sections/segments for different problem types as an integral part of ME business, engineering, and production systems.

In the next section of this paper, currently deployed decision making arrangements are observed in example MEs. These observations illustrate a need for a wide diversity of decision making roles because in some exemplar cases holisms amongst decisions made by holders of cognate groupings of roles can much improve the competitiveness of any given ME. However also observed is that the task of unifying the many decision types and instances of decisions made in large MEs is a far from a trivial exercise and requires the use of a number of suitable decision making frameworks. In the MEs observed *typically the decision making frameworks deployed are in the form of multiple, and typically ill defined, decision making processes that were overlaid in seemingly ad hoc ways onto a complex institutional framework with its plethora of organisational structural elements.*

The author presumed that the interdisciplinary nature of decisions made, coupled to the invisible impacts of adopting nonsystematically designed and poorly defined decision

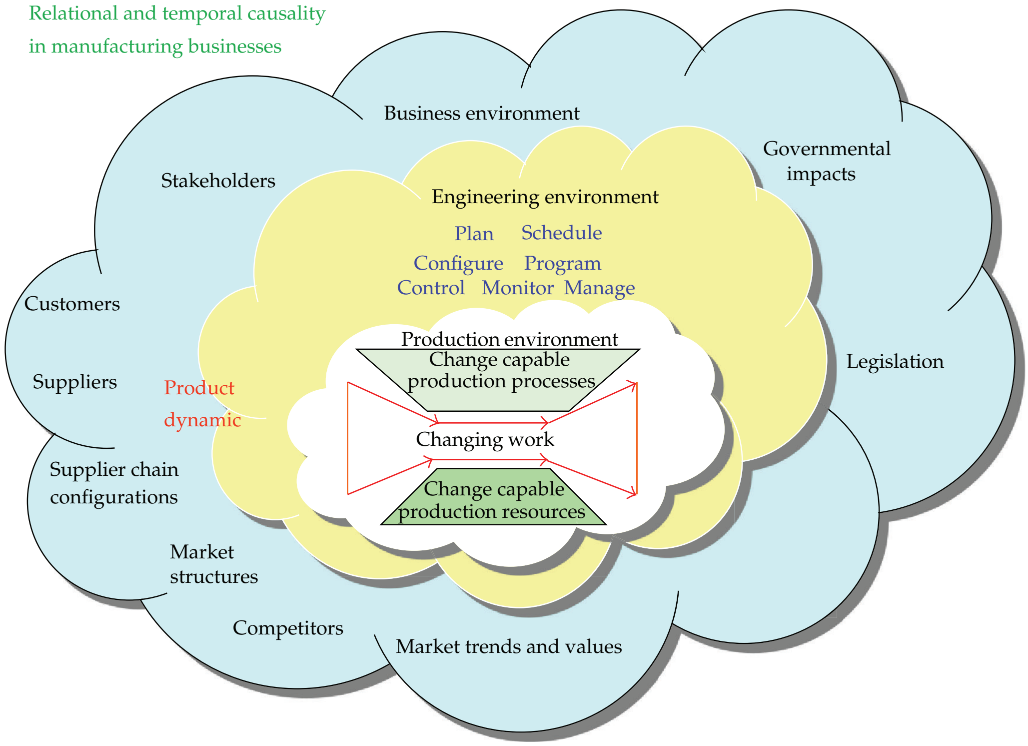


**Figure 2:** Some common examples of causally related variables.

making architectures, makes it extremely difficult to monitor and resolve partial conflicts of interest amongst decision makers and that this must restrict any moves to optimised holistic ME behaviours, short and long terms. Out of this presumption and desire to address a related gap in industry provision a proposed model-driven approach to designing and virtually executing ME architectures was conceived. This approach, as well as an example of its testing, is outlined in the following paper sections.

## 2. Observations Made about Decision Making in Four Case Study MEs

Four case study MEs are considered with respect to the way they make decisions. Each ME selected is regarded in its respective industry sector as realising world class levels of performance; as a consequence it may be presumed that its decision making methods are world class by some measure. The discussion will (a) illustrate key statements made in the forgoing section and (b) provide a founding rationale for a new systematic approach to conceptually "*underpinning integrated ME decision making.*"

### *2.1. General Characteristics and Observations in Four MEs Studied*

Table 1 characterises properties of four case study MEs for whom the author and his colleagues in the MSI Research Institute have carried out a number of research and consultancy

**Table 1:** Four example case study MEs.

| | | | |
|---|---|---|---|
| Air-Con<br>World leading supplier of industrial air-conditioning systems [15] | Focal activities of the ME: mixed realisation of (a) “special,” (b) “customized,” and (c) “standard” products with a largely common set of human, IT, and machine systems<br>Product complexity: low to medium<br>Product variance: high<br>Lead-times: short to medium<br>Product cost: medium | Key concerns of company: major cash flow problems because of late contract fulfilment apparently arising mainly from poor assembly system behaviours<br>Hypothesise sources of the problem: (A) over the wall planning enterprise wide (short and medium terms) and (B) lack of informed choice of best manufacturing paradigm (longer term) | Project aim: decision support and integrate multifunctional, enterprise wide planning<br>Research/consultancy approach taken: three-level modelling of various ME system behaviours set within a common specific case structural model of the organisation |
| ISF (International Shop-Fitter)<br>European and north American supplier of point of sale furniture [16, 17] | Focal activities of the ME: mixed realisation of (a) “customized” and (b) “standard” products with a largely common set of human, IT, and machine systems<br>Product complexity: low<br>Product variance: high<br>Lead-times: short to medium<br>Product cost: low to medium | Key concerns of company: excessive inventories and contract delays leading to significant cash flow problems<br>Hypothesise problem sources: (A) poor planning of impacts of product variance enterprise wide (short and medium terms) and (B) lack of informed choice of assembly paradigms (longer term) | Project aim: decision support and integrate multifunctional planning enterprise wide<br>Research/consultancy approach taken: three-level modelling of various ME system behaviours set within a common specific case structural model of the organisation |
| AEM<br>World leading aircraft engine manufacturer [18] | Focal activities of the ME: modular assembly and late customisation of limited number of aeroengine variants with a partially common set of human, IT, and machine systems<br>Product complexity: high<br>Product variance: low<br>Lead-times: medium to long<br>Product cost: high | Key concerns of company: contract fulfilment delays and high assembly costs leading to penalties or loss of contracts and thus cash flow problems<br>Hypothesise sources of the problem: disjunct between manufacturing operations, tactical and strategic | Project aim: decision/information support and integrate 3 levels of manufacturing planning<br>Research/consultancy approach taken: three-level modelling of ME system behaviours set within a common specific case structural model of the organisation with real-time information support provision |
| AMC<br>Commercial aircraft manufacturer [15] | Focal activities of the ME: introduce new assembly technology for a new generation of aircraft and for future product generations to reuse the developed supply chain and assembly methods and techniques<br>Product complexity: very high<br>New product variance: very low<br>Lead-times: long<br>Product/project cost: very high | Key concerns of company: how to virtually engineer new production systems and to reuse production systems engineering methods in the longer term<br>Hypothesise problem source: lack of knowledge about coherently using virtual engineering at multiple abstraction levels for reusable engineering of aircraft production | Project aim: to provide reusable decision support capabilities targeted at aspects of the virtual engineering of aircraft assembly lines of concern to the company<br>Research/consultancy approach taken: simulated behaviours of targeted systems set within a common specific case structural model of the ME’s supply chain |

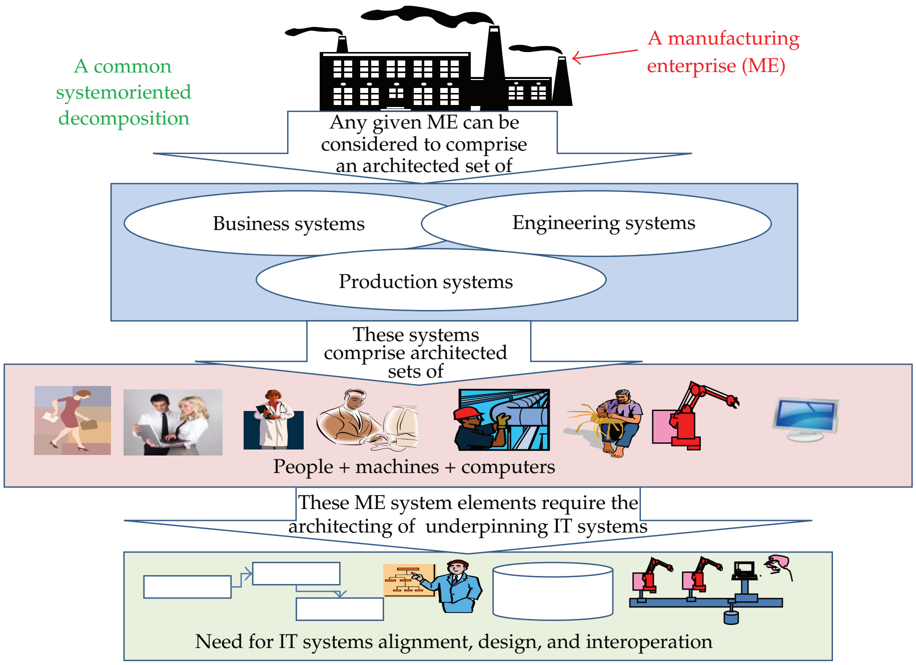


**Figure 3:** A conceptualisation of the system of systems deployed by the four example case study MEs.

studies. A common aim of those studies has been to address problematic areas of decision making; as indicated in the table. All four of these MEs are considered to be LMEs (i.e., large MEs) in the sense that the smallest employs circa 750 people worldwide and the largest around 2.5 K persons.

Readers are directed towards more detailed study findings; published primarily in PhD theses (as itemised in Table 1). Similar decision making studies have also been carried out by the author and his colleagues in a significant number of other MEs, around two-thirds being SMEs (small and medium sized MEs) operating in various industry sectors.

All of the four case study LMEs were observed to deploy a complex system of systems; see Figure 3. The system of systems they deploy is the following: conduct business with external customers and suppliers; engineer products; engineer production systems needed to make products; plan purchases and product realisation; realise products and services in response to the receipt of customer contracts and orders; develop and operate its supply chains. All ME systems are resourced, in conformance with strategic steers and tactical analysis, via the assignment of competent people to a vast range of operational activities that must be adequately performed within specified time-frames; so as to compete in the specific environment that each ME must function within. All four MEs were observed to deploy a variety of organising (or architectural) structures that bind the operation of assigned resources to required ME processes; so as to systemise and facilitate very many required behaviours, while constraining any unwanted behaviours.

Figure 4 illustrates common examples of "elemental structures" deployed within the four case study MEs to systemise the interworking of people, machines, and computers deployed. Some of these "binding structures" had been well defined at some previous point

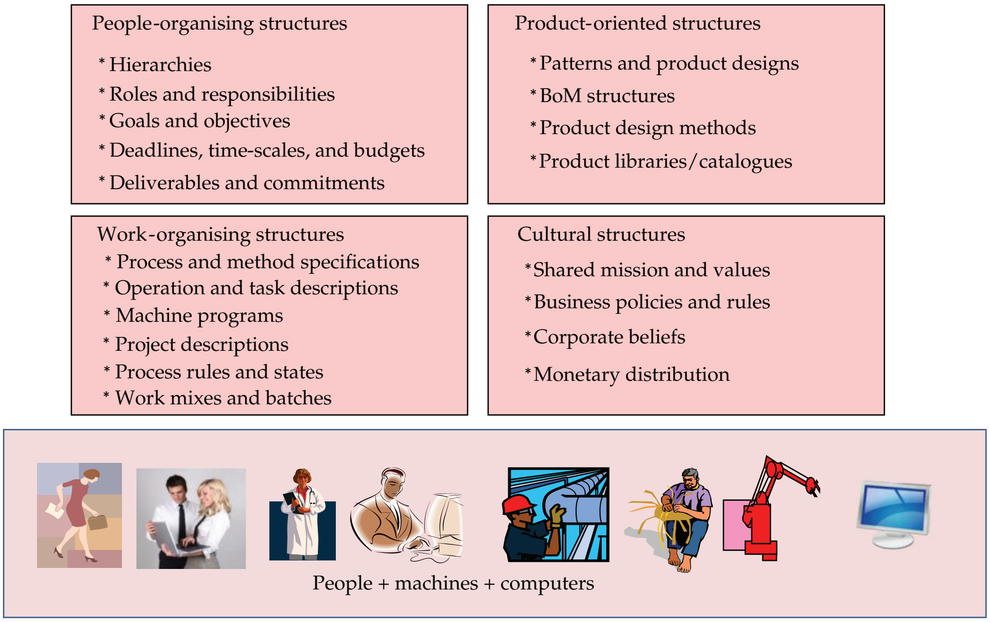


**Figure 4:** Common organising structures deployed in the case study MEs.

in time via a process of reasoning and decision making, which may or may not have been made transparent, and had remained essentially unchanged (i.e., "static") over a significant period of time. Common examples of well-defined static types of organising structures observed were business rules, operating policies, design methodologies, process and operation descriptions, human assignment policies and task descriptions, and BoM (bill of material) structures. However, other less visible and implicitly defined "static structure" types (such as cultural traits) also played a critical role in organising the functioning of each LME. By contrast other organising structure types were observed to be "semi-static," that is, remain constant for case specific periods of time, typically in response to exceptional circumstances; such as when new major contracts have been won or prime contracts are lost, and/or when the introduction of new products leads to significant variations in workloads for certain periods of time.

Despite evident similarity in the types of organising structures used, each LME had configured a unique and complex set of these organising structures; such that collectively they systemise the short- and long-term workings of the enterprise. Although each LME deployed a unique set of these structure types, also observed was that people operating as part of the ME business system reasoned about patterns amongst structural elements and their impacts quite differently to people operating as part of engineering systems or production systems. Presumably that these different perspectives on patterns in ME organising structures are conditioned by the distinctive roles they play, by their educational, training, and work experiences and possibly by certain vested interests. This led the author to align the observed differences in perspective on organisational structural patterns to four distinctive schools of thought as shown in Figure 5. This line of reasoning also led to the presumption that these different perspectives on structural elemental elements provide alternative dis-

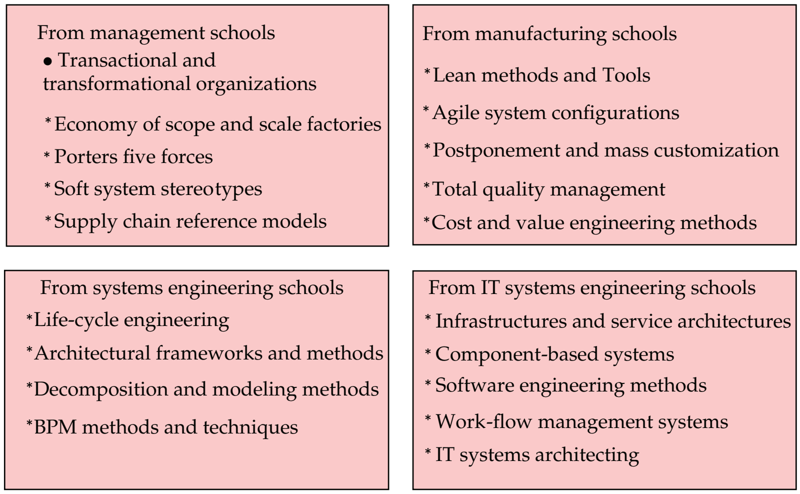


**Figure 5:** Interdisciplinary perspectives on patterns of structural elements used by MEs.

cipline-based reference models, which can inform the conceptual design of "operational," "strategic," and "tactical" aspects of ME business, engineering, and production systems.

Figure 6 was therefore constructed to illustrate conceptually how the author perceived various interdisciplinary strategic and tactical decision makers in the study. LMEs have deployed alternative architectural reference models to satisfy the following:

(a) the need to get all types and instances of ME resources to function systematically in conformance with defined structural patterns;

(b) at various points in time, modify structural elements of a chosen multidictionary ME architecture.

Critically as previously discussed, actions under (b) can enable or constrain the behaviours of other people, machine, and IT resource systems; therefore, it is presumed that actions under (a) and (b) will best be performed with holistic understandings about causal impacts of their actions. However, in each of the LME study cases, many examples were observed where structural change occurred without due cognisance of impacts on the functioning of others; particularly where those others were aligned to a different school of thinking.

Another way of viewing the observed behaviours in the LMEs is that at various points in time alternative "configurations of resources" (or indeed "configurations of systems" or "systems of systems") must be flexibly assigned to required enterprise activities; such as in response to changing workloads or distinctive work types that necessitate the realisation of changing multiple instances of those enterprise activities over time. Consequently, competent decision makers (such as directors, managers, and engineers responsible for planning long and short terms) were needed in the LMEs studied, who can analyse and predict various aspects of enterprise futures so that they can decide how best to change the way that day to day, month to month, and year to year the operations of resource systems (i.e., people, machines, and IT) can be restructured to remain positioned to respond in cost-effective and timely ways to changing environmental needs and conditions.

Also observed was that the way in which organising structures are specified and implemented is uniquely peopled centred. Information and communication systems can help

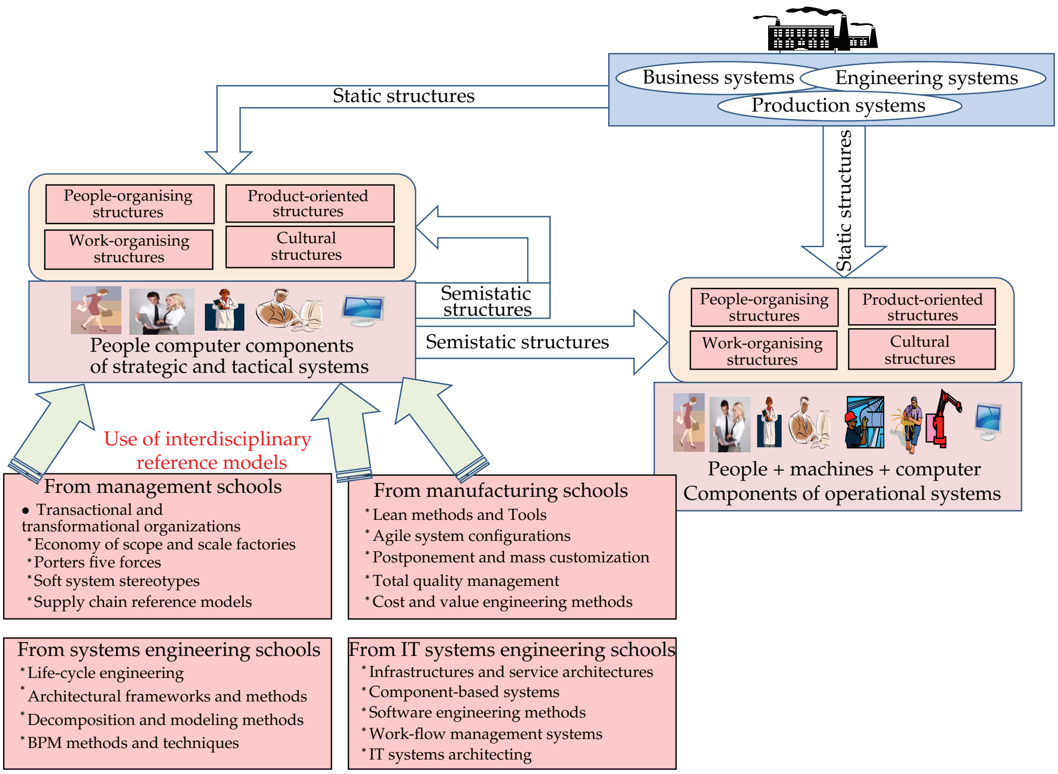


**Figure 6:** Use of interdisciplinary reference models by strategic and tactical teams in the case study MEs.

people to do this, but it is vital for people who are competent to reason about structural implications and to make final decisions. Indeed ideally all people performing LME roles should have clear understanding about their responsibility boundaries and reporting structures; so that they function without overdue risk to the enterprise as a whole. But many examples were observed in the four LMEs where this was not the case. A further general observation made was some of the decisions made could be semiautomated and underpinned by a suitably designed and engineered IT system (such as an engineering design and database system, an enterprise resource planning system, or a work-flow system); therefore, as appropriate embedded structural links can be embedded into computer tools to support improved interoperations between people and automated machines (such CNCs, robots, FMSs, and specialist automated systems) to improve the holism of decision making and action taking. But at best only semiautomated integration of decision making centres/roles had been achieved in the four study LMEs, and examples of this were observed to be the exception, rather than the norm.

## 2.2. *Reflection on Observed Decision Making Practices*

Generally none of the LMEs studied appeared to strategise or systemise their overall approach to decision making, rather they had appeared reactively to select specific case decision making processes, interdisciplinary frameworks, and related tools (such as in response to problems and observed needs or by responding to competitor actions) and then to overlay their chosen methods of decision making in ad hoc and partially invisible ways onto other adopted patterns of structural elements that bind the many activities that need to be performed by MEs.

All four case study LMEs are subjected to a variety of dynamic impacts which can arise within, or external to, the ME system of systems deployed. The primary sources and frequency of external dynamic impacts that occur were observed to be ME specific, but in all cases the rate of their occurrence was largely related to the rate at which significant product or service system change is needed.

For example, the Air-Con and ISF LMEs function competitively in very different industry sectors by deploying a largely common set of human, IT, and machine resources to make many product variants; that is, they realise economies of scope and scale (EoSS) by deciding upon and realising needing system reconfigurations on an ongoing basis Cui and Weston [19]. Essentially they use the same semiflexibly structured set of (business, engineering, and production) systems (and their embedded decision systems) to realise "special," "customized," and "standard product" types. It was observed that customers (and their requirements and desires) constitute the primary source of impinging dynamic on Air-Con and ISF; because in a partially unpredictable manner Air-Con and ISF customers place orders and contracts which must be fulfilled in conformance with customer-specified product qualities, at competitive prices, within agreed lead-times. The needed decision making and subsequent system reconfigurations in Air-Con and ISF are therefore dominated by a requirement to engineer and manage effective responses to these customer-induced dynamics.

By contrast, the dominant change in AEM and AMC is normally driven by market and technology trends; rather than directly by any single customer. The AMC and AEM LMEs realise products (i.e., "aircraft" or "parts of aircraft," resp.) that have a relatively very long lifetime in comparison to Air-Con and ISF products. Hence, a relative low frequency of decision making is required to decide when to develop new aircraft types or variants and when to deploy new production processes and technologies. But generally in the aerospace sector any new design decision may induce a complex chain of causally related changes to complex products; extended supply chains; processes which must be reliable/risk free; the deployments of adequately proven competent human and machine resources; possibly even to the proven global location and distribution of the business, engineering, and production systems deployed. Therefore, often because of the inherent complexities and investment risks involved (strategic, tactical, and operational), decision making in AEM and AMC occurs over significantly longer time frames (spread over many years) than equivalent time frames in Air-Con and ISF (spread over many months).

Despite evident differences in the dominant source of dynamic impacts and the rates at which decisions need to be made, similarity was observed amongst the types of "decision making roles" that need to be performed. Figure 7 shows key decision making roles observed within the four LMEs which were embedded in a *distributed* fashion into the complex system of (business, engineering, and production) systems deployed by each LME.

Figure 8 illustrates commonality observed in the distribution of those roles in the four LMEs. The relationships between these distributed roles were both hierarchical and sequential in nature. In all four LMEs, strategic decision making was focussed on deciding how the enterprise should be steered and changed; so that it remains competitive, despite many causal factors impacting on the ME from its environment or from within the ME. Those strategic steers were used as key inputs by tactical decision makers who needed to action the changes directed from above, whilst also ensuring that operational processes perform properly and remain well managed. The tactical decisions made were observed to control

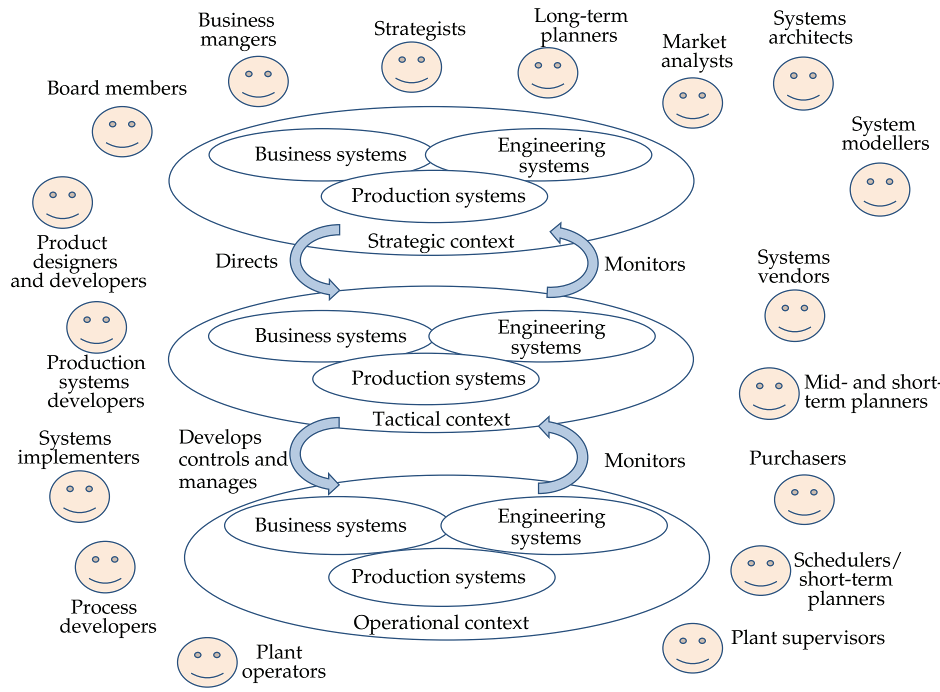


**Figure 7:** Common decision making roles observed in the case study LMEs.

the instances and synchronisation of instances of operational processes; as new contracts and orders were won by the enterprise from customers. Whereas needed logical sequencing of decision making was also observed at all three levels in the decision hierarchy as instances of strategic processes, tactical processes, and operational processes needed to be realised. A further observation made was that in general all decision making roles required a local decision making processes to be performed (to satisfy local functional requirements), but in addition each local decision process needed to be an integral part of *a wider sequence* of decision making functions. In the case of local decision making processes, very significant variation was observed which in general was aligned to the needs of the system or departmental unit in which the decision maker resides; therefore, their related disciplinary school of thinking; such as business-oriented, engineering-oriented, or production-oriented schools.

A further observation made was that in all departmental units studied local decision making processes were generally well matched to specific ME requirements. But by distinct contrast, the integration of local decisions into wider decision making processes generally was troublesome and was frequently reported by company decision makers interviewed to place severe constraints on the overall ME performance; often with each ME "silo" seeking to blame other ME silos for not understanding the importance of their local decisions. Furthermore, interviewed managers commonly stated that seldom was there any grand design of ME decision making process (such as those illustrated in Figure 8 which generally had evolved in an ad hoc fashion over many years), nor was there any good representation of decision making available with respect to decisions made outside of local units. Therefore, apparently in each study LME, the distribution and reintegration of these decision making roles were based on practical but generally limited experience. The case study modelling reported in Section 4 will provide a good example of poor ME behavioural outcomes that

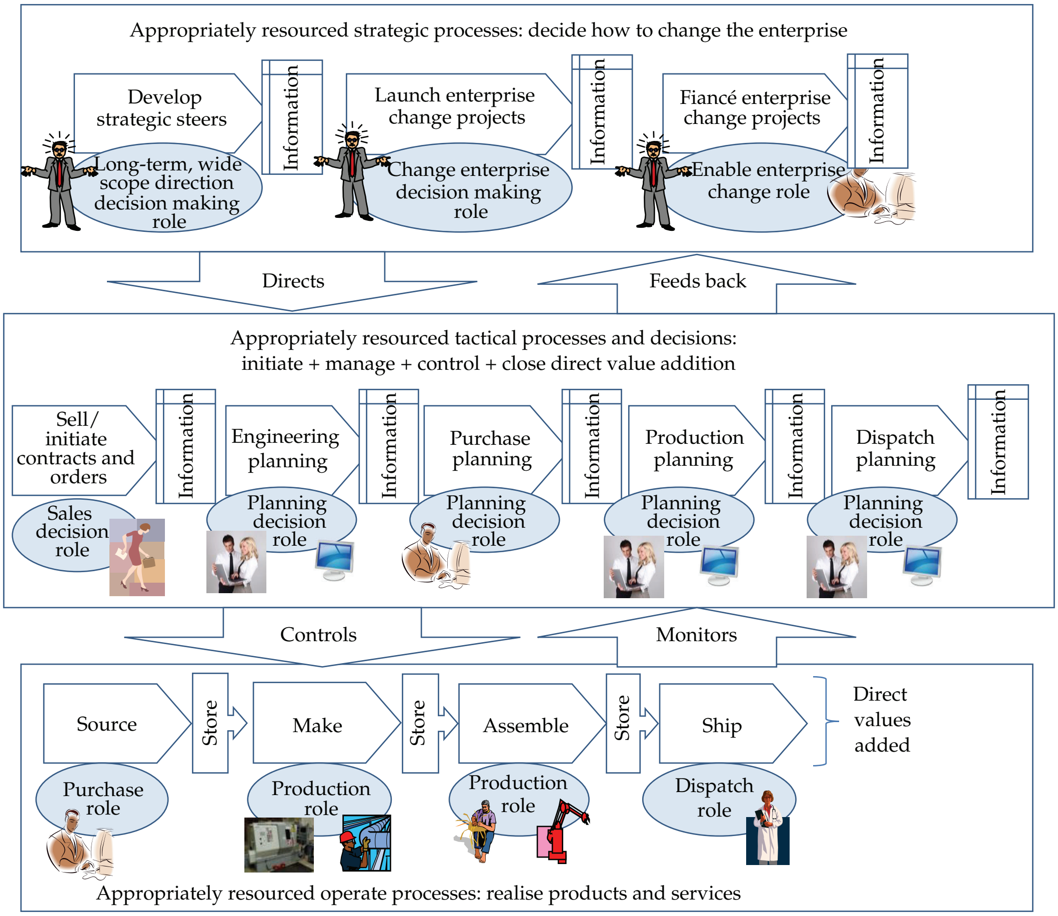


**Figure 8:** Commonality observed in the distribution of decision making roles in the case study LMEs.

arose in the case of the Air-Con LME because of in appropriate distribution and integration of local unit decisions; while similar troublesome integration problems were reported and observed in the other LMEs studied.

The author observed that in all four companies the ad hoc developments leading to a specific decomposition of decision making roles (and their assigned resource systems) had however all been conceived and organised based on the ad hoc use of three distinctive types of decomposition mechanism; as visualised by Figure 9. Namely decompositions are based on differences in concern about the following:

(i) "system scope,"

(ii) "system viewpoint,"

(iii) "timeframe of concern."

Two of these types of decomposition, namely, "system scope" and "system viewpoint" decomposition mechanisms, are illustrated in Figure 9 in the form of a development of Zachman framework ideas; where the originating ideas were conceived in the context of large IT systems engineering [20]. It was presumed that the usual purpose of using these and other

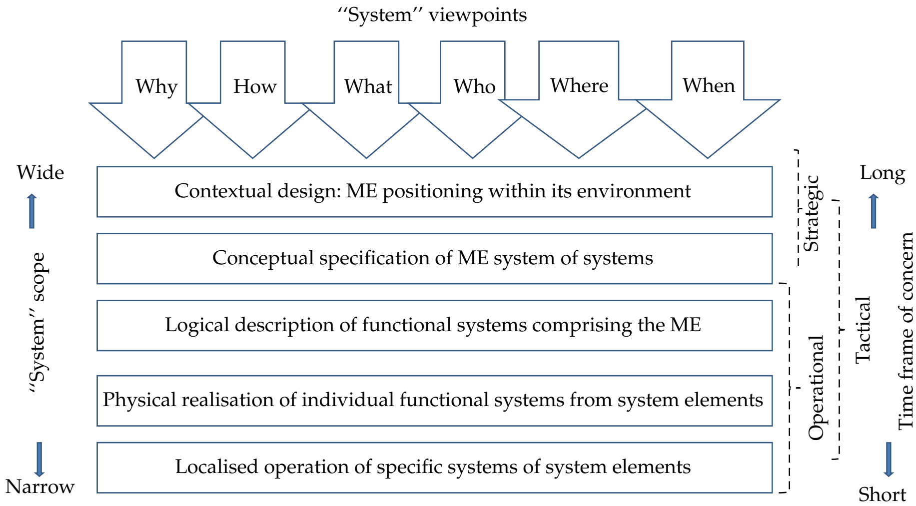


**Figure 9:** Common decomposition ideas in ad hoc use in the case study MEs to simplify individual decision making roles.

approaches to decomposition, in relation to complex entities such as MEs, is to break-through inherent levels of complexity. In all four LMEs, an ad hoc and largely transparent application of this form of "complex systems reasoning" had enabled decision making requirements in each case LME to be adequately aligned to the variety of roles played by directors, financiers, technologists, engineers, and managers deployed by the enterprise. Via the application of these decomposition ideas simplified individual decisions can be specified, so that holders of those roles only need to "wrestle with a head full of issues"; focussing only on matters of relevance to them (and the competencies they possess); such that they can perform assigned analytical and decision making tasks in effective and timely ways. In all four LMEs also, each role holder is a "person" or some "grouping or system of persons"; either of which may be supported by well-specified methods and technology; but for all decision types observed people were the final arbiter.

Clearly the various decision making roles so distributed (and graphically illustrated in Figures 7 and 8) are not islands of decision making. Rather as discussed above in general they are related to a number of other cognate decisions (normally through specific case causality, hierarchy, and temporality) which will in some ways be "governed" by the organising/architectural structures deployed by the LME concerned. Consequently following the execution of any such decision making role, resultant decisions will normally need to be considered in relation to outputs of other decision making roles.

In summary, many decision making roles need to be performed to realise competitive ME behaviours, short and long terms. Hence, the quality and timeliness with which assigned role holders make individual and collective decisions are critical to MEs. Those roles can take various forms but similarity in the distribution of ME decision making roles can be observed in different LMEs. Also local decisions are made by numerous persons who possess the competencies needed to make decisions for which they have responsibility. Any specific ME distribution of decision making roles must be executed with frequencies that "fit the purpose" of the decisions made. But deployments of these decision outputs must be positioned into the wider context of decision making in the host enterprise. The integration of decision making outcomes may be of vital importance when seeking to overcome bias from vested interests, so as to generate competitive enterprise behaviours. Unless the causality, hierarchy and temporality of all critical decisions are well understood, then any given ME may perform badly, lose market share, or even fail to survive in today's competitive world.

Indeed many cases of poorly integrated decision making were reported by employees in the LMEs, yet despite that fact it was observed that the processes of integrating multiple decision making outcomes were not generally being visibly strategized or systemise. Furthermore, deficiencies in holistic decision making observed by LME managers resulted in a commissioning of the research projects previously itemised in Table 1; each of which was subsequently linked to a number of Ph.D. styled research projects focussed on using state-of-the-art modelling technologies to better understand (i) how individual decision making types can impact on overall ME behaviours and (ii) how collective decision making types can impact on overall ME behaviours.

The author and his MSI research colleagues presumed that in many LMEs (as was the case in the four study enterprises) frequently occurring deficiencies in integrated decision making commonly stem from a lack of understanding about how *ME structural relations and associated decision making structures enable and/or constrain reachable ME behaviours*. This presumption was initially partially verified anecdotally by all key LME decision makers contributing to the author's industrial case study research. Furthermore, a number of ME senior and middle managers consulted about problems of holistic decision making observed that *generalisations about ME decision making that are visually articulated via Figures 7, 8, and 6 provide a useful "reference model of ME decision making"*; because collectively these visual models can help various ME decision makers to begin to position their own decision making role within the context of their host ME. However, with a view to instrumenting, validating, and quantifying the potential importance of these ideas, subsequent modelling studies were devised and carried out in respect to a number of commonly occurring decision making scenarios.

Based on the above reasoning, we can conclude that models of organisational structures are a key repository of knowledge that can be reused to structure the integration of various outcomes from individual distributed decision making roles. Therefore, the remainder of this paper majors on describing a *model-driven approach to predicatively understanding casual impacts of organisational relationships on ME systems behaviours.* This approach incorporates a method and framework for modelling ME systems at multiple levels of abstraction. By such means complexity handling is formalised and the explicit capture of key ME organising structures is enabled. By so doing the approach can facilitate and provide structural support for "fit for purpose predictive decision making" amongst cognate groupings of ME decision makers. The model-driven approach proposed is not intended to directly facilitate new understandings about possible impacts of cultural factors on the quality of ME decision making and it is acknowledged by the author that physiological aspects of human decision making can also be of critical concern. But proposed model-driven approach can capture a rational basis and organisational framework within which impacts of such factors can be qualified and quantified.

### *2.3. Need to Model ME Organising Structures*

The foregoing observations made in the four LMEs show that decision making is highly system, viewpoint, and time-scale dependent. To cater for this, a variety of decision making roles are commonly defined that subsequently are realised primarily by people who are assigned responsibilities for performing those roles; possibly supported but very seldom wholly replaced by computers or machines. A consequence of the high levels of complexity is that decision making in large complex organisations normally needs to be distributed amongst many roles; therefore, amongst many role holders. As previously illustrated in Figure 8, in addition each ME decision making role will need to contribute to one or more holistic processes: where such an holistic process can involve the following:

(i) abstract reasoning and general direction setting;

(ii) further mid-level of abstraction reasoning, mid-scope decision making, and direction setting;

(iii) further mid-level of abstraction reasoning (possibly involving long-term planning/decision making, and action taking and mid-term planning/decision making, and action taking);

(iv) short-term planning/decision making/action taking;

(v) and so on.

Through adopting processes of decomposition (as discussed in Section 2.2), individual reasoning, decision making, and action taking can be simplified such that people and their supporting machines can possess sufficient competency to fulfil the roles assigned to them. But the negative side of that decomposition and distribution of ME decision making into a complex system of ME systems is that both visible and invisible interdependencies exist between any given role and other ME roles. If these interdependencies are not well understood, so that each decision can be appropriately positioned into the LME, then poor holistic decision making functions will result.

It also follows that persons made responsible for "life cycle engineering the organising structures of MEs" (i.e., for the "Architectural Engineering of Enterprises") have a critical role to play in ensuring that reasoning, decision making, and action taking are geared towards holistic ME competiveness. Indeed in the four LMEs studied, it was observed that potentially all holders of decision makers roles have some elemental part to play in that architectural engineering; But they can only play that role in effective and timely ways if they have good understandings about the following:

(A) current ME architecture that structures and positions their activities,

(B) how their decisions will impact upon existing architecture and how those impacts may lead to alternative ME behaviours.

Without sufficient understandings about (A) and (B), ME decision makers will need at least partially to have to "work it in the dark."

In recognition of this need to visualise, position, and integrate decision making roles, over more than a decade the author and his research colleagues have studied ways of "explicitly describing" and "computer exercising" ME architectures. To facilitate key aspects of "Architectural Engineering," a coherent set of modelling formalisms has been developed, which can be used in association with well-defined system decomposition and integration techniques to explicitly capture relationships between key structural elements of enterprises and thereby specify current or possible future models of ME organising structures. At multiple level of abstraction the creation and ongoing reuse of these "structural models" is designed to "qualify" reasoning and decision making about the deployments of alternative system configurations. In addition at multiple levels of abstraction the modelling formalisms

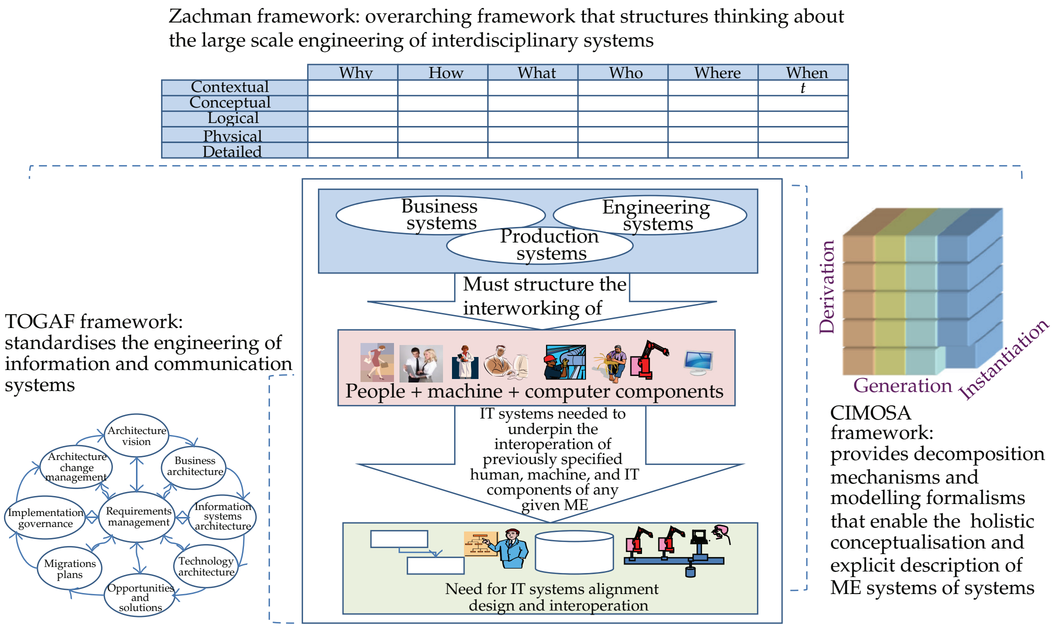


**Figure 10:** The model-driven framework developed to life-cycle engineer ME architectures, based on a unification of Zachman, CIMOSA, and Togaf ideas.

are designed to systemise the virtual (simulated) execution of possible reachable states of the modelled structures, so as to quantify likely behavioural outcomes from a given set of ME organising structures and their embedded decision making organisation. In this way likely ME behavioural outcomes of prime concern can be predicted for given possible scenarios of operation. Essentially the models of organising structures so created provide a ME specific architecture (or specific case "ontology") which can be reused to systemise the conceptual design of multiple " fit for purpose simulation models. In this way, coherent sets of simulation models at needed levels of abstraction can support both individual and collective decision making about a focal objective function.

## 3. Modelling ME Structures and Behaviours in Support of Integrated Decision Making

Driven by the forgoing reasoning, the author and his colleagues have conceived, instrumented, and case-tested a new model-driven approach to the life-cycle engineering of ME architectures. The case testing carried out so far has focussed on unifying decision making amongst cognate groups of influential ME decision makers; as earlier indicated by Table 1.

Figures 10 and 11, respectively, conceptualise the "*modelling framework*" and the "*modelling method*" that constitute the developed model-driven approach.

The primary purpose of the *modelling framework* is to provide a consistent set of decomposition mechanisms and integration concepts that can systematically cope with the levels of complexity found in many MEs. Essentially the Zachman framework is a metamodel (i.e., a "model of models of complex systems") which provides a holistic frame that encompasses alternative modelling viewpoints and concepts [20]. The application of Zachman

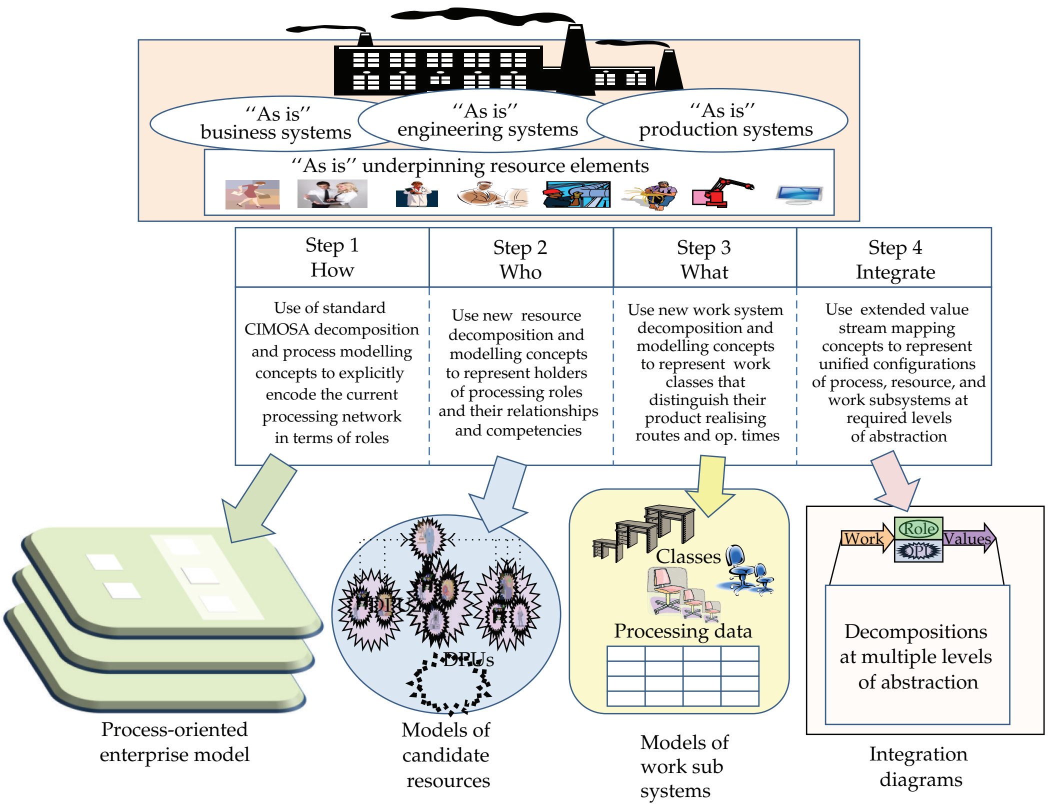


**Figure 11:** Conceptualisation of the "structural" modelling steps for modelling alternative ME systems of systems configurations.

framework ideas has been extended by the author to decompose and holistically represent complex systems comprising people and machines, in addition to complex information and communications systems (for which the original Zachman framework was intended). Furthermore, an extension of CIMOSA modelling formalisms is used within the context of the Zachman framework [21]. This enables explicit capture and coherent visual representation of people, machine, and information systems, with their specific case organising structures. The CIMOSA extensions developed by the author and his research colleagues enable explicit representation and model capture related to "process oriented roles"; "people, machine and IT resource components" as potential role holders; "work flow classes", "work type attributes," and characteristic work rates.

Additionally, the author and his colleagues have developed sets of "integration diagramming templates" which at multiple levels of abstraction can visually represent candidate "configurations of complex ME systems of systems"; in order to match the various scopes and foci of concern of many possible ME decision making roles. A simplified use of these diagrams is illustrated in Figure 12. Via such means support is given to the thinking and reasoning of interdisciplinary decision makers; so that they can reason about and communicate understandings related to the pros and cons of alternative system designs; about how those designs can match (current or possible future) system requirements. Having used the extended CIMOSA enterprise modelling formalisms to formally captured and represented

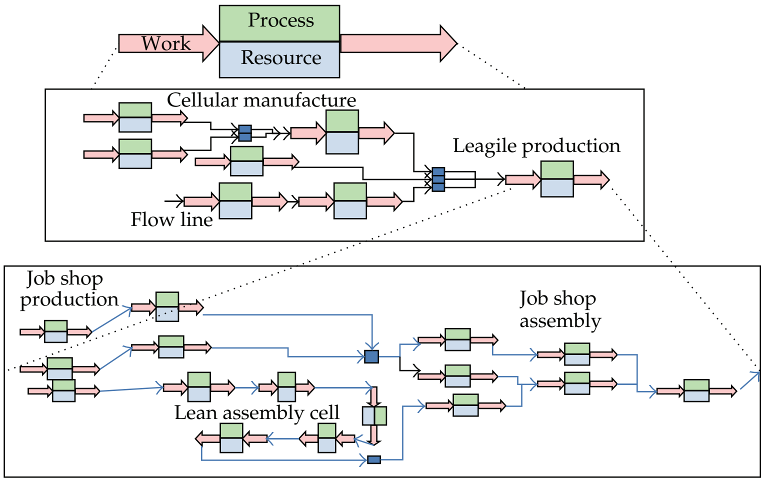


**Figure 12:** Example of multilevel representations of structural decompositions of systems visualised by using integration diagrams.

ME system of system models, structural relationships and information entities encoded into the CIMOSA models can then be reused as inputs to the TOGAF framework (along with its recommended tools for building complex but scalable and changeable information systems) [22]. By such means well-defined information structures can be positioned, at required abstraction levels, within their specific ME context; thereby support to the holistic design of database systems can be provided. The developed data bases can be populated by real-world and/or simulated data to enable processing by sets of "fit for purpose" decision support tools. Thereby these tools can underpin both (a) specific case decision making processes used by individual decision makers and (b) collective decision making processes realised by cognate decision making groups. The Zachman, CIMOSA, and TOGAF framework ideas are each powerful in their own right; but as a collective they can be highly complementary so as to create a synergistic and even more powerful whole.

The *modelling method* comprises an IT instrumented set of coherent modelling formalisms which are used systematically by following the modelling steps itemised in Figure 11. As discussed above modelling is begun via the capture (or modification) of a process-oriented enterprise model. Here use of CIMOSA formalisms enables operational, tactical, and strategic processes and their interactions to be defined at multiple levels of abstraction. By adopting use of the extended CIMOSA-based process modelling formalisms complex system decompositions are explicitly modelled and can naturally be encoded and represented via a suitable proprietary IT tool, or indeed set of tools. The scope of process modelling can be confined if desired but the technique is scalable and eclectic. Having validated developed models (and the hierarchy of processes and their elemental activities they encode) with relevant ME decision makers, "role modeling" can be conducted at multiple abstraction levels; where roles are formed from cognate groupings of specific case enterprise activities, while maintaining their process-oriented structural relationships and precedence logics. Next resource modelling is carried out to define current or possible future holders of roles. Here, the so called dynamic producer unit (DPU) modelling constructs were defined [23] to explicitly model key attributes of people, machines, and IT components (and their structural relationships) in terms which are coherent with the way in which role modelling had pre-

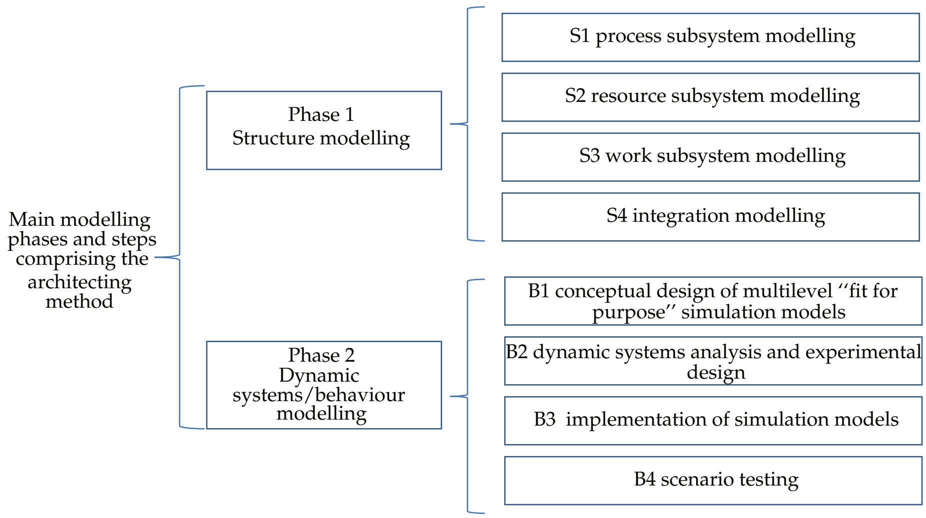


**Figure 13:** Combined structural and behavioural steps of the model-driven method.

viously been achieved. Following which work system flows, work classes, and work types attributes are modelled; where work classes are formed based on similarities in their processing and resourcing needs. Having separately modelled the "how," "who," and "what" of ME systems of systems at needed abstraction, the fourth stage of structure modelling is centred on representing various integrated configurations of these three views (as illustrated in outline by Figure 12) to facilitate the conceptualisation and development of individual and collective decision making processes and their positioning in ME system of systems, long and short terms. Being structural and static by nature, the models created at this stage are not computer executable. Hence, in order to computer (virtually) execute the reachable states of the alternative system configurations so defined, it was necessary to facilitate a second phase of behaviour modelling which can enable various ME decision makers to quantify the relative performances of alternative ME system of system designs; from their own respective point of view with their "fit for purpose" objective functions and key performance indicators (KPIs).

The second, behavioural phase of system of system modelling so developed is outlined in Figure 13 and conceptualised in Figure 14.

Critical in the design of the second behavioural phase of the model-driven method has been a general principle that any virtual testing of the reachable states of any previously defined system of system architecture should not normally be carried out in an isolated piecemeal fashion. If this is the case a possible natural outcome is one of seeking to optimise some part of the ME, or some chosen perspective on the ME, at the expense of other parts or perspectives; being armed with quantified facts about such a focussed set of concerns the modelling might more readily encourage the wider ME decision makers to adopt a narrow and vested interest at the expense of overall ME behavioural performances and competitiveness. Therefore, the virtual testing approach developed is centred on satisfying the need to

(i) place within the wider context of any given ME, model-driven behavioural modelling support for specific case decision makers, necessitating the coherent development of multiple "fit for purpose" behavioural models, at required abstraction

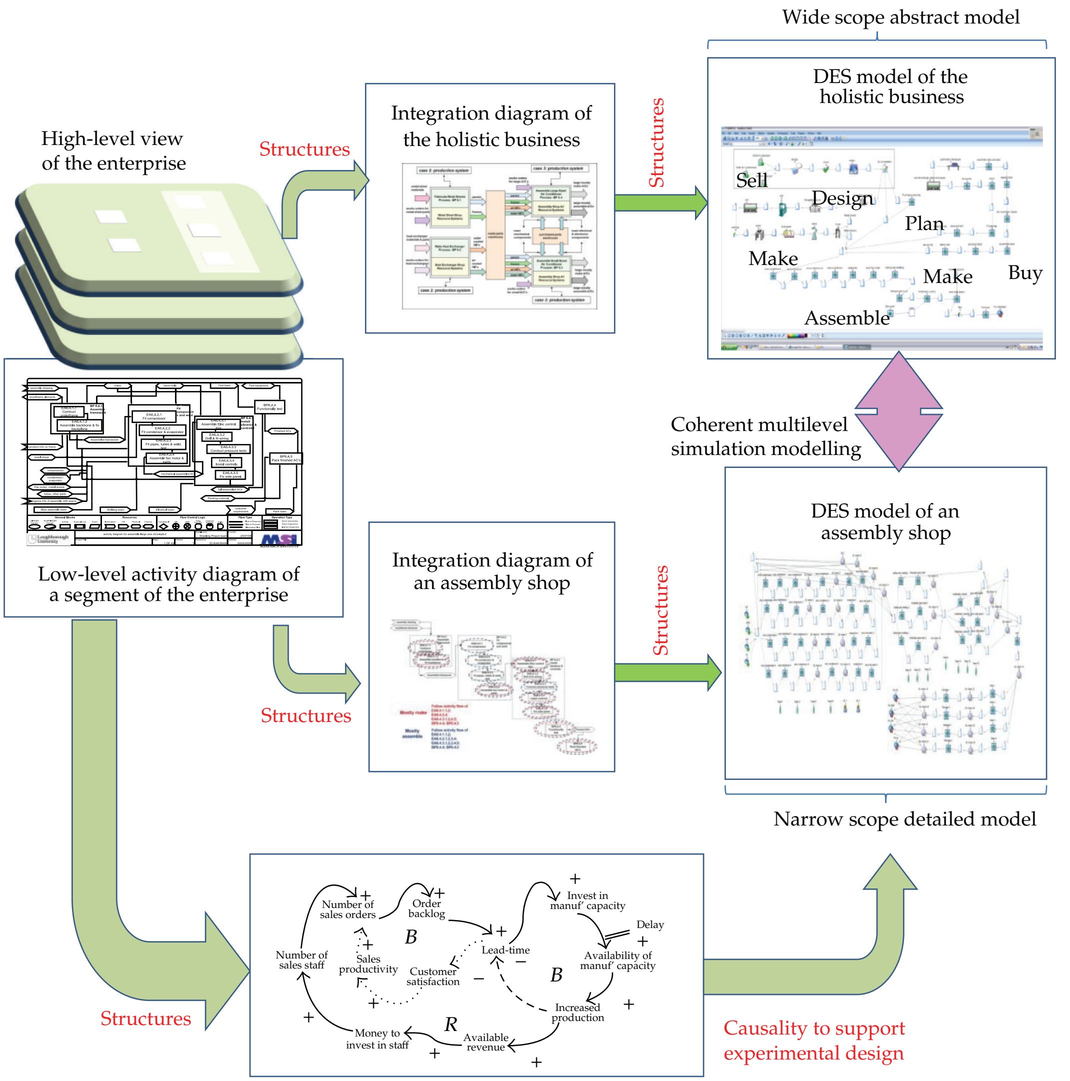


**Figure 14:** Conceptualisation of common behavioural steps of the modelling method.

levels with suitably embedded modelling simplifications, and with a modelling scope and focus which fits the purpose of the targeted decision making role or roles;

(ii) computer exercise the specifically defined ME structures of concern with "fit for purpose" modelled system causality and temporality, system element interactions, parameter variations, and selected KPIs, such that elemental ME systems are duly cognisant of possible scenarios of causality and temporarily within the wider ME;

(iii) having modelled the reachable behaviours of targeted groupings of ME system structures, the modeller is well placed to compare and contrast behavioural performances of "as is" (or current) organising structures adopted by any given ME with those of possible future ME configurations; by so doing to manage changes made to ME structural and behavioural models.

As depicted by Figure 14, the author and his research colleagues have addressed the above needs by promoting and enabling the reuse of process, role, resource, DPU, and work system elements/modelling constructs (and structural relationships connecting these elements), via the conceptual mapping of those entities as encoded by integration diagrams onto equivalent structural entities used to encode discrete event simulation modelling structures. Further this has been facilitated at multiple levels of abstraction, where multi-level mapping is managed with reference to the process-oriented decompositions embedded into the CIMOSA enterprise model. This describes in outline modelling step B1 in Figure 13.

During modelling step B2, the model-driven method recommends the use of dynamic systems modelling in order to understand the likely causality within the boundaries of any "fit for purpose" behavioural model and between that model and the wider specific case ME. Here the author and his colleagues have found that the use of causal loop models (CLMs) can have great benefit in support of the design of "fit for purpose" simulation modelling experiments; whether the target simulation tool is a DES tool or a continuous simulation modelling tool [16].

Having followed steps B1 and B2, in various real cases, ME system of system modelling the author has observed that during steps B3 and B4, the approach has led to coherent multilevel, in context modelling which enables fit for purpose testing of ME architectures which can naturally lead to the design of decision support tools for a variety of ME decision making roles.

The following section briefly illustrates how the model-driven approach to virtually testing ME architectures was used in respect to Air-Con, see Table 1.

## 4. Illustrative Case of Improving Integrated Decision Making

As summarised in Table 1, the model-driven modelling approach described in Section 3 has enabled enhanced integrated decision making in four LMEs. In this section, one of these cases (i.e., Air-Con) is considered in further detail with a view to illustrating typical benefits that can be realised by the approach and also to consider likely incurred difficulties and costs from its practical application.

To avoid duplicated discussion, the reader is referred once more to the first row of Table 1, which describes distinguishing characteristics of Air-Con and of the purpose of the modelling study conducted for that enterprise, which was determined by Air-Con senior managers in view of critically bad ME behaviours which were threatening its leading edge market position. As illustrated conceptually in Figure 15, it was assumed but needed to be proven (ideally in quantitative terms) that inappropriate and poorly understood causality amongst Air-Con departments was a prime source of Air-Con business problems. These problems were assumed to arise as follows:

(i) in appropriate interdepartmental planning structures promoted "over the wall planning,"

(ii) resultant poorly integrated business, technical, production, and purchase planning decisions were a major contributor to up to 15 percent of contract due dates not being satisfied (with significant loss of customer satisfaction and some loss of customer despite world class functional qualities of Air-Con products),

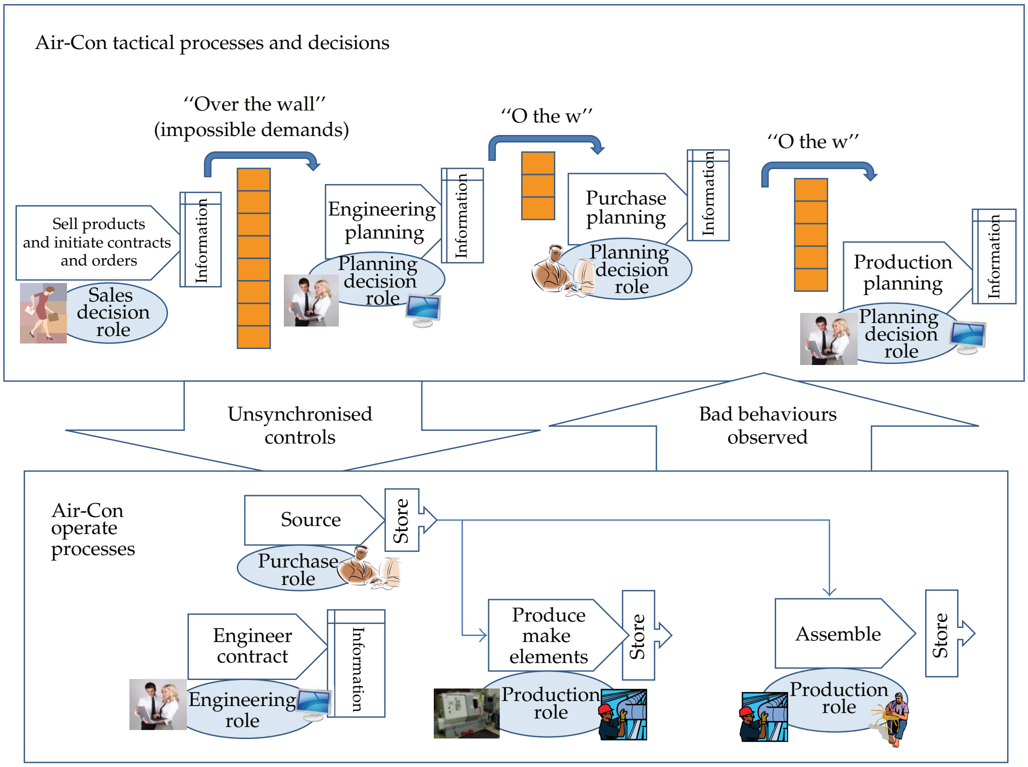


**Figure 15:** Conceptualisation of Air-Con decision making problems.

(iii) that lack of capacity in the Air-Con production system was a secondary cause of late deliveries and was a prime limit to company growth which was not well understood,

(iv) that the above causal effects were contributing to major cash flow problems; which because of resultant unavailabilities of cash on demand further delayed contract realisations.

The author and two of his research colleagues (Z. Cui and K. Agyapong-Kodua) visited the company in southern China over a period of two working weeks and applied the model-driven approach previously described, to seek in Air-Con to

(a) quantify impacts of the above assumptions and observed behaviours,

(b) identify feasible improvements in organisational structures,

(c) determine needed capacity increases in production system sections,

(d) show how new decision making approaches can ease cash flow problems.

### *4.1. Phase 1, Multilevel of Abstraction Structure Modelling in Air-Con*

This subsection describes how the structural modelling steps of the model-driven approach illustrated in Figures 11 and 13 were taken to explicitly capture a model of the then current Air-Con enterprise architecture; to attribute then current (people, machine, and IT system resources) to operational and tactical process oriented roles performed in Air-Con; to use integration diagrams to map families and types of work flows through process-oriented roles and their assigned role holders; to validate the structural models of Air-Con prior to conducting phase 2 behavioural modelling.

During phase 1, modelling step S1 (of the model-driven approach, see Figure 13), a comprehensive enterprise model of Air-Con (comprising of 44 “context,” “interaction,” “structure,” and “activity” CIMOSA diagrams) was captured and documented (using a standard VISIO tool, for which a coherent set of visual modelling constructs was defined). This enabled the authors to gain and communicate many understandings about the company by visually representing knowledge systematically obtained; mainly from Air-Con executives/senior managers and from middle managers with responsibility for various Air-Con departments. Also direct observations were made during a number of factory tours. This provided a multilevel of abstraction, process-oriented, structural model of operational and tactical processes (and their elemental activities) used by Air-Con; also detailed interactions and interdependences between operational and tactical processes and between different organizational units of Air-Con. Understanding the interdependencies between tactical and operational processes (such as those conceptualised by Figure 15) was found to be critical to later conceptually designing multilevel of abstraction “fit for purpose” simulation models which enable integrated planning decision making. Step S1 modelling also provided a structural framework for later system of system decomposition, which at needed levels of abstraction described Air-Con departmental units and their subsections; that is, organised sets of product realization, engineering, and business functions carried out in the various sections of the company.

To facilitate steps S2, S3, and S4, the authors also captured a significant body of resource subsystem and work subsystem data. This data specified the current “actors” (i.e., supply chain partners, departments, people and supporting machines and IT systems) assigned to process-oriented roles; the way that work flows (physical and logical) are currently routed through various “process-resource couples” deployed by the company. The used coherent modelling concepts were set within the modelling framework illustrated in Figure 10, such that S2, S3, and S4 modelling led at multiple levels of abstraction to explicit representations of “as is” configurations of process, resource, and work subsystems (in the form previously illustrated in Figure 12). Those visual representations helped communicate current patterns of use of valuable resources. They also help to qualify how different classes of product flow through Air-Con product realising processes added value to products and subproducts and how they incurred product realising costs. This ability was later proven to be critical to enabling Air-Con personnel to better understand resultant impacts when they do not satisfactorily constrain product customisations. At those various levels of abstraction, the correctness of the multilevel visual structural models was tested by consulting Air-Con managers and engineers with relevant assign responsibilities. As outlined further in Section 5, an estimate total modeller time spent conducting phase 1 modelling is 15 person days, while the aggregate time involvement of Air-Con personal when informing that modelling is estimated at 18 person days.

The authors met again with senior and middle managers and engineers to review the graphical models of Air-Con’s current architecture and to consider what was collectively believed to be Air-Con’s primary opportunities and problems. Middle managers articulated many problems, but there was a common view that lack of integrated working between departments was leading to poor due date adherence and major difficulties in adhering to cost estimates. It was agreed that the outcomes of these integration problems were felt at all (strategic, tactical, and operational) levels. Two highly troublesome operational behaviours were articulated as being the following: Air-Con assembly shops need to be rescheduled 70% of the time; cash flow constraints were significantly delaying purchasing work which causally resulted in high make shop and assembly shop inventories and late deliveries of final products to customers; a need to reschedule with further cash flow problems ensuing. It was believed the fault was poor integrated working between departments (as a consequence of lack of understanding and data about other company sections, but also for organisational reasons) and that then current Air-Con planning activities were "infinite capacity" based, resulting in impossible demands being placed on colleagues.

During phase 1 modelling additional and parallel causal loop modelling ([16, 24]) was also carried out to investigate the nature of some of the key interactions between the so called CIMOSA domain processes; with particular emphasis on trying to explain observed cash flow behaviours.

The authors characterised the observed phenomenon as "over the wall planning" and previously illustrated in Figure 15; a consensus view held amongst the modellers and managers was that this was due to lack of clarity and suitable integration of the roles illustrated; which was leading to piecemeal, ill-informed, and frequently "self-interested" decision making and action taking.

After these discussions, by following modelling steps B1 to B4 of the model-driven approach the authors conceptually designed and then created a set of multilevel of abstraction SMs which (as discussed in detail in the PhD theses of Cui [15] and Kodua [16] were designed to provide an analytic basis for determining improved patterns of enterprise behaviour. Here focus of attention was on

(i) changing the sales, engineering, purchasing and production planning architecture, and the processes used individually and collectively by holders of sales, engineering, purchasing and production planning roles, and to determine some critical future operational policies which will reduce delays in product realisations and improve cash flow behaviours,

(ii) investigating impacts of alternative product classes (families and types) on profit generation and feasible capacities of the various make and assembly production system units deployed by Air-Con.

Significant phase 2 modelling efforts, linked directly to the Ph.D. studies of Cui and Kodua, were expended when exploring both general model integration issues involved when transforming model structures, between multilevel structural models and coherent "fit for purpose" behavioural models; on Air-Con specific case problem solving and new policy recommendation. Therefore, it is difficult to estimate the total time spent on phase 2 modelling for Air-Con—but this was considerably in access of the time spent during phase 1 Air-Con modelling.

Consequent on phase 1 and initial phase 2 Air-Con modelling by the authors, the company wanted to consider three optional ways of achieving the planning of its operations. Therefore, it was decided that predicted behavioural outcomes from using three decision making structural arrangements would be simulated; during which it was envisaged that our modellers would quantify impacts of alternative types of synchronous and asynchronous decision making on the running of multilevel of abstraction models of Air-Con product realisation. This was expected to enable the company to visualise and predict likely contrasts and comparisons between the three planning options in terms of due date adherence, profit generation, and cash flow behaviours; given alternative scenarios of work types and mixed workloads that could feasibly be received from customers and their mappings onto alternative production system configurations.

Option 1 was to retain their current approach to planning. Option 2 was to utilise a new distributed planning team; with members from sales, engineering, purchasing, and production departments armed with new planning and work attribution policies which had been virtually tested. While option 3 was to first adopt option 2, then in addition to commission a proven IT system vendor to implement new “proprietary enterprise planning” and “contract progressing” software which would support the new distributed planning organisational structures; by so doing would more definitively systemise and semiautomate Air-Con planning practice.

The simulation study needed to make assumptions about how improved quality and timeliness of information interchange between sales, contract planning, production planning, and purchase planning person roles might occur. Following which during virtual testing, it was shown that based on the various assumptions made improved decision making polices could in theory significantly reduce late deliveries and cash flow problems. The thesis of Cui (2001) explains that a key change in policy recommended was for planning personnel to be cognisant of data about (1) significant product type differences their impacts on lead-time, value generation, rework, purchasing delay, and production costs and (2) impacts of capacity constraints in various Air-Con product realising sections. By following the prime recommendations of Cui’s simulation study, Air-Con successfully implemented significant organisational change towards team-based (and hence better integrated) holistic planning of their many product realisations; they are now negotiating the implementation of new IT systems. Longer term they may consider a fourth option in which “fit for purpose” SM-based decision support tools are developed for particularly exacting planning roles.

It is observed however those downsides of Air-Con’s next set deployment of any large scale proprietary planning system are likely to be (1) additional high investment and running costs and (2) that some poor architectural aspects of the Air-Con business may become fixed invisibly into a monolithic software system. Unfortunately however available Air-Con project time did not permit a follow-up study centred on using Zachman/CIMOSA driven model creation, as a front end to the use of TOGAF concepts, to design and implement a suitable and changeable IT system; that better systemises and provides coherent information support for the newly integrated roles of its planning team.

## 5. Reflections and Conclusion

This paper has provided some background definitions related to ME architectures and has made observations about the state of play in the use of enterprise and decision-making architecture in a significant number of companies. Also described has been a current gap in the provision of analysis tools that can virtually test the efficacy of any architectural design in current use (or in proposed use) given properties of a particular ME and its working environment. Further reported is how the authors and their research colleagues have begun to address this lack of modelling provision in support of the design of better integrated decision making systems. A new approach to creating and testing architectural models is described. Particular attention is paid to describing the potential role that decomposition and multi-perspective, multiple level of abstraction modelling can play in formally and explicitly capturing architectural structures of manufacturing enterprises. Also described in overview has been how this approach has been case-tested with estimates given regarding the modelling efforts required. Finally a more detailed case description is included to explain how the results of the virtual testing of an ME architecture can practically deliver significant competitive advantage to the company concerned.

The reader is requested to reconsider Figure 14 at some length as in concept this figure describes the basis via which architectural structures encoded by any given EM can be coherently transformed (using the developed set of modelling concepts) so that they can be reencoded into sets of coherent simulation structures that can be computer executed by a selected class and type of simulation tool. Because there are potentially many strategic and tactical decision making roles that people must play in MEs, potentially that recoding needs to be done in multiple ways so that simulation experiments can be performed with custom built scope and focus of concern; related to the decision making roles requiring analytical support and the types of experiment the role holders need to carry out.

In the current version of the model-driven approach, the structural transformation process (needed to map between enterprise and simulation model forms) is not carried out in an automated fashion. Rather the required transformations have to be conceived and used by the modeller relative to an agreed specification. But the systematic structural modelling steps (S1 to S4) are founded in general systems engineering thinking and decompositions and thereby enable initially separated but subsequently integrated modelling of process, resource, and work structures. This is supported by suitable formal modelling decompositions and representational mechanisms so that a parent process-oriented architecture encoded by an EM can be fleshed out with resource system assignments and/or with attached work flow attributions at required levels of granularity. This is done using the integration diagrams and associated spreadsheets to organise and record specific case data. Essentially therefore the model-driven architecting approach provides an extension to public domain knowledge and best practice enterprise architecture by focussing explicit representation of architectural structures in ways that can be recoded using typical modelling constructs provided by various proprietary simulation tools.

As described in a number of Ph.D. theses, it has proven practical in Air-Con and other companies for our researchers to conceptually design a variety of simulation models, with related sets of simulation experiments that have provided decision making support for a number of strategic and tactical decision maker roles. Furthermore, we have proven that by such means possible changes in architecture (coded into a developed EM) can be virtually tested prior to any implemented decision making. Additionally, we have shown that because SMs are derived from the same parent architecture, experimental results can be semiautomatically ported from one experiment to another, despite change in scope and abstraction level. Essentially this is a key step to achieving holistic decision making. We have also in example experimental scenarios qualitatively compared our use of multiple fit for purpose models with that of using a single more complex SM to serve a number of ME roles; from which generally we have found that the later approach only proves practical where the reality is heavily constrained such as where only "toe in the water" virtual testing can prove satisfactory.

We refer to the process of transforming structures between enterprise and simulation models, and then running them in a virtual environment (i.e., in a simulation tool), as "*executing architecture.*" Of course that architecture, or even a selected part of it, is not executed automatically. Rather currently the model-driven approach requires the modeller (and/or the model user) to carrying out architecture execution via conceptual thinking, experimental design, data capture, then the running of models and results interpretation. But the model-driven approach can provide a vital step towards being able to simulate the reachable behaviours of different architectural structures, as its process gains synergy from using two

**Table 2:** Person-days involved during S1, S2, and S3 structural modelling in the four case study MEs.

| | | | |
|---|---|---|---|
| Air-Con<br>World leading supplier of industrial air-conditioning systems<br>(i) Improved due date adherence and cash flow management, via integrated planning and purchase planning policy improvements | Process-oriented enterprise model<br>(i) 7 days via<br>capture<br>structured interviews and ongoing development | Work system classification and work flow modelling<br>(i) 4 days by interviews and ongoing dialogue | Three-level resource systems modelling<br>(i) 4 days by observation, accessing documents, and interviews |
| ISF<br>(International Shop-Fitter)<br>European and north American supplier of point of sale furniture<br>(i) Improved design of the ISF multiproduct supply chain and focussed on assembly systems balancing | Process-oriented enterprise model capture<br>(i) 20 days via structured interviews and ongoing development | Work system classification and work flow modelling<br>(i) 15 days by accessing documents and interviews | Three-level resource systems modelling<br>(i) 12 days by accessing documents and interviews |
| Project aim<br>AEM<br>(Aircraft Engine Manufacture)<br>(i) Conceptual design of AEM supply chain focussed on assembly systems balancing | Process mapping and enterprise model development<br>(i) 10 days via structured interviews and document analysis | Work system classification and work flow modelling<br>(i) 3 days by accessing documents and interviews | Three-level resource systems modelling<br>(i) 4 days by accessing documents and interviews |
| Project aim<br>AMC: commercial aircraft manufacturer<br>(i) Conceptual design of the AMC supply chain focussed on assembly systems balancing | Process-oriented enterprise model capture<br>(i) 5 days via structured interviews | Work system classification and work flow modelling<br>(i) 3 days by accessing documents and interviews | Two-level resource systems modelling<br>(i) 6 days by accessing documents and interviews |

types of modelling technology (enterprise and simulation). Currently in industry we have only seen people enacting architectural structures in strategic or tactical senses by talking about and drawing architectural structures, by borrowing reference architectural patterns (like Postponement, Lean, or RMS) from other companies/domains and then by implicitly enforcing structure via chains of command. We have yet to observe cases where this kind of practice is supported by analytic reasoning about the efficacy desired/implemented/imposed structures. Critical in seeking to rationalise aspects of architecture is an ability to handle complexity and change, and that is why the model-driven formalisms are designed to cope with the high levels of complexity we have observed in our collaborating partner businesses.

A further important point to make is that Phase 1, structural modelling alone can lead to significant company benefit by helping ME decision makers to visualise and communicate the importance of ME system of system architectures and how they are positioned within a wider decision making process. Relative to phase 2 modelling, the authors have observed that normally phase 1 modeling is much the simpler and requires significantly less technical knowledge and effort before benefit begins to be gained. Table 2 has been constructed to illustrate that in the four LME cases earlier discussed significant benefit was quickly realised from better understandings gained ME structures; that is, by investing in (expert) modeller times of the order of the person days shown.

The authors believe that their approach can lead to an advance in best practice architecting and that successive and successful case study virtual testing should lead wider industry in the not too distant future to address some of its outstanding complexity and change issues. Currently the authors are formally redocumenting their modelling methods so that they can be exploited as part of wider management and technical consultancy methods and/or so that opportunities to create various decision support tools can be investigated further.

## Acknowledgments

Sincere thanks go to the author’s very many research colleagues and collaborators for their friendship and shared ideas over the last three decades. Particular recent thanks are due to Dr. Zihua Cui and Dr. Kobby Agyapong-Kodua.

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Hindawi Publishing Corporation
Advances in Decision Sciences
Volume 2012, Article ID 804324, 25 pages
doi:10.1155/2012/804324

*Research Article*

# The Integrated Use of Enterprise and System Dynamics Modelling Techniques in Support of Business Decisions

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Received 16 December 2011; Revised 23 March 2012; Accepted 6 April 2012

Academic Editor: Bernard Grabot



Enterprise modelling techniques support business process (re)engineering by capturing existing processes and based on perceived outputs, support the design of future process models capable of meeting enterprise requirements. System dynamics modelling tools on the other hand are used extensively for policy analysis and modelling aspects of dynamics which impact on businesses. In this paper, the use of enterprise and system dynamics modelling techniques has been integrated to facilitate qualitative and quantitative reasoning about the structures and behaviours of processes and resource systems used by a Manufacturing Enterprise during the production of composite bearings. The case study testing reported has led to the specification of a new modelling methodology for analysing and managing dynamics and complexities in production systems. This methodology is based on a systematic transformation process, which synergises the use of a selection of public domain enterprise modelling, causal loop and continuous simulation modelling techniques. The success of the modelling process defined relies on the creation of useful CIMOSA process models which are then converted to causal loops. The causal loop models are then structured and translated to equivalent dynamic simulation models using the proprietary continuous simulation modelling tool iThink.

## 1. Introduction

A body of literature related to current trends in MEs has explained the enormous complexities and dynamics associated with the design and realisation of business processes [1–7]. Although MEs are inherently complex, traditional methods for solving problems in MEs have not fully accommodated complexities and causal relationships associated with processes in MEs [8, 9]. MEs are inherently complex because they are composed of complex process networks which are interrelated in a way that changes made to one process thread induce dynamics in the ME by having causal and temporal effects on other process threads [10].

System dynamics has been defined as a computer-aided approach to policy analysis and design. It has usefully been applied to dynamic systems characterised by interdependence, mutual interaction, information feedback, and circular causality [5]. Research in the modelling and management of complexities in dynamic systems has resulted in the derivation and application of a number of system dynamics modelling tools and techniques. Notable among these are fuzzy logics (FLs) [11–15], neural networks (NNs) [16–20], Bayesian networks (BNs) [21, 22], Petri nets (PNs) [7, 23–25], causal loops (CLs) [7, 26–30] and stock and flow models [5, 7, 31, 32]. Reflecting on the above-mentioned system dynamic modelling techniques and their application in managing complexities and dynamics in MEs (see Table 1), the CL modelling technique is considered most suitable for representing, qualitatively, the cause and effects evident in dynamic systems [32, 33]. Other researchers [33, 34] have mentioned that CLs are useful for creating dynamic models of businesses for alternative policy verification. Their unique advantage stands on their being able to be aligned with appropriate simulation software for quantitative business analysis. Further basis for the support of the CL modelling technique was based on a set of performance criteria reported earlier by one of the authors [6]. In this earlier work by the first author, it was established that different assessment indicators may be considered when reasoning about suitable modelling techniques for business analysis of complex and dynamic manufacturing systems. This work showed that for a modelling technique to be relevant and provide useful inputs for multiproduct manufacturing systems' design and business analyses, it should have

(i) the ability to analyse multiproduct flows and their associated product dynamics,

(ii) the ability to identify and capture aspects of complexities and dynamics in MEs,

(iii) the ability to reflect causal impacts of activities in MEs on performance indicators especially in financial terms,

(iv) the ability to support business analysis especially in a virtual environment,

(v) the capability to decompose processes into elemental activities to enhance understanding and process analysis.

Although many other factors such as lead time, quality, and innovation are necessary, it was considered at this stage of the research that the above five criteria were useful for detecting modelling techniques which were capable of supporting business analyses of complex and dynamic manufacturing systems.

Based on these indicators, Table 1 shows a review of 5 of the major system dynamics tools available in the public domain. From the review it can be mentioned that although CL modelling had been useful in many business analyses, it generates qualitative results and cause and effects cannot be simulated using CLs alone [10, 32]. Thus on its own, CL cannot facilitate quantitative prediction of outcomes. As a result, the authors are of the view that although the CL modelling technique performs better than other SD modelling techniques in some aspects, the technique requires further support for it to be suitable for systems' design and business analysis [29]. Because of these limitations, the authors are of the view that, for full benefits of CL modelling in support of business decision analysis to be obtained one has the following.

(1) There is the need to provide a structure around the modelling technique. This implies providing a means of specifying actual factors which influence situations in their context of application; in-effect modelling in context.

**Table 1:** Review of system dynamics modelling tools [6].

| Modelling tools | Analysis of multiproduct flows and product dynamics | Identification and capturing of aspects of complexities and dynamics in MEs | Reflection of causal impacts of activities on financial indicators | Business analysis in virtual environments | Suitability for process decomposition |
|---|---|---|---|---|---|
| (a) Causal loops (CLs) [5, 26, 27, 35] | Causal loop models are not product specific. They represent the causal effects of activities. Specific product-based causal loop models can however be generated | The identification of aspects of complexities and dynamics can be modeled through CL modelling technique | CL models can be made to depict the causal impacts of activities on financial and economic indicators in MEs. This depiction is however qualitative and cannot accurately be quantified in the CL technique | CL cannot be simulated | Processes are not decomposed in the CL modelling technique. It aggregates processes for top-level business analysis |
| (b) Petri net (PN) [23, 24] | PNs can accommodate levels of product complexities but will require a formalized approach for doing so | PNs are suitable for capturing aspects of system dynamics. Process models can be extracted from CIMOSA or IDEF3 models | PNs are able to analyse qualitative causal effects of activities of dynamic systems | They support alternative business decision making and PNs make simulation explicit on graphical tools | Petri nets inherently support the end-to-end modelling of processes without consideration of organizational boundaries. |
| (c) Bayesian networks (BNs) [36] | BNs are a statistical modelling tool and could help classify products but not model products with their process. It is not a process modelling tool | BNs are capable of representing aspects of dynamics and complexities in MEs in the form of variables and their probabilistic independencies | Causal relations can be captured and represented as conditional dependences and used for onward analysis | BNs support decisions of alternatives but will require rigour to exemplified in the virtual world of MEs | There are no decomposition techniques associated with BNs |
| (d) Fuzzy logic (FL) [11, 12] | FL feeds on the fuzzy set theory to support reasoning, but it does not explicitly model processes | Complexities can be expressed but in a statistical manner | Causal relations could be depicted but limited to variables and not processes | It is a probabilistic tool which supports programming languages | No decomposition required |
| (e) Neural networks (NNs) [16–18] | Factors influencing multiproduct flow can be developed and modelled through the application of NNs but not as a process. For example, NNs can be used to group products into their respective classes based on a mathematical or relational algorithms. It cannot match graphically products to their processes | The application of NNs in real life is suitable for modelling complexities especially the complexity of data and not ME design | It is capable of reflecting ca usal impacts through the expression of algorithms | It is a useful decision modelling tool which support computer applications | Processes are not decomposed. It is not a process modelling tool |

(2) The useful models derived from the use of CLs should be transformed into equivalent dynamic simulation models so that alternative business scenarios and "what-if" experiments can be conducted.

(3) There is the need to develop a methodology which addresses the requirements specified in (1) and (2).

A number of researchers have provided explanations to how CL models can be quantified. Key findings and recommendations on the transformation of CL to quantifiable models have been made by researchers such as [5, 27, 32, 35, 37]. These researchers from the systems modelling school have enhanced CL modelling by providing mathematical and social support to the technique. Unfortunately, only little has been done towards the comprehensive use of the technique in support of manufacturing process design and analysis as well as the translation of qualitative CL models to quantitative simulation models. In many instances, CL modelling has been considered as not being suitable for modelling "processes." They are used to capture factors which induce dynamics on systems.

To help overcome the limitations observed in the use of CLs, the authors have developed and tested an integrated EM-SD methodology comprising the systematic use of CIMOSA, CLs, and a continuous simulation modelling tool called iThink. Also the fundamental purpose of harmoniously deploying a combined enterprise and dynamic systems modelling approach was to address critical issues of complexity handling observed when problem solving in many example manufacturing enterprises (MEs). This paper describes how a specific case selection and unification of enterprise modelling and dynamic systems modelling concepts, methods, and techniques was developed and usefully deployed in the a case study described in Section 3.

The application of the proposed methodology was tested in a rapidly growing bearing manufacturing company called ACAM Ltd. The motivation of the company in supporting the deployment of this modelling methodology was to help better understand

(1) the impact of variations in their customer demand on actual value generation and material cost,

(2) the effect of constant sale orders on material supply,

(3) the effect of company operations on payments or revenue generation.

These issues were considered complex by the managers of ACAM Ltd., and most importantly, they felt that demand variation and material supplies were critical factors impacting negatively on their business.

Section 2 of this paper considers the essence of the proposed combined enterprise and dynamic systems modelling approach and reflects on knowledge contributions made, whilst Section 3 centres on the case application of the integrated EM-SD methodology. In Sections 4 and 5, the observations, recommendations, and conclusions are mentioned.

## 2. The Integrated EM-SD Modelling Methodology

The starting assumptions made when conducting the research were as follows.

(1) MEs commonly deploy a system of systems so that they conduct business, engineering, production, logistical, servicing, and other, functions in an effective and well-ordered manner. The elemental systems of MEs typically comprise people,

machine, information, and communication resource elements onto which various kinds of organisational structures are overlaid, such that deployed resource elements function coherently as part of one or more wider systems.

(2) To achieve the purposes of each ME, complex interactions need to occur between the various resource elements deployed. If the impacts of these interactions on the behaviours of the ME can be better understood and predicatively quantified then potentially, desirable interactions can be enabled and undesirable ones constrained. But observations made in many different MEs have shown that those understandings need to be developed from a variety of decision-making viewpoints requiring multiple and (ideally) coherent models of ME systems at a number of levels of abstraction.

(3) To cater for inherent system complexities and enable multilevel of abstraction modelling, it was assumed that a number of approaches to decomposition (which had been developed previously by the systems engineering and enterprise Modelling communities) could be deployed in a unified fashion.

(4) Bearing the forgoing in mind, three primary forms of decomposition selected and deployed by the authors were (a) separated development and deployment of structural and behavioural model, such that differentiation could be made between system characters that are essentially static (during the time frame of modelling) from other system characters that will posses dynamic (changing) behaviours; (b) during structural modelling to separately capture and visualise process, resource, work subsystem viewpoints, so that during subsequent modelling and decision making amongst alternative system configurations (comprising (current or possible future) system components and their organisation structures) that can be explicitly and visually represented and communicated, as needed with reference to various other system viewpoints; (c) the use of various hierarchy concepts, particularly to identify and encode boundaries, ownerships, and encapsulations embedded within actual and modelled systems and their processes, resource elements, and work structures.

(5) Also bearing in mind the forgoing, the authors perceived that various forms of "fit for purpose" system behaviour modelling would need to be conducted, at required levels of modelling abstraction that normally would require aggregations of process, resource, and work model viewpoints, such that qualitative and predictive decision making support can be provided as commissioned for many potential types of model users that could be supported. Critically, however, the authors observed the need for "fit for purpose" behaviour modelling to be conducted with reference to the organisational context in which specific and collective ME decisions are made, that is, with reference to previously conducted ME structure modelling. The purpose of doing so would typically be to facilitate coherent decision making amongst multiple decision making groups (such as ME directors, multilevel managers, and plant personnel).

Figure 1 conceptualises the essence of the combined enterprise and dynamic systems modelling approach developed and reported upon in this paper. As shown in Figure 1, having captured the process-oriented "big picture" of any subject ME, the next structural modelling steps are to (a) attribute (current or possible future) resource models to segments of process which as explained in Weston, Rahimifard et al. 2009 [38] require the matching

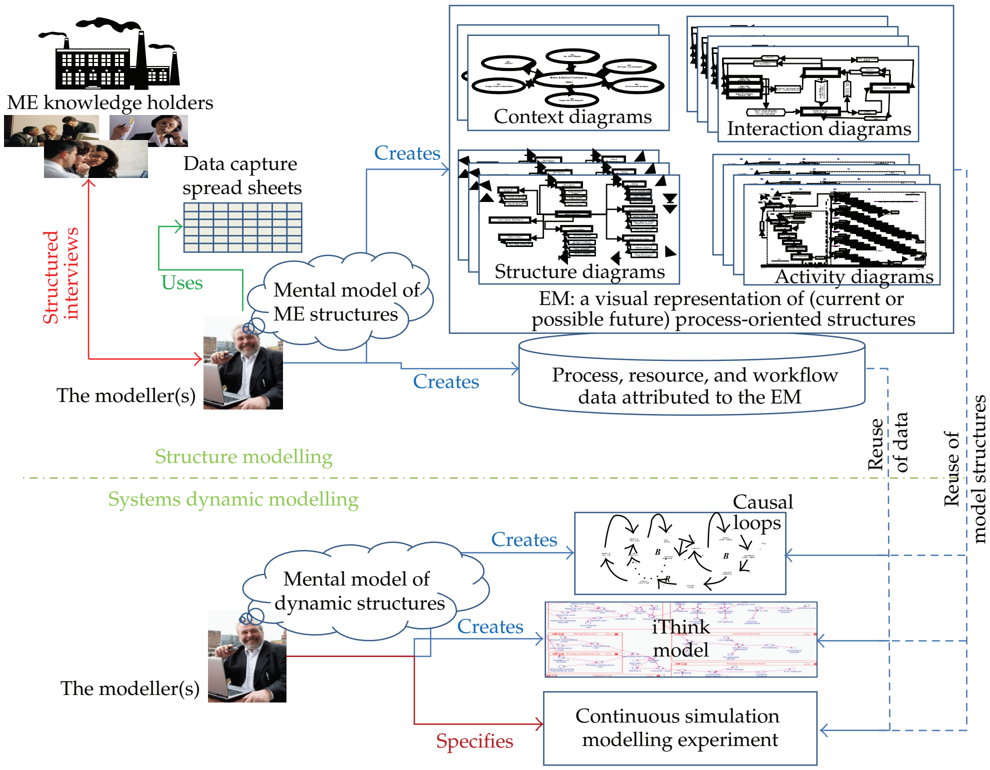


**Figure 1:** Combined enterprise and system dynamics modelling approach.

of "role requirements" to "competencies possessed by (human, machine or IT) resource candidates, that is, as potential role holders" and (b) map modelled flows of cognate work types through combined models of process and resource subsystems [38]. At this stage of modelling the explicit capture of many types of real case ME data needs to be encoded at multiple levels of abstraction so that the validity of the captured data and the organisational structures that are represented can be assessed by relevant ME knowledge holders.

Further work by the authors and their colleagues has shown how processes can be classified as enterprise domains (DMs) and decomposed into their respective domain processes (DPs), business processes (BPs), and elementary activities (EAs) [2–4, 39–43]. In essence, Enterprise Domains represent functional areas of the enterprise which are decoupled from each other with clearly identified objectives which enable them to be composed of well-defined processes for achieving the objectives defined for the domain. Based on the observed goals and associated processes, stand alone processes, called domain processes (DPs) are grouped to reflect the distinctions in goals and deliverables. In a graphical form, the achieved goal of a collection of DMs is modelled using suitable templates and this is termed as "context diagram." At the next stage of the process decomposition, interactions between respective domains in terms of information and material flow are modelled. The outcomes of this modelling stage are captured using a so called "Top-level Interaction diagram." The interaction diagram therefore shows relationships that exist between the domain processes. Textual descriptions can be expressed but for the sake of simplicity a graphical representation of the interactive processes and their resultant elements of interaction are normally developed. At the next stage of modelling, DPs belonging to CIMOSA conformant DMs are further decomposed into lower-level processes called Business Processes (BPs). Relationships between BPs are described in subinteraction diagrams. Based on the sub-sub interaction diagrams, which represent aspects of flows among BPs, a top-level causal structure can be created to clearly represent the direction of flows.

The explicit structural model of the subject ME so created is not directly computer executable in the sense that it cannot support quantitative prediction about the many possible time-based ME interactions and behaviours that might lead to competitive performance given a set of external or internal change scenarios. This is because the structural models produced do not encode system dynamics, such as events and state transitions. In the authors' studies, this has proven to be both an advantage and disadvantage. It is advantageous because it has systemised and enabled decomposition, captured and explicitly integrated representations of structurally connected sets of relatively simple multiperspective, multilevel of abstraction models which collectively illuminate a big picture of the ME. This picture can also be progressively detailed as needs and funds come on stream, and can cope with the presence of high levels of inherent systems of system complexity. But the disadvantage is that quantitative assumption testing is not readily supported.

On completion of this modelling stage, generally significant new insights will be inducted into the subject ME, as knowledge holders discuss the pros and cons of their best practices which are illuminated by the structural model. Essentially the big picture ME model so captured has proven to be an extremely valuable repository of ME knowledge which can be reused in a variety of ways. Those ways include helping decision makers position their thinking and then subsequent more holistic decision and action taking, reuse of the encoded organising structures to enhance decision and action processes and to underpin those processes with better design IT systems, and constructing "what if" scenarios which can begin to justify improved policies and practices throughout the ME.

Typically, for further dynamic analysis, the initially created CL models have to be redefined and "structured" to be able to provide useful contributions towards analytical decision making and quantification of CLs. Thinking about developing structured causal loop models (SCLMs), a set of rules are defined to help reorganise the variables identified in the initial causal loops. The starting point is to identify variables with measurable and operational meanings. Starting from this point enable other variables to be connected in such a way that estimation of "operational variables" can be determined through the "factual analyses" of the connecting variables. Whilst doing this, care is taken to ensure that the resultant SCLMs consist of variables which are causal, deterministic, time variant, directed and signed.

Although the resulting SCLMs are still qualitative, all parameters will have operational and measurable indicators so that at the next stage a "stock and flow model" can be created by defining stocks, flows, and converter variables. The quantifications of the final stock and flow model are supported with the iThink simulation tool.

Essentially the method of modelling described in the forgoing is not the prime focus of modelling science contribution reported in this paper. Rather the focus is on a newly developed means of reusing big picture models of ME structures (that are populated with a myriad of real case ME data) within multipurpose dynamic systems models that can support predictive scenario analysis at multiple levels of abstraction. To maintain the paper within acceptable limits, this paper is focussed on one form of big picture structural and data model reuse. Whereas other research of the authors [2–4, 39–41, 43] reports on complementary reuses of the same structural models and data in support of (a) multilevel of abstraction "fit for purpose" discrete event simulation modelling of alternative manufacturing paradigms, including the use of Lean, Agile, Economies of Scope, and Scale and Postponement strategies and (b) as a front-end to IT data base and decision support system design/specification.

Because of the observed complexity involved in doing so, the authors have not made any attempt to fully systemise the reuse of ME big picture structural models, such as by automatically transforming them into coherent sets of multipurpose dynamic systems models; rather as also conceptualised by Figure 1, the authors' focus of study has been on enabling

(i) big picture decomposition and representation that allows dynamic systems modellers to form effective and flexibly configured mental models of ME structures which can be mentally transformed by the modeller at appropriate levels of abstraction into equivalent mental models of casual and temporal structural dependencies between variables of systems that impact significantly on ME behaviours of current modelling concern,

(ii) big picture decomposition and representation that allows dynamic systems modellers to form effective and flexibly configured mental models of ME structures that guide the specification of mental models of scenarios of system and subsystem change, along with appropriate KPI determination that will lead to qualitative analysis of relevant objective functions,

(iii) the combined reuse and transformation of effective mental models of ME structures, causal and temporal relationships, and scenarios of system and subsystem change into mental models of stock and flows that can be readily encoded using stock and flow modelling concepts; which subsequently can be implemented and run using an appropriate choice of continuous simulation modelling tool.

## 3. Case Application of Integrated EM and SD Modelling Methodology

ACAM Ltd. is a small-to-medium-sized bearing manufacturing company located in the United Kingdom. ACAM Ltd. makes ordering of a range of advanced composites bearings. These products are normally fibre-reinforced plastic laminates, ideally suited to highly loaded bearing applications in agricultural, marine, mechanical, pharmaceutical, and food processing environments. In addition to producing customised bearings and specialized structural bearings, washers, wear rings, wear pads, wear strips, rollers, and bushes, ACAM Ltd. also produces semifinished bearing materials which are made available in tube and sheet forms.

To help provide in-depth understanding about the processes involved in ACAM Ltd. and also provide a context for the application of SD models, an enterprise model (EM) was created and used as the backbone for the creation of SD models. The EMs so created show how ACAM processes can be decomposed into elementary activities and used to support further business analysis.

### *3.1. Creation of the CIMOSA Enterprise Model of ACAM Ltd.*

Initial steps taken to understand ACAM processes involved the creation of a "static" enterprise model that captures relatively enduring aspects of the processes and systems used by ACAM.

On resumption of the modelling exercise, a series of structured and unstructured interviews and shop floor visits were conducted to enable better understanding of ACAM

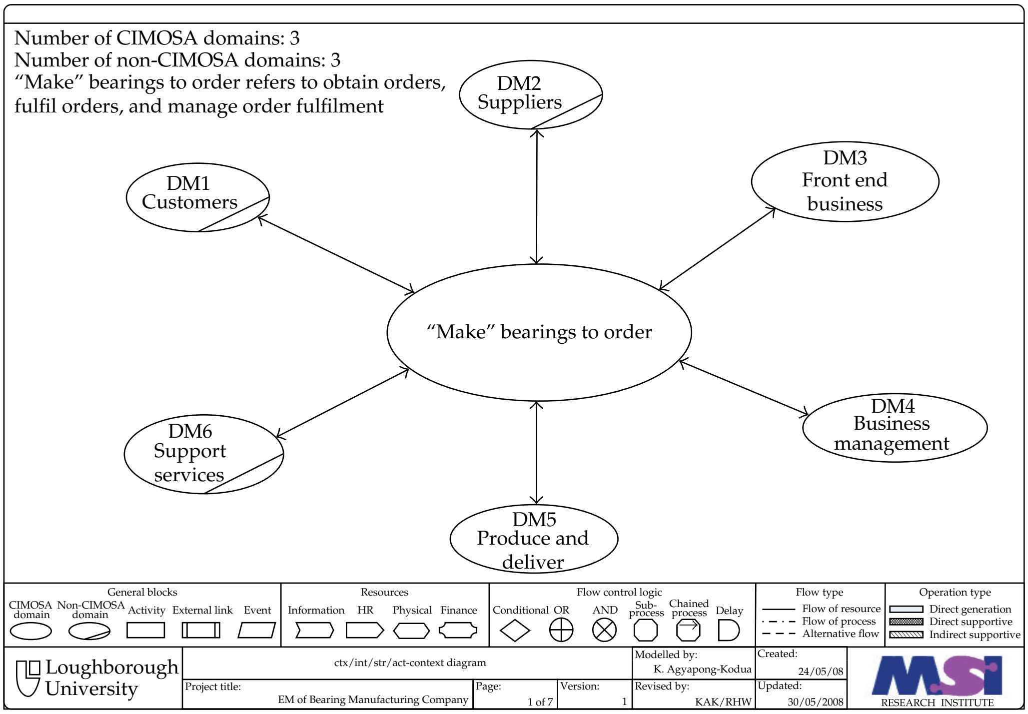


**Figure 2:** Context diagram of ACAM Ltd.

Ltd. processes. A full documentation of the interview questions and their responses is provided in [6]. In addition to the data and information gathering exercises, company production data, human resource organization charts, sales, and finance data were also examined. Initial understandings of the company processes were documented and described in the form of a spreadsheet and later transformed unto revised versions of the CIMOSA modelling templates, as described in [6, 41]. Based on these earlier understandings about process decomposition, a context diagram, as shown in Figure 2, was created to represent all the DMs observed in the company. As can be seen from Figure 2, six main domains were observed with three of them being considered to be Non-CIMOSA domains. DM1 is used to represent the set of processes belonging to the customer domain. DM1 is therefore responsible for providing orders to ACAM Ltd., receiving finished bearings in time and making prompt payments. DM2 is used to describe the processes performed by the suppliers of raw materials to ACAM Ltd. A set of processes belonging to sales, planning, and designing was classified as "front-end businesses" and denoted as DM3. The managerial and supervisory activities needed to ensure the fulfilment of orders were termed the "Business Management" (DM4) domain. DM5 refers to the "physical processes and activities" required to fulfil customer orders. This represents the actual material transformation processes required to convert raw materials into finished goods. Finally, DM6 is used to represent the support processes required for the fulfilment of the other domains.

In correspondence with the main theme of the DMs, a high-level interaction diagram was created to depict how respective domain processes interact (see Figure 3). At the next stage of the enterprise modelling exercise of ACAM Ltd., a decision was taken to further understand the process interactions that existed between the sub-business processes of DP3

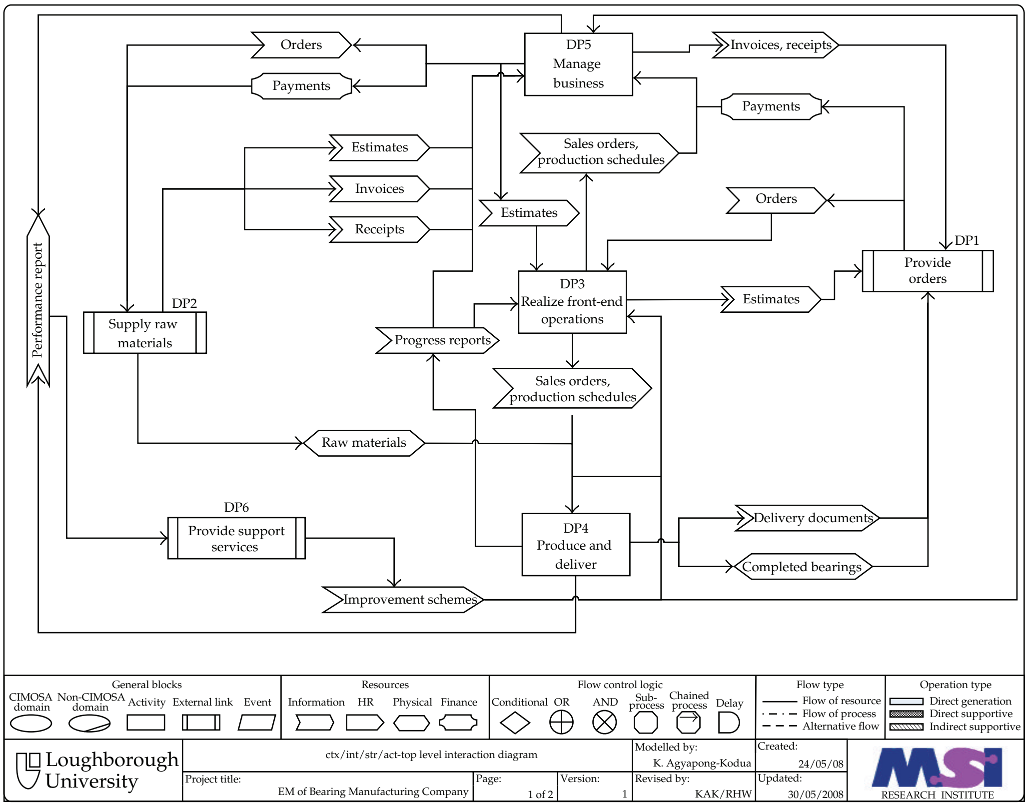


**Figure 3:** Top-level interaction diagram.

and DP4. Efforts were concentrated on further decompositions of DPs 3 and 4, because discussing with the Production managers of ACAM Ltd, it was concluded that the company was essentially interested in knowing how front-end, and production activities impacted on their business. This decision matched well with the research objectives since basically the objective was to further help provide a backbone for understanding the impacts of dynamics on subprocesses. A subinteraction diagram showing how material and information flows between BP3.1, BP3.2 and BP3.3 is shown in Figure 4. Instances of interaction of these BPs with external DPs such as DP1, DP2, DP4, DP5, and DP6 are also shown in the figure.

A careful study of the subinteraction diagram shown in Figure 4 shows that, orders are received by the "obtain and process orders" (BP3.1) from the external domain process belonging to the customer domain. By realizing BP3.1, sales orders are generated and transferred unto a job card which becomes the major input information for "produce designs" (BP3.2) and "plan and schedule production" (BP3.3) processes. Bills of materials (BOMs) derived from the realization of BP3.2 are transferred to DP5 for purchases and estimated to be prepared and sent to suppliers and customers, respectively. Product drawings, BOMs, and design specifications are also derived through BP3.2 and transferred to DP4. Upon receipt of purchase orders, suppliers supply raw materials to DP4 for further processing.

A second subinteraction diagram showing the flow of materials and information between BP4.1 and BP4.2 is shown in Figure 5.

Knowledge gathered from the creation of the subinteraction diagrams showed that BP4.1 and BP4.2 were the main production business processes. Thus to fully understand

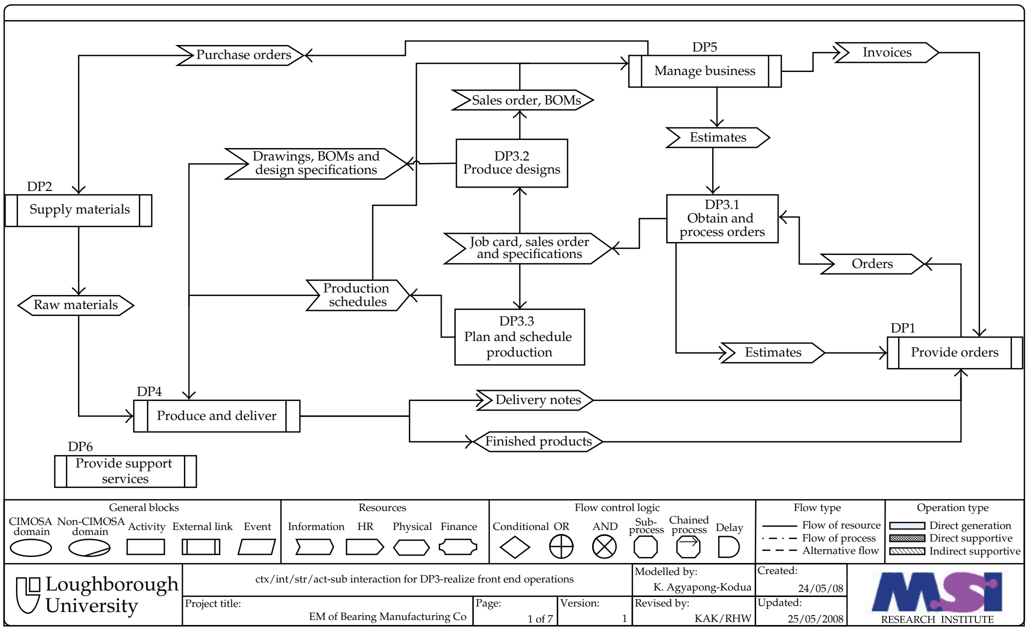


**Figure 4:** Subinteraction diagram for DP3.

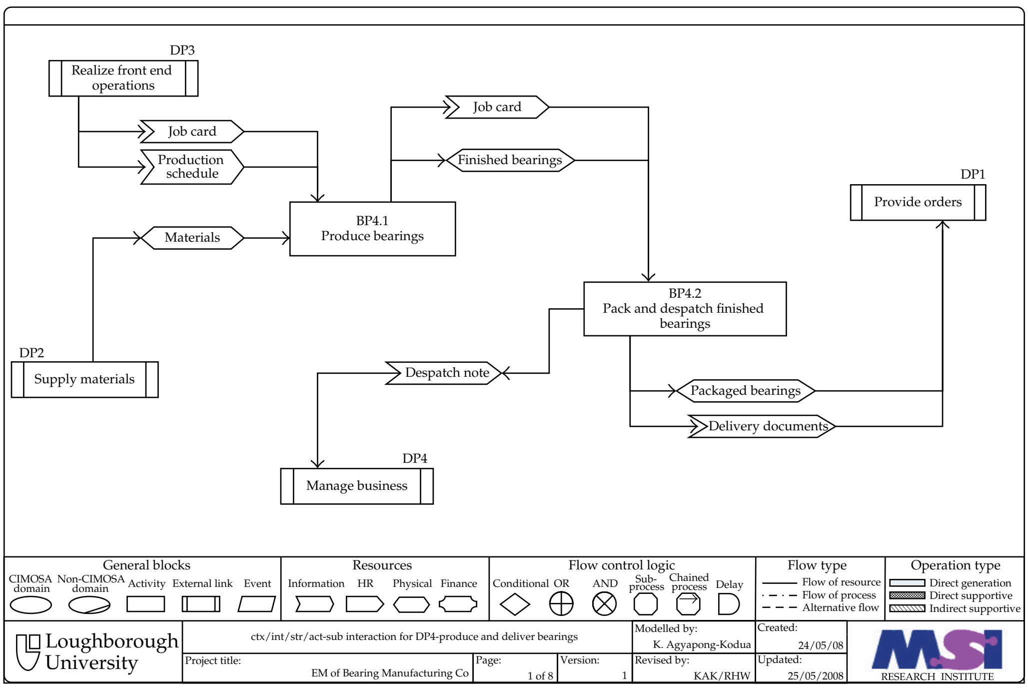


**Figure 5:** Subinteraction diagram for DP4.

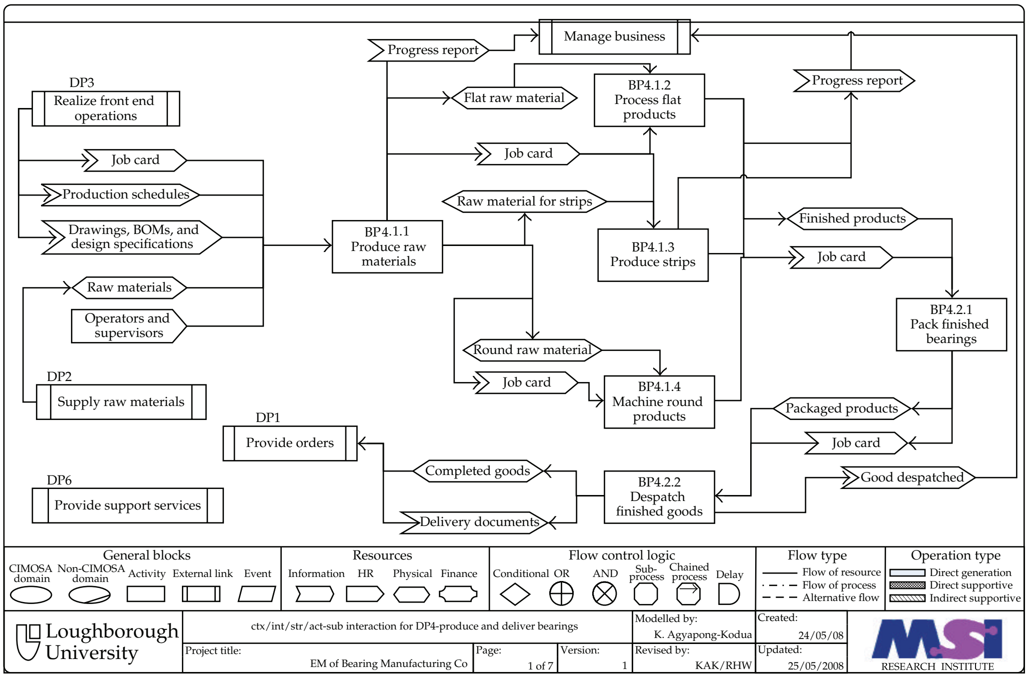


**Figure 6:** Sub-sub interaction diagram for BP4.1 and BP4.2.

implications of production activities on business indicators such as cost and value generation, there was the need to further create interaction diagrams describing the various flows that exist between the sub-business processes of BP4.1 and BP4.2. These further elementary interaction diagrams were called "sub-sub" interaction diagrams. Figure 6 shows the sub-sub interaction diagram describing the flows that exist between subprocesses of the BP4.1 and BP4.2.

Activity diagrams for each of the BPs described in the sub-sub interaction diagrams can be created to illustrate how BPs are decomposed into their elementary activities. At this stage, the creation of activity diagrams for each of the BPs was considered not necessary. This is because, fundamentally, the CIMOSA models created are to serve as a backbone for understanding process interactions and the various flows among BPs so that dynamic analysis of factors which impact on business processes can be understood and based on the understanding derived, provide solutions for managing complexities and dynamics in manufacturing processes. The sub-sub interaction diagram was adequate to provide the basis for understanding the cause and effects structure of the company.

### *3.2. Creation of Dynamic Models of ACAM Ltd.*

The sub-sub interaction diagrams created enabled understandings to be gained about the various flows and interactions that exist between key production business processes. A careful study of the top level interaction diagram (Figure 3) reveals that there is no direct interaction between "provide orders" (DP1) and "supply raw materials" (DP2). Also there is a unidirectional interaction between "supply raw materials" (DP2) and "produce and

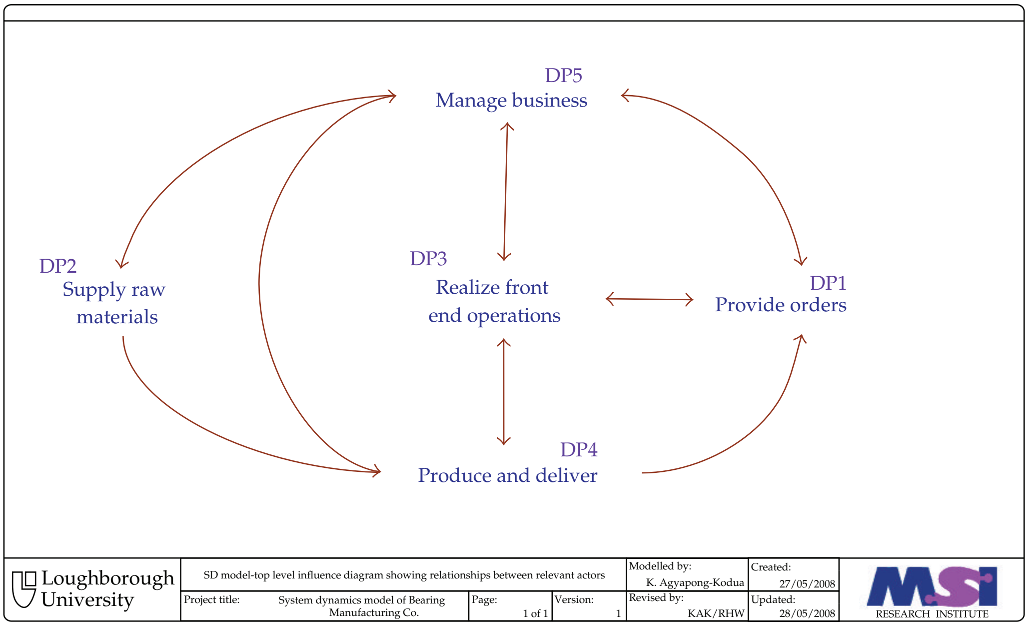


**Figure 7:** Top-level causal structure of domain processes.

deliver bearings" (DP4). Similarly, a unidirectional interaction exists between "produce and deliver bearings" (DP4) and "provide orders" (DP1). However bidirectional interactions exist between "provide orders" (DP1) and "realize front-end operations" (DP3); "provide orders" (DP1) and "manage business" (DP5); "realize front-end operations" and "produce and deliver bearings" (DP4); "produce and deliver bearings" (DP4) and "manage business" (DP5); "manage business" (DP5) and "supply raw materials" (DP2). Identifying the directions of flows and interaction between domain processes led to the creation of a "top level causal structure" diagram (see Figure 7) which was considered to be the starting point for the derivation of causal loop models from enterprise models. The top level causal diagram shows a simplified illustration of the domain processes which interact with each other and their direction of interaction. The top level causal structure diagram served as the parent model upon which specific process parameters were extracted and modelled in detail.

An initial causal loop model describing how customer orders influence purchases and supply of raw materials is shown in Figure 8. Customer demand is influenced by a number of factors but because these factors are external to the main business domains, investigations were not carried out to establish the actual variables influencing customer requests.

Internal sales records showed that customer demands were received through e-faxes, emails, post and telephone. About 92% of these customer requests turned out to become sales orders. As would be expected, the increase in customer demand increased the number of sales orders produced. The preparation of sales orders is performed through BP3.1.1 (create sales order/job card) which belongs to DP3 as shown in Figure 8. An increase in the number of sales orders created will increase the material requirements as well as the number of different bearings required. Increase in material requirements implies that the number of individual material components will increase. From their material purchase records, normally four main raw materials are purchased. These are broadly classified as paints, clothes, resins

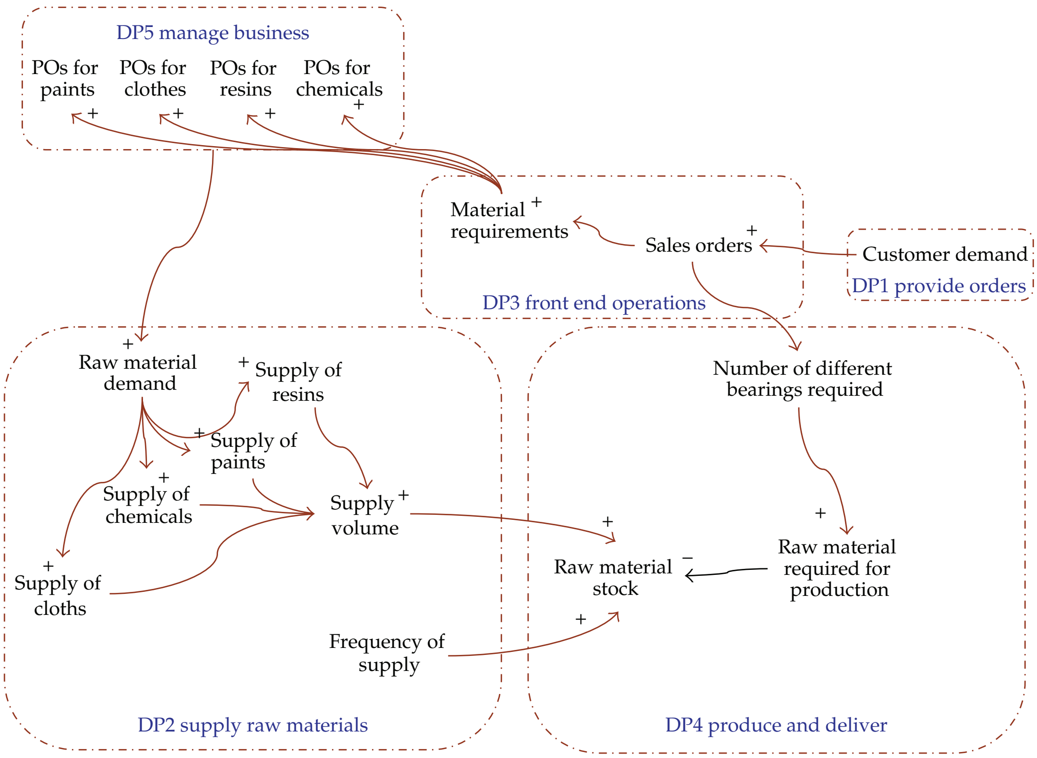


**Figure 8:** Initial CLM illustrating factors affecting raw material stock.

and other chemicals. Thus an increase in material requirements means an increase in the purchase orders (POs) of these components. Collectively as the number of POs raised by the "manage purchases" business process (BP5.4) increases, the total raw material demand also increases. This demand triggers the supply of the materials specified by the POs. In effect, the total supply volume increases as shown in the CL model in Figure 8. However the actual raw material stock is influenced by a number of factors which include the supply volume and supply frequency. Internally, the raw material stock is negatively influenced by the consumption of material through production processes. This is expressed in the form of material required for production in the "produce and deliver" domain process (DP4).

A more detailed description of the causal influences of BP4.1 is shown in Figure 9. A study of the sub-sub interaction diagram showing the process interactions of BP4.1 and BP4.2 shows that in the "produce and deliver" domain process (DP4), raw materials are processed to meet the material requirements for producing flat products (BP4.1.2), strips (BP4.1.3) and round products (BP4.1.4). Therefore the total raw materials required will be equivalent to the sum of the total raw materials for flat, strips and round products, whose quantities are grossly influenced by the total number of bearings derived from the sales orders. As shown in Figure 9, the total number of flat, strips and round products is dependent on the processing rates of the production shops in charge of producing these components. The processing rates of the three shops are themselves influenced by a number of factors such as: number of activities, resource requirements, resource capabilities and competence, material availability, machine availability, among others.

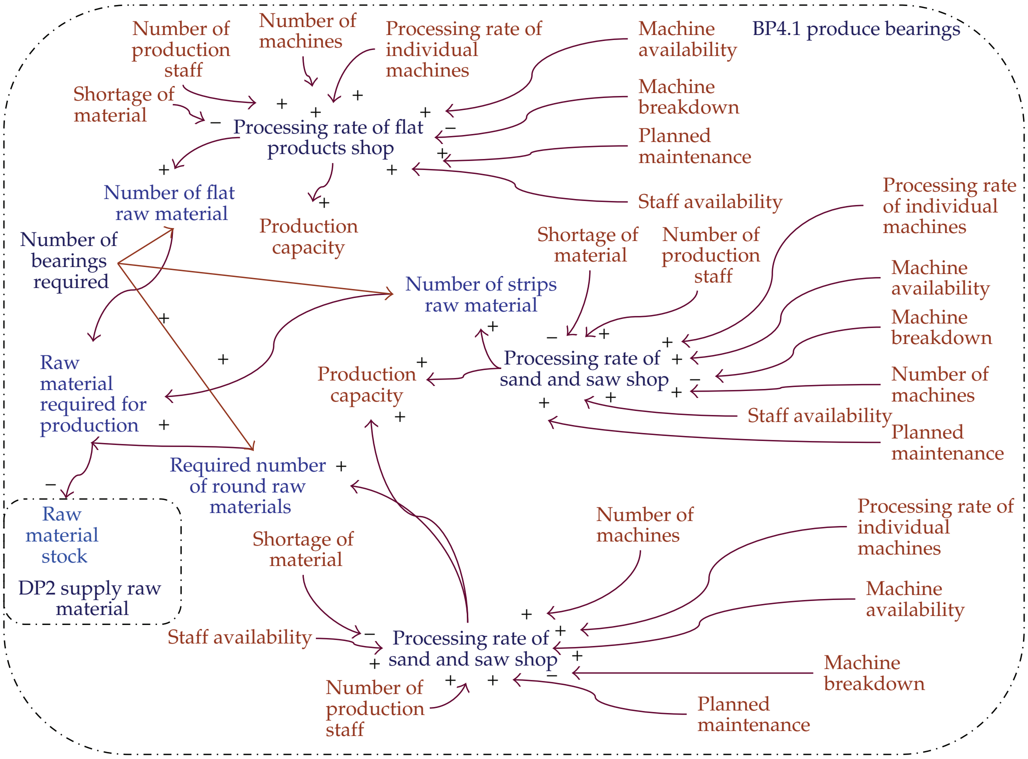


**Figure 9:** Initial CLM for bearings production (BP4.1).

Another initial CLM created to describe the influences of process variables on the "pack and despatch of bearings" business process (BP4.2) is shown in Figure 10. As shown in the figure, the actual numbers of flat, strips and round products realized is dependent on the processing rate of the various production shops responsible for the making of these products. Other factors which influence the processing rate of the shops are described in Figure 10. In the CLM for the "pack and dispatch" (BP4.2) process, the number of products packaged is dependent on the total products finished. Other factors include the availability of packaging materials and the rate of packaging. The increase in number of packaged products increase the number of bearings despatched. However, other factors such as delivery rules, availability of despatch vans and internal despatch priorities positively affect the number of bearings despatched.

### *3.3. Creation of Structured Causal Loop Models (SCLMs)*

The CL models shown in Section 2.2 were helpful in describing qualitatively the causes of dynamics in selected key business processes of ACAM Ltd. With the view to achieving SCLMs of relevance to performance indicators such as cost and value, the initially created CLMs (see Figures 8, 9, and 10) were revised based on the requirements described above. Figure 11 is an extension of the initial CLMs presented in Figures 8, 9, and 10. It was derived through an extensive study of the previously created CLMs. As shown in Figure 11, to quantify customer needs, customer stock levels are taken into consideration. A negative

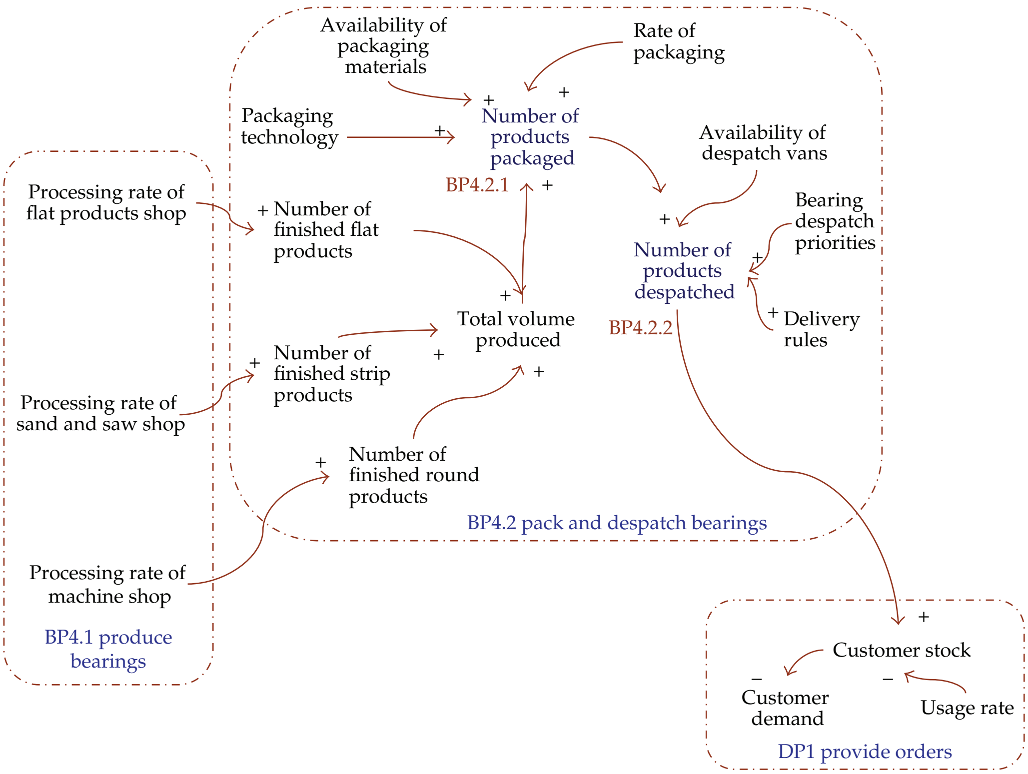


**Figure 10:** Initial CLM for "pack and despatch bearings" (BP4.2).

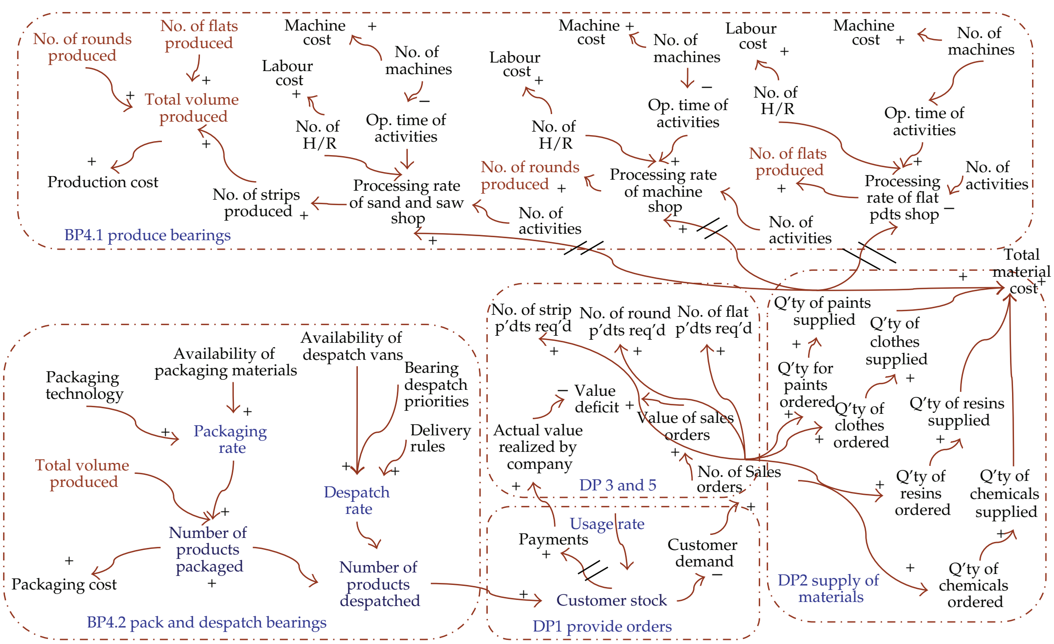


**Figure 11:** Extended CL model.

polarity is indicated because as customer bearing stock level reduces, customer demand increases. Customer stock level is affected by a number of factors. Again, for the purpose of creating a structured causal loop model, the broad range of factors such as customer bearing failure rate, machine breakdowns, preventive maintenance schedules, customer stocking policies and other influencing factors are described simply as customer usage rate. In practice, ACAM Ltd. operates directly with most of the engineering departments of their customers and is able to predict their maintenance cycles. Although ACAM Ltd. is not in favour of stocking bearings, their historic patterns of sales are able to predict the bearing usage rate of their customers. In a more complex model, customers will have to be classified based on their usage rates, so that distinct analysis can be made for each customer. One critical thing derived from customer demand is the number of sales orders prepared by ACAM Ltd front-end business (DP3) process. It was verified that about 92% of customer enquiries become sales orders; hence the number of sales orders generated within six months can be estimated. One other critical information from customer stock level is "payments received" by ACAM Ltd. Although this link is not vivid, it is implied that since bearings are supplied before payments are made by customers, the quantity of bearings required to be paid by a customer is the difference between the "paid stock of bearings" and the "unpaid received stock of bearings".

Most often there are some delays in payments. The actual value realized by ACAM Ltd is the total payments received from customers. But for budgeting purposes, ACAM Ltd estimates the total sales value from the number of different sales orders received. The estimated value of sales orders almost always exceeds the actual payments received from customers, so a "value deficit" is created.

From the number of sales orders received, useful production and supply information can be deduced. This is reflective in the information presented on job cards and production schedules. On the production schedule the expected number of strips, round and flat products is indicated. The difference between the expected number of products and the actual manufactured products is the backlog ACAM Ltd needs to deal with. The actual production volume is affected by real production variables such as processing rates of the production shops, materials available, human resource, machine availabilities and bearing type. Based on the number of sales orders, the designers estimate the quantity of materials required. These quantities are compared with existing stock levels of materials to enable specific material orders to be raised. Historic data exist for number of material orders raised over the six-month period. In some cases, the actual materials supplied did not match exactly with the quantity of materials ordered. Reasons provided by the Production Managers included the unavailability of materials in the suppliers' domain, counting errors and wrong deliveries, among others.

The total material cost is estimated by the cost of the total materials supplied. There is also a difference in actual cost of materials and material cost paid by ACAM Ltd. This is due to the payment arrangements and delays between ACAM Ltd. and some of their suppliers.

In the "produce bearings" domain, the factors specified in Figure 8 were simplified and reorganized to provide a background for quantitative analysis of the production requirements in the shops. The key factors influencing the production rate of the shops were observed to be the number of activities required to fulfil specific orders. Taking into consideration the operation time of these activities, the number of bearings produced over time can be estimated. The operation time is a historic data which takes into account human resource and machine availabilities, breakdowns and all necessary adjustments in the shops. To help estimate the machine and labour cost, the number of machines and human resources required for the activities in the shops are shown. The labour, machine, material and storage cost influence

**Table 2:** Classification of stock and flow variable.

| List of relevant modelling variables | Stocks | Flows | Converter |
|---|---|---|---|
| Customer stock | x | | |
| No. of sales orders | | | x |
| Usage rate | | x | |
| Payments | | | x |
| Actual value realized | | | x |
| Value deficit | | | x |
| Sales value | | | x |
| Volume of materials ordered | | | x |
| Volume of materials supplied | | | x |
| Material cost | | | x |
| Volume of products required | | | X |
| Processing rate of shops | | x | |
| Number of activities, machines, and human resource | | | x |
| Operation time of activities | | | x |
| Stock of bearings produced | x | | |
| Labour, machine, storage, production cost | | | x |
| Packaging rate | | x | |
| Volume of products packaged | x | | |
| Volume of products despatched | x | | |
| Despatch rate | | x | |
| Packaging cost | | | x |
| Delivery cost | | | x |

the total production cost. If these cost components are expressed in units related to number of products realized then production cost can be deduced from the production volume.

In the "pack and dispatch" business process, it was also understood that packaging technology, and availability of packaging materials were factors which affected the packaging rate. In the same way delivery rules, despatch priorities, and availability of despatch vans affected the despatch rate. Packaging cost can be estimated by deriving the unit cost per product packaged from the resources and materials required for packaging. Finally, the increase in the number of products despatched increase the customer stock.

As can be seen from the SCLM, efforts were made to express the otherwise descriptive variables into variables with operational and measurable meanings whilst taking care not to violate the rules for the creation of effective CLMs. To gradually transform the qualitative model into a quantitative model, at the next stage of modelling, the variables specified by the SCLM were classified into stocks, flows and auxiliaries.

### *3.4. Determination of Stock, Flows, and Converters*

Based on these definitions and distinctions, Table 2 was created to help specify the stocks, flows and converters in the SCLM shown in Figure 11.

### *3.5. Creation of iThink Simulation Models*

The identification of stocks, flows, and converters in SCLM makes it possible for an iThink model to be created. Referring to Table 2 and the SCLM presented in Figure 11 and adding

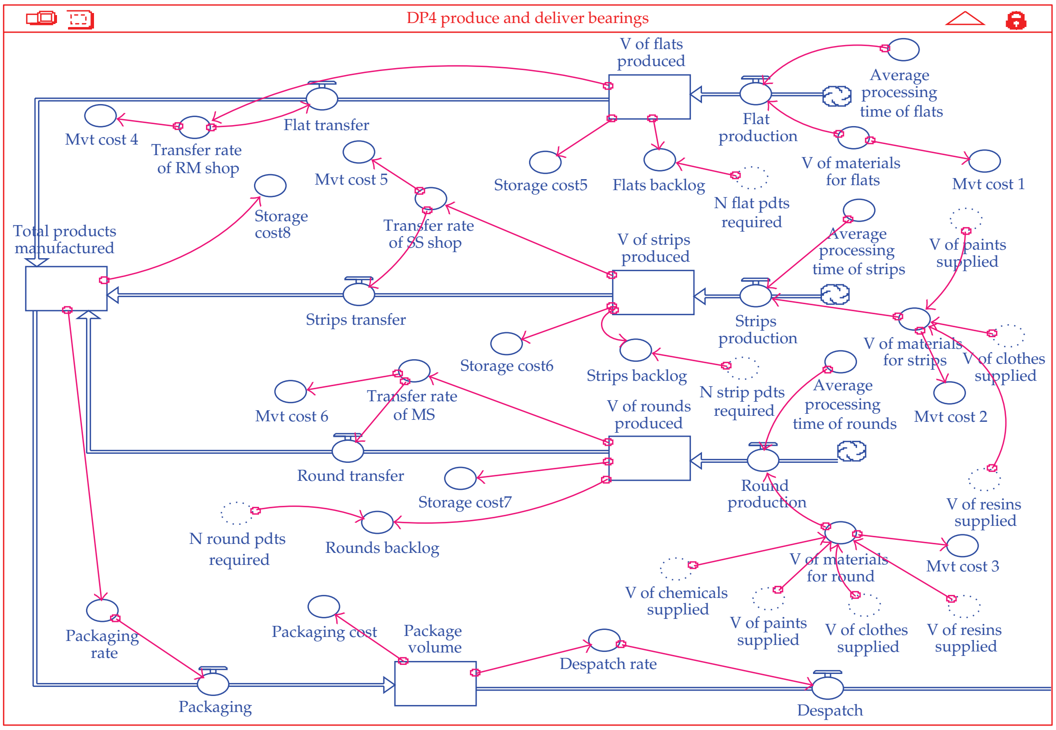


**Figure 12:** iThink model of DP4.

additional process variables which will enhance the algebraic relationship between process variables, iThink simulation model for various DPs was created. A snapshot of iThink model for one frame belonging to the "produce and deliver" domain process (DP4) is shown in Figure 12. Similar iThink models for the other DPs were created but not presented in this paper for the lack of space.

### 3.5.1. *Simulation Results and Business Analysis*

To help verify the iThink models, efforts were made to observe how the structure of the model reflected the reality. This was done through studying the already created SCLMs and asking the managers of the shops to help verify if the model structure fairly represented the processes under consideration. To validate the process logics and controls of the simulation models, actual historic data in the form of production orders, interarrival times, order batch sizes, operation times and resources deployed, were inputted into the models. When the data set was inputted into the model, the operation cost, revenue generated, average throughput, process times and delivery volumes were found to conform to the real state of ACAM Ltd.; hence the model was found to be sufficiently valid for use for further experimentation.

Figure 13 shows graphically the relationship between customer demand, value generated and material cost. As shown in Figure 13, because of the nature of the production system, the relationship is not linear. A study of Figure 13 shows that, in ACAM Ltd., customer demand fell gradually from the beginning of the accounting year. The fall in demand had significant impact on actual value realized. Because of the random nature of

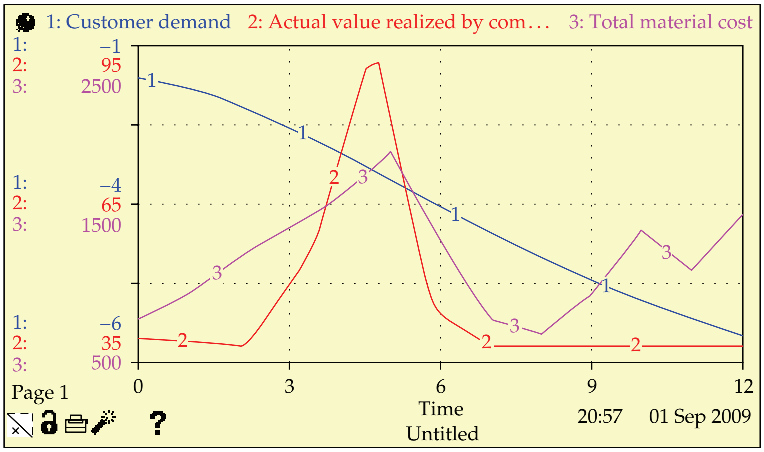


**Figure 13:** Results showing the impact of customer orders on value realization.

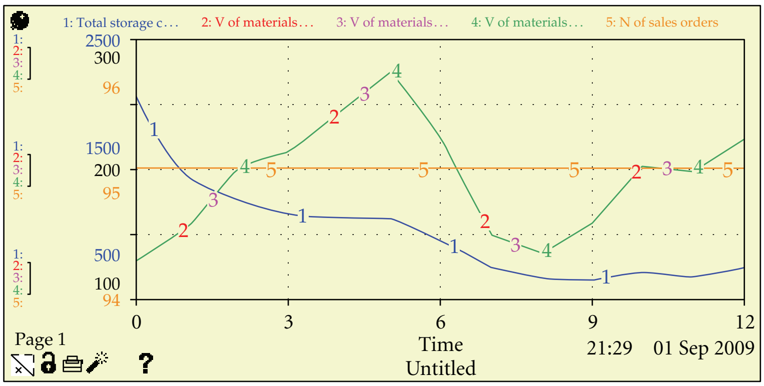


**Figure 14:** iThink model results for supply of materials.

payments received from customers, actual value realized is largely different from "expected value" which is essentially dependent on number of sale orders for a given month. As shown on the graph, there is a gradual rise in value which means more payments are received at the beginning of the year with the peak of "actual value realized" being in the fifth month. As customer demand reduces, there is a sharp fall of "value realized" until it reaches its lowest level in the seventh month.

Another set of results showed the effect of constant "sales orders" on "volumes of strip, paints and chemicals supplied" as well as "total storage cost" (see Figure 14). It was expected that when customer orders are steady, volumes of materials supplied will be constant, but the model assisted in understanding quantitatively the impact of material supply policies on ACAM Ltd. production system. The graph showed that purchasing was not synchronized with customer orders. When this was verified from the managers of ACAM Ltd., they explained that supplies of materials are forecasted based on previous production orders. As actual production orders achieved differ largely from customer orders, actual number of sale orders did not directly impact on their volume of material supply.

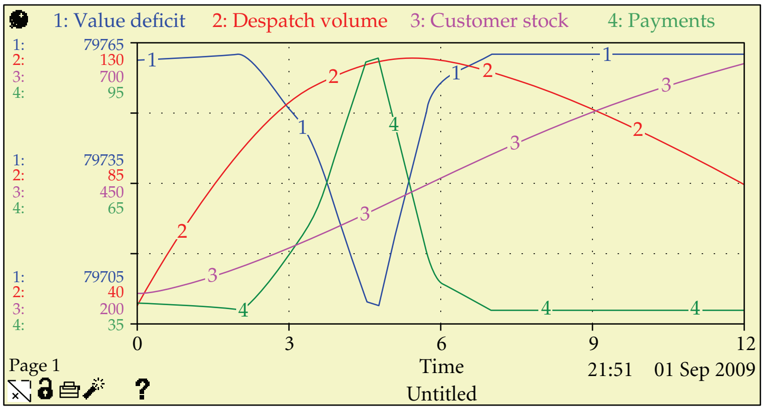


**Figure 15:** Effect of variables on payments.

Figure 15 also shows that payments are inversely proportional to "value deficit," but as "supply" increases, "customer stock" increases whilst "despatch volume" increases and falls over the period.

Many other results related to total manufactured products, despatched volumes, process cost, material storage cost, and packaging cost were collated but have not been presented in this paper for the lack of space.

## 4. Observations and Recommendations

### *4.1. Observations about the Integrated EM and SD Methodology*

Previous sections of this paper have shown example outcomes of how structural models and their encapsulated data can be reused via the use of suitable "in context" mental models of types outlined in Sections 2 and 3. The authors have yet to find a good way of representing the visual models so created, but Figure 16 has been constructed to show the types of system entity that are naturally encoded in the structural model and through processes of mental modelling are positioned appropriately into structural designs of causal loops and continuous simulation models. The reuse so enabled has proven effective in positioning and creating "fit for purpose" multilevel, multipurpose CLM, and continuous simulation tools for clients, where the clients have anchored the understanding so generated both within ME wide and with respect to specific domains of their expertise.

It follows that the new science reported in this paper is about showing how the synergistic use of various kinds of mental, structural and dynamic systems model can facilitate complexity handling and lead to better and faster dynamic analysis of complex systems.

The combined approach to modelling is not tied to any specific case modelling methodology or tool. Rather in several of their other complementary papers, the authors describe the use of alternative frameworks and tools, but the essence of this contribution is the conceptualisation of a methodology for creating and positioning "fit for purpose," multilevel of abstraction models within the context of a host ME and its environmental stimuli.

In the study case, as in many other MEs, the authors and their former colleagues in the MSI Research Institute at Loughborough University extended the use of CIMOSA modelling concepts. Those extensions were made primarily to provide support within any

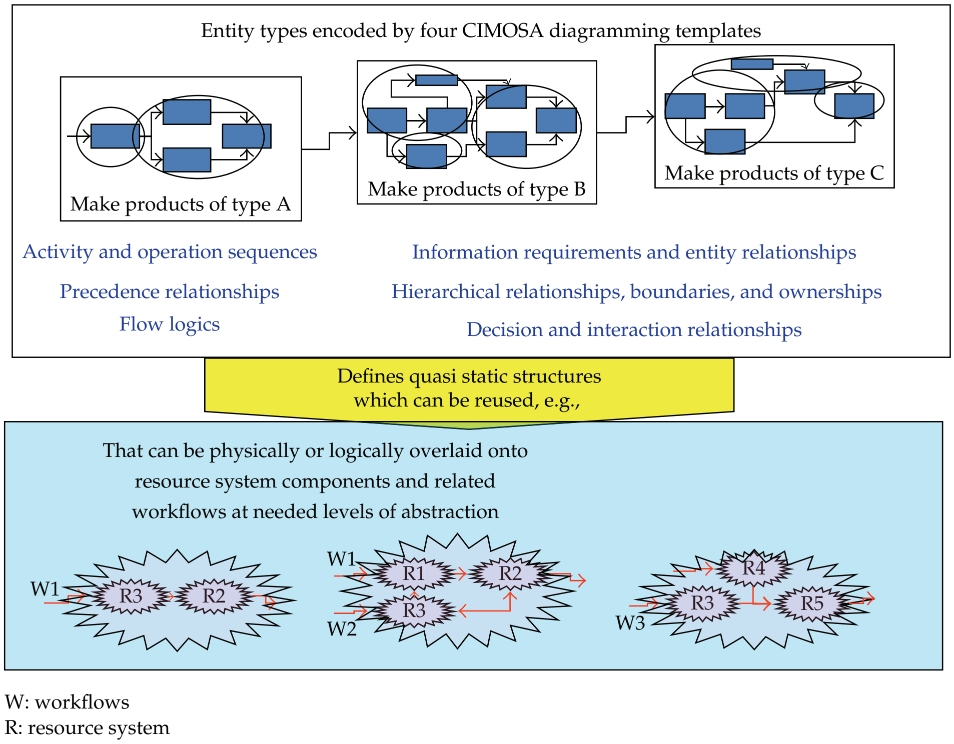


**Figure 16:** Entity types encoded in structural models.

given ME setting the rapid and effective capture, visual representation and validation of process-oriented structures used by the ME being studied. The purpose of doing so was to create a "backbone process-oriented **structural model**" the detail of which can be fleshed out over time and onto which other modelling viewpoints can be attached. To enable this stage of process-oriented modelling two main extensions were developed, namely (1) to visually document the ME's (current and/or possible future) processes (and their elemental activities) using the four types of diagramming templates illustrated earlier by Figures 2–5 (which in effect implemented CIMOSA function modelling viewpoint) and (2) to create and deploy a simple structured questionnaire which is used as a common basis to consult with all relevant types of decision makers, in order to ensure that sufficient real case data is elicited to populate the four process-oriented modelling templates, and to provide a structural framework onto which captured real case data encoding entities related to the resource and work subsystem viewpoints could be attributed. To instrument (1) and (2) and reduce the (company and modeller) people times involved during modelling, the authors developed and used a combination of Visio and Spread Sheet tools as reported in Agyapong-Kodua [6]. As earlier discussed, CIMOSA was by no means the only viable choice of enterprise modelling technique. However its process-centric approach to decomposition was found to provide a useful starting point for structural modelling onto which other viewpoint and modelling concepts (such as those supported by the GRAI methodology, ARIS, and the IDEF suite of tools) can be added.

### 4.2. *Observations about the Application of the Modelling Methodology in ACAM Ltd.*

The Managers of ACAM Ltd. confirmed that the integrated modelling approach enabled understanding about their business, especially how resources and information flow from one unit to the other. This was helpful for them to understand the implication of activities in one department on the other. More critically, it was an excellent way of illustrating the factors which could be controlled and monitored to reduce cost and improve value. It was observed that the integrated method served as a strong modelling tool for capturing most of the salient factors in the company related to its "architectural structures" and how these structures impact on (time based) "organisational behaviours".

With a base model created for analysing the performance of ACAM Ltd., further experiments on process variables can be conducted to analyse optimal business performance in terms of process efficiencies, cost, and values generated by the company, resource utilisation, among others. Essentially, the integrated models offer a means of:

(a) replicating and understanding historic enterprise behavior,

(b) predicting future enterprise behaviours and impact on performance indicators,

(c) experimenting alternative decisions before implementation, to save cost and minimize errors.

## 5. Conclusions

Dynamics impacting on business processes (BPs) have been modelled using an integrated EM and SD approach. Following the modelling approach, complex structure and dynamics impacting on aspects of the business, especially those influencing cost and value, were captured. Also the interaction between key system parameters was identified. The efficient modelling of the interactions was necessary, since it provided a thorough understanding of the system behaviour and provided basis for assessing the system performance under various operating conditions. The models supported the company in measuring their state of performance under varying conditions. In principle, the approach enabled the systematic deployment of candidate EM and SD tools for assessing the impact of decisions on key performance indicators including cost and value.

Future research work will look at alternative means of simplifying the integration methodology so that nonexpert system modellers can also populate data into enterprise models for in-depth business process analyses.

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Hindawi Publishing Corporation
Advances in Decision Sciences
Volume 2012, Article ID 589254, 19 pages
doi:10.1155/2012/589254

*Research Article*

# Design of an Integrated Methodology for Analytical Design of Complex Supply Chains

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Received 5 February 2012; Accepted 2 May 2012

Academic Editor: Bernard Grabot



A literature review and gap analysis indentifies key limitations of industry best practice when modelling of supply chains. To address these limitations the paper reports on the conception and development of an integrated modelling methodology designed to underpin the analytical design of complex supply chains. The methodology is based upon a systematic deployment of EM, CLD, and SM techniques; the integration of which is achieved via common modelling concepts and decomposition principles. Thereby the methodology facilitates: (i) graphical representation and description of key "processing", "resourcing" and "work flow" properties of supply chain configurations; (ii) behavioural exploration of currently configured supply chains, to facilitate reasoning about uncertain demand impacts on supply, make, delivery, and return processes; (iii) predictive quantification about relative performances of alternative complex supply chain configurations, including risk assessments. Guidelines for the application of each step of the methodology are described. Also described are recommended data collection methods and expected modelling outcomes for each step. The methodology is being extensively case tested to quantify potential benefits & costs relative to current best industry practice. The paper reflects on preliminary benefits gained during industry based case study modelling and identifies areas of potential improvement.

## 1. Introduction

Supply chain systems are inherently complex [1]. With reference to manufacturing enterprises (MEs) and their supply chains, the term complexity has been defined in different ways. For example, Kambil [2] states that complexity is related to the amount of variety at and across processes, while Snowden [3] defines complexity in terms of visibility and order in casual relationships [4]. Also observed that supply networks are dynamically changing webs of relationships that are becoming more complex. Wider product variety, smaller production lot sizes, more tiers, and different actors involved in coordinated supply chains also cause supply chain complexity [5]. Factors that have resulted in the need for greater variety of products realised by common sets of resources are presenting major challenges to ME managers and engineers, including production managers and engineers. Greater emphasis is often being placed on redesigning products and processes, so that the negative impacts of product variety due to product proliferation (and thence increased system complexity) can be partially overcome [6]. This kind of phenomenon has led modern organizations to implement new supply chain paradigms and adopt new techniques to support rapid design, analysis, and implementation of these new paradigms [7].

Fine [8] observed that an important core competence of an organization is its ability to design an effective supply chain. Supply chain management (SCM) techniques can be drawn from a collection, customization, and implementation of tools to that fit the environment in which they are to be used [9]. Knowledge about business processes (and their impacts on supply chains), and their supporting information technology systems, can help to underpin the reengineering, integrating, planning, and optimizing supply chains [10]. Supply chains are dynamic in the sense that they involve a changing flow of information, products, and funds, between their different operational stages; it is important to visualise information, funds, and product flows in both directions through this chain [11]. System simulations and nonlinear dynamic analysis of key outputs should be a mandatory part of any supply chain reengineering proposal [12]. Simulation can be used to study effects of uncertainty [13]. GCI [14] states that future supply chains should embrace leading supply chain practices and new ways of calculating causal impacts of such practices on supply chains [14]. With these above-stated requirements in mind, the focus of the research reported in this paper has been on developing an integrated modelling methodology which can support the analysis and design of complex supply chains.

Different state-of-the-art solutions have been reviewed with potential to support the analytical design of complex supply chains. Some of the techniques reported on include supply chain mapping [15], use of the supply chain operations reference (SCOR) model [16, 17], and the combined use of optimization, simulation, and heuristics [13]. These techniques can lend support to supply chain analysis with reference to particular focal concerns such as by modeling some structural aspects of the supply chain or by analyzing selected behavioral aspects of the supply chain.

Prior to the authors research described in this paper, little had been reported in the research literature about integrated means of deploying enterprise modelling (EM), causal loop diagramming (CLD), and simulation modelling (SM) in support of the lifecycle engineering of complex supply chains. Whereas, it was evident that when used on their own, EM techniques are suited to modele process-oriented organisational structures of complex organisations in ways that support various kinds of organisational decision making. While CLD and SM techniques have had widespread application in recent decades, in respect of modelling and predicting the behaviours of key performance indicators (KPIs) used by organisations operating in various industrial, commercial, and governmental sectors. Consequently the authors explored how EM, CLD, and SM technologies might be used synergistically, so as to bring together structural views of supply chains with behavioural views related to the reachable states of alternative supply chain structures. In this way, the authors' aim was to be able to explicitly describe supply chains from an organisational point of view and then to virtually test the ability of those organisational structures to facilitate competitive organisational behaviours. Consequent to their initial research explorations,

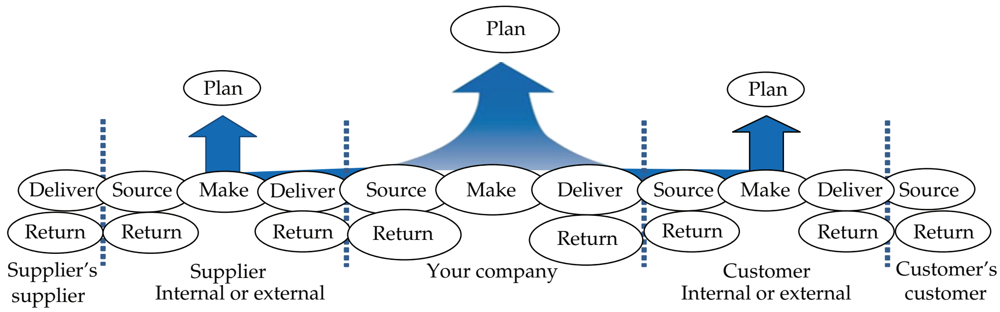


**Figure 1:** SCOR Model [16].

the author's research objective crystallised to become centred on conceiving and implementing an integrated methodology for the analytical design of complex supply chains. The design and application of this methodology is outlined in later sections of this paper.

## 2. Literature Review

### *2.1. Complex Supply Chains*

The APICS dictionary, 10th edition, defines the term supply chain as "the global network used to deliver products and services from raw materials to end-customers through an engineered flow of information, physical distribution, and cash." This supply chain network provides a continuous path from dirt to the paying end-customer and operates through the integration of its three flows, namely, information, physical distribution, and cash [18]. According to supply chain operations reference (SCOR) model, each basic supply chain include five standard processes, namely: planning, source, make, deliver, and return [16]. SCOR chains can span from the supplier's supplier to the customer's customer [19]. The SCOR model is shown in Figure 1.

Each interaction between two execution processes (such as between source-make-deliver) is a "link" in the supply chain. Planning sits on top of these links and manages them [20]. Realistic supply chains have multiple end products with shared components, facilities, and capacities [21]. A focus on cash flow involves conceptual differences among supply chain management, logistics, and/or lean manufacturing [22].

Various dimensions of complexity that impact on supply networks are as follows: scale, technological novelty, quantity of subsystems components, degree of customization of components in the final product/service, quantity of alternative design and delivery paths, number of feedback loops in the production and delivery system, variety of distinct knowledge bases, skills and competencies incorporated in the product/service package, intensity and extent of end-user involvement, uncertainty and change of end-user requirements, extent of supplier involvement in the innovation and transformation process, regulatory involvement, number of actors in the network, web of financial arrangements supporting the product/service, and extent of political and stakeholder intervention [23]. Wider product variety, smaller production lot sizes, more tiers, and different actors involved in coordinated supply chains also cause supply chain complexity [5]. Complexity is a key driver for failure of synchronization among material, information, and cash flows across business processes [2].

To analyse strategic logistic and supply chain management systems, Meade and Sarkis [24] used graphical representation of supply chain entities and relationships between the entities. Christopher [15], Scott and Westbrook [25], and Christopher and Gattorna [26] used supply chain mapping to represent structural (i.e., relatively enduring aspects of) supply chain processes and activities in support of the reengineering of supply chains.

## 2.2. Complex Systems Modelling Methods/Techniques

### 2.2.1. Enterprise Modelling (EM)

A model is "a representation of some aspects of an entity under study which can be used to facilitate visualization, analysis, design, and so forth" [27]. Enterprise models capture certain perspectives (or foci of concern) about an enterprise, such as financial, business, information, and function views. When formally modelling any complex system, it is necessary to decompose (or breakdown) the system into manageable system elements [28]. A model can provide insights into system capabilities and highlights alternative solutions and application scenarios that prepare the system to adapt to business change [29]. There are many potential benefits from using enterprise modelling in respect of the life cycle engineering of a manufacturing system [30, 31]. Modelling techniques can help to analyse alternatives and help analytically to determine new system configurations that best fulfil requirements change before any real system reconfiguration needs to be activated [32].

A number of public domain EM techniques are described in the literature that provide systematic means of decomposing and representing, at various levels of abstraction, the network of processes used by any subject complex system (or indeed system of systems). This enables subject networks of processes to be decomposed into their subprocesses and unitary activities; following which other representational concepts can be used to attach other modelled entities to the process representations. Example entities that can be attached in this way (and hence positioned relative system processes and activities) include related information requirements, information and decision flows, required resource system functionality and behaviours, needed material and product flows and resultant value streams, and processing costs. By formally decomposing a complex (specific, semigeneric, or generic) process network into descriptions of its elemental parts and their dependencies, subsequent systems integration aspects of organization design and change can be enabled [33].

It follows that the application of EM techniques explicitly captures and helps to communicate requirements for system design and captures structural (i.e., relatively enduring) relationships that govern interactions among the elements of complex systems. It follows that EMs do not really capture time-dependent interactions among system elements, although some efforts have been made to view enterprise models with respect to time [34].

Different enterprise modelling architectures have been developed and used around the globe to model and design manufacturing enterprises (ME). Well-documented example EM methodologies and architecture include ARIS: Architecture for Information Systems, CIMOSA: Computer Integrated Manufacturing Open Systems Architecture, GERAM: the Generalised Enterprise Reference Architecture and Methodologies, GRAI/GIM: the Graphs with Results and Activities Interrelated/GRAI Integrated Methodology, IEM: The Integrated Enterprise Modelling, and PERA: The Purdue Enterprise Reference Architecture. CIMOSA is considered as a comprehensive EM architecture and is used for more than two decades by the authors and their colleagues in the Manufacturing Systems Integration Research Institute at Loughborough University [35].

### 2.2.2. *Causal Loop Diagramming (CLD)*

Causal loop diagrams (CLDs) are very commonly used to characterise system dynamics as they are easy to understand and can be used to show and explain the impacts of different feedback structures on dynamic behaviours of subject systems [36]. In this way, hypothesis about the causes of dynamics can be developed and theoretically tested. Essentially CLDs capture and visually represent the mental models used by individuals and teams [37]. It is a way used for communicating ideas and rationale that a modeller believes are responsible for a problem [37]. A causal loop diagram can show explicitly the direction and type of causality among major factors that influence a subject system [38]. Causal loop diagrams are flexible and useful for diagramming the feedback structure of systems in any domain. Causal diagrams are simply maps showing the causal links among variables with arrows from a cause to an effect [37]. It is important to mention that these diagrams capture the structure of the system and not its behaviour [37].

Any CLD should contain a careful selection of variables which are decided on the basis of the observed issue. The use of interviews, surveys and archive data relating to the enterprise issue under observation can be of great importance. These interviews are typically either structured or semistructured in which useful views of the people involved in the issue(s) give rise to understandings about causal variables [37]. Relationships in the causal loop diagram must be causal and not corelational. Correlation among variables shows the past behaviour of the system only and do not represent the structure of the system. Rather correlations among variables will influence the outcome from behaviour of the model after simulation. If there is an existing correlation in the enterprise among some widely different variables which are not causally related, their inclusion within CLDs must be avoided [37].

Limitations of causal loops are that these can never be comprehensive and should not be because "effective modelling" is the art of simplicity [35]. These are also never final, but always provisional. These maps evolve as the understanding of the modeller improves and as the modelling effort evolves. Causal loop diagrams do not distinguish between stocks and flows but are often helpful in this respect as they encode aspects of a stock and flow structure [37].

### 2.2.3. *Simulation Modelling (SM)*

Simulation modelling has been widely deployed in many disciplines to replicate and predict behaviours. However, in general, it is known that because simulation models need to encode both static and dynamic properties of systems then their complexity grows rapidly as either the scope or depth of modelling increases. Therefore, their practicability will depend upon a suitable matching of level of modelling abstraction to the problem being tackled [33]. Simulation modelling has been shown to be useful for capturing dependences among design elements of manufacturing organizations that change with time [39, 40]. During simulation modelling experiments, system behaviours can be compared with reference to selected performance measures [35].

Normally when simulation modelling is performed, a suitable simulation tool is required. Different simulation tools are available like SIMUL8, Arena, and iThink. Today's discrete event simulation modelling tools provide behaviour analysis capabilities which can predict system outcomes with reference to selected system performance measures [41, 42]. It provides means of computer executing discrete event simulations. SIMUL8 is a user friendly tool as it provides a simple pick and place approach to creating graphical and computer executable models [43]. Different types of entities need to be modelled including work entry points, work centres, and work exit points each with a range of attributed properties that correspond to real conditions of an enterprise [35]. It is, therefore, necessary to populate attributes of the simulation model with specific case enterprise data and rules in order to replicate real working conditions of the enterprise. SIMUL8 also provides optional links to Microsoft Excel sheet data and also different checks and conditions can be applied when different simulated events occur [44].

### *2.3. Discussion and Gap Analysis*

From the forgoing discussion and recent literature reviewed, the authors observed that graphical representation and mapping of complex supply chain has provided a key first step when reengineering complex supply chains and that it has been widely used for analysis and reengineering of complex supply chains. Particularly, for example, process mapping is very widely used by the providers of IT systems used to underpin supply chain integration and operation. Christopher [15], Scott and Westbrook, [25] and Christopher and Gattorna [26] separately report on their use of supply chain mapping to visualise their thinking when reengineering supply chains. Also Meade and Sarkis [24] used graphical representation of supply chain entities to support the strategic analysis of logistic and supply chain management systems.

Notwithstanding an apparently growing use of process mapping as a first step towards achieving various forms of supply chain reengineering, it is evident that graphical representation and mapping can only qualitatively analyse structural and relatively enduring characteristics of complex systems such as supply chain systems and supply chain systems of systems [33]. Quantitative analysis of the dynamic behaviours of supply chains can also provide a vital step towards virtually testing and comparing the design of current and possible future supply chain configurations; as time-based simulation can provide important information about ways of improving the performances of supply chains without making in appropriate investment risks [45]. Therefore, both static and dynamic analysis of the complex supply chain is required to be included in analytical design of complex supply chains. Furthermore, the authors observed that these two forms of analysis should be carried out in a coherent and synergistic manner at all needed levels of modelling abstraction needed to support reengineering decisions made.

Based on the forgoing, Figure 2 was constructed by the authors to conceptualise the need for the research reported in this paper, the current state of the art in modelling solution techniques that can contribute towards satisfying that need, and potential solution technologies that can be developed, and their application systematically integrated, to bridge the current gap in current industry provision when modelling complex supply chains.

Keeping in view the above requirements, an integrated methodology for the design of complex supply chains is needed which can address both static and dynamic aspects of any subject complex supply chain. The authors proposed that such a methodology should have the following capabilities.

(i) To graphically represent and explicitly describe key characteristic properties of complex supply chains.

(ii) To analytically explore dynamic properties of complex supply chains, so as to provide analytic means of reasoning about impacts of uncertainty in complex supply

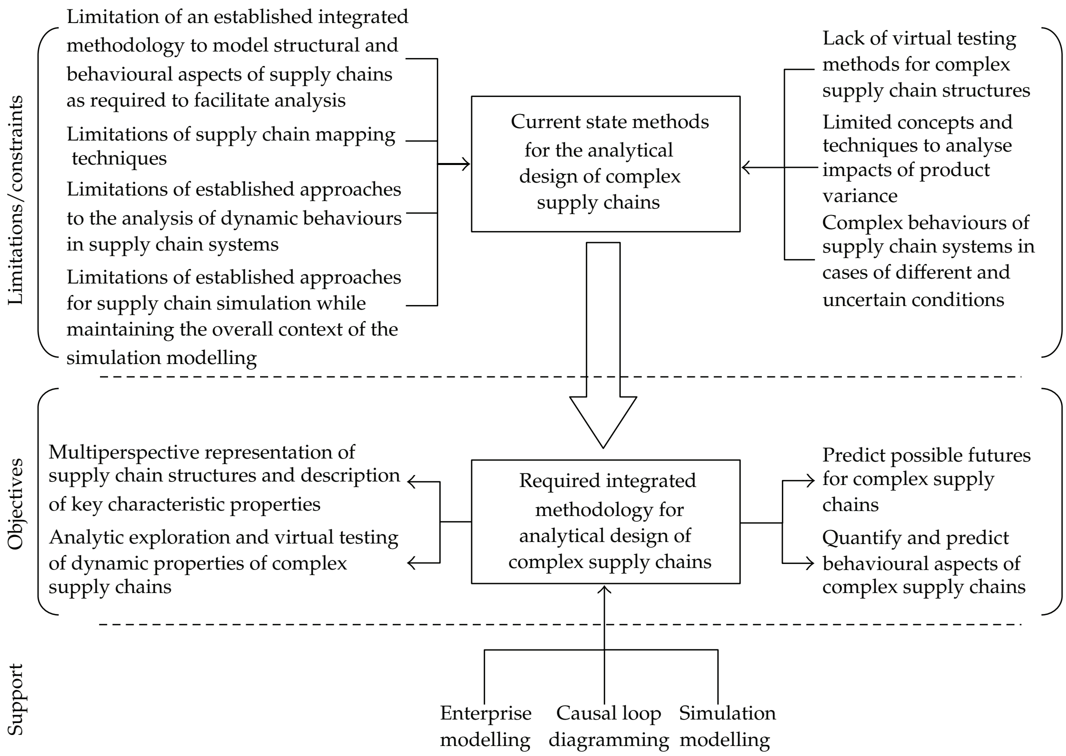


**Figure 2:** General review for research need.

chains, such as those introduced due to changes in demand, supply, make, delivery, and return processes.

(iii) To quantify and predict behavioural aspects of complex supply chains, so as to observe impacts of uncertainties and to assess possible risks should potential uncertainties arise; hence, a need to predict the reachable time-based behaviours of different supply chain structural configurations leading to improved supply chain performance and reduced the risk when justifying/making investments in new or changed supply chain systems.

## 3. Design of an Integrated Methodology for Analytical Design Complex Supply Chains

A number of different enterprise modelling (EM) techniques have been used by industry and academia to represent businesses and companies from various perspectives. These EM techniques can capture and enable the reuse of knowledge normally distributed amongst many knowledge holders who have various company and business roles. The kinds of knowledge that can be captured within an EM include relatively enduring models of processes, information, material flows, human and technical resources, and cash flows inside any subject enterprise [7]. A primary constraint on the application of any EM technique is its focus on modelling structural rather than time-dependent behavioural characteristics of the enterprise. This is, however, a necessary constraint on EM techniques as their prime purpose is to capture a big picture of an enterprise and to decompose this big picture into essentially decoupled elements so that subsequently those elements can be analysed in detail within the specific context defined by their parent EM [33]. Therefore, the inclusion of both structural and behavioural aspects into the big picture would make any developed EM overly complex. However, the literature review also showed the importance of modelling dynamic, time-dependant characteristics of supply chains to enable performance prediction and measurement when alternative candidate supply chain configurations are conceived and developed [45]. With this second modelling purpose in mind, it was observed that causal loop diagramming and simulation modelling are capable of modelling time-dependant characteristics of complex systems such as complex supply chains. However, prior to the authors present research, the literature had not reported on ways of synergistically deploying EM, CLD, and SM in a coherent fashion to support the lifecycle engineering of complex supply chains. Hence, the exploration and development of such a coherent use was the subject of this research.

### *3.1. Potential Use of the Enhanced CIMOSA-Based MSI Technique*

During the 1990s, various researchers in the Manufacturing Systems Integration (MSI) Research Institute at Loughborough University developed a CIMOSA-based enhanced enterprise modelling technique which can usefully be used to explicitly represent and decompose a "big picture" of the network of processes used by any enterprise. The extended CIMOSA modelling technique can also facilitate the detailing of structural aspects of some focused shop floor section of that ME or alternatively allow abstract representations of the ME and its complex supply chain domains to be developed and used as a basis for collective qualitative analysis.

Selection of the scope and focus of enterprise modelling depends on the purpose and the context of the current modelling exercise and particularly on what the enterprise model is to be used for short or long term. The big picture of enterprise processes can be created so as to encode various perspectives of the ME, which will be of concern to potential or specified model users. The perspectives may include processing and activity requirements, flow controls, information, physical (material) and human resources, and cash flows. The big picture can be created for one or more specific "contexts," and this helps to maintain a focus of the modelling work such as, in support of operational, tactical or strategic change projects. The extended CIMOSA EM building is carried out using four kinds of CIMOSA-MSI diagramming templates, namely, "context diagram," "interaction diagram," "structure diagram," and "activity diagram." Essentially these models can be used to visualise the processing requirements of an enterprise; namely, (1) the operational process network that is realised by the subject ME so that it adds value to "products" and "services" needed by "customers" and/or (2) those enterprise transformation processes that are or could be realised by the subject enterprise in order to maintain the currency (and hence efficacy) of its operational network of processes. CIMOSA-MSI enterprise modelling can be used to help identify and represent different actors and stakeholders involved and interactions between those actors centred on the flow of information, materials, and cash; thereby, it can explicitly represent the structure of the interacting processes and logical flows of processes. For the above reasons, enterprise modelling was selected by the present authors as a best in class technique to statically model, represent, and visualise a "big picture" of complex supply chains from the point of view of "defining the processing requirements" of any specific ME or indeed semigeneric processing requirements of any subject group of "similar" MEs.

### 3.2. *Causal Loop Diagramming (CLD)*

Also described in the preceding literature review, causal loop diagramming can be used to understand and represent system dynamics associated with causal relationships that link different variables of complex systems. Change in system variables can affect other associated variables with a positive or a negative effect on behaviours of the complete system. Therefore, causal loop diagramming was also selected as a technique to be used as an integral part of a set of modelling approaches aimed at understanding and assessing the dynamics of complex supply chains. Here, it was presumed that causal loop diagramming would enable qualitative understandings to be developed about complex supply chain behaviours, when any given supply chain is subjected to uncertain conditions caused by change in selected variables where the source of those changes may be external to, or internal to, the system being studied. For example, change in demand, change in supply, change in resource availability, change in plant performance, change in production and inventory management, change in delivery, or indeed change in some "mix" of these different variables.

### 3.3. *Simulation Modelling (SM)*

Also observed in the preceding literature review was that simulation modelling can be used to computer exercise and graphically visualise time-based "flows" through complex supply chain "processes" and "resources;" thereby, it can predict and quantify likely outcomes from different what-if scenarios. For different combinations of uncertain conditions, different resource configurations can be tested and results can be quantified. In this regard, the suitability of industry best practices can be analysed, as can new emerging manufacturing paradigms (from academia and industry) in any specific case enterprise. Furthermore, it is presumed that quantitative results from using simulation modelling can be helpful to predict future behaviours of complex supply chain and can support analysis leading to improvement in any given supply chain design. However, it was also clear that some systematic stepwise technique of applying simulation modelling would be needed to undertake complex supply chain modelling which in general will involve interaction between many dependent variables on a large scale. Both discrete event simulation (DES) modelling and continuous simulation (CS) modelling could prove useful, so that both were selected as key contributors to an integrated complex supply chain analysis methodology which can graphically visualise and quantify behaviours of work flows through alternative complex supply chains. Selection between DES and CS modelling techniques depends on the requirements of simulation. For instance, if the requirements of simulation are to simulate a scenario at a high level of abstraction or for taking a policy decision in a complex supply chain, then CS is expected to prove most appropriate. While to implement the policy and to verify its impacts on operational level activities, DES is likely to prove most suitable. Also expected was that simulation modelling would quantify aspects of complex supply chain behaviours under different uncertain changes with this could help to quantify aspects of associated risks, such as when virtually testing the introduction of a new policy or when purchasing new supply chain systems in response to a changing scenario.

**Table 1:** Key observations about use of different modelling techniques.

| Concept reviewed | Summary of purpose | Observations/limitations |
|---|---|---|
| Enterprise modelling (EM) | The CIMOSA EM architecture has been used by many researchers around the world and extensively in MSI to capture the big picture of the processes of an enterprise operating within a specific business context | EM techniques explicitly capture and help to communicate requirements for system design and capture structural (i.e., relatively enduring) relationships that govern interactions among the elements of complex systems. EMs do not really capture time-dependent interactions among system elements |
| Causal loop diagramming (CLD) | CLD has been widely used to capture mental models of systems subjected to different dynamic situations presented in terms of cause and its effects | Causal Loop modelling can facilitate representation and understanding about complex system dynamics. However, on its own it cannot quantify issues numerically |
| Simulation modelling (SM) | Simulation modelling is widely used by industry, commerce, and government to simulate different what-if scenarios and numerically quantify different performance variables | Small process portions of an enterprise can be simulated precisely, but as the size of model grows it become too complex and degree of precision decreases. Large process portions of an enterprise can be simulated at abstract level. Generally though current best practice simulation modelling is typically carried out in a piecemeal/stand alone way |
| Combined use of EM, CLD, and SM | Research has previously been conducted at MSI to unify EM, CLD, and SM to address different problems and support decisions within manufacturing enterprises | Ways of synergistic deployment of EM, CLD, and SM in a coherent fashion to support the lifecycle engineering of complex supply chains had not reported prior to the presentation of this research |

### *3.4. Integrated Application of EM, CLD, and SM Techniques*

Furthermore, the preceding literature review has shown that in other complex system domains significant benefits have arisen from applying enterprise modelling, causal loop diagramming, and simulation modelling techniques in an integrated fashion, thereby providing an analytical basis for underpinning key aspects of large-scale organization design and change (OD&C). However, in view of the context of this study, it was necessary to scope and focus an integrated use of these modelling approaches, by specifying and testing their systematic use as potentially widely applicable methodology which supports analyses needed by relevant actors as they engineer aspects of complex supply chains of concern to them.

Table 1 was constructed to summarise the intended purpose of the modelling techniques selected as base technologies to realise an integrated methodology for the analytical design of complex supply chains.

Based on the key observations presented in Table 1 about their potential to fulfil the required characteristics of an integrated methodology for the analytical design of complex supply chains, the candidate modelling techniques presented in Figure 2 were selected.

Figure 3 shows a static match between the required characteristics of an analytical design methodology for complex supply chains and state-of-the-art candidate techniques

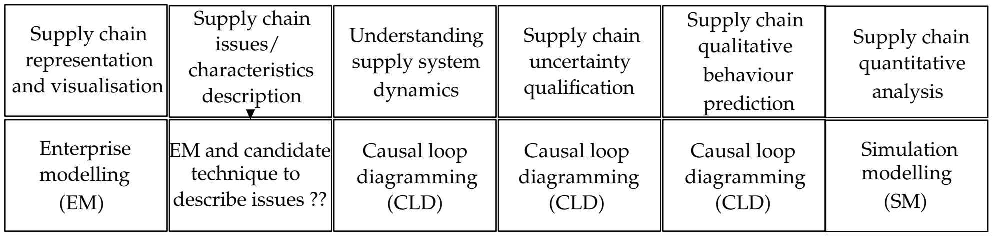


**Figure 3:** Required supply chain analysis characteristics and its candidate techniques.

**Table 2:** The domain table.

| Domain table for CIMOSA-conformant domain(s)-DM | | | | | |
|---|---|---|---|---|---|
| DPs and BPs | | Domain issues related to enterprise modelling entities | | | |
| | | Information | Physical | Human | Financial |
| DPs | BPs | ** | ** | ** | ** |
| | BPs | ** | ** | ** | ** |

**Description of issue(s) with reference to related EA(s).

currently developed and used by different manufacturing enterprises. Selected EM, CLD, and SM techniques can provide some of the modelling capabilities required to develop an integrated analytical methodology for complex supply chains. However, to unify the use of these modelling techniques it was necessary for the authors to define characteristic entities of supply chains along with a suitable set of modelling concepts that can be implemented using the candidate technologies of Figure 3 to (a) explicitly represent organising structure of those entities and their interrelationships and (b) computer execute (and hence virtually test) reachable behaviours of selected entity configurations used to characterise subject supply chains. To define these characteristic “supply chain entities,” “their interrelationships,” and “their associated modelling concepts” the authors built upon the modelling concepts previously defined by CIMOSA-MSI diagramming templates. This thinking was facilitated by adopting the use of a so-called “Domain table.” The domain table “relates” data entities which parameterise supply chain properties from different perspectives associated with information, physical (material), financial, and human aspects. The general structural design of such a domain table is illustrated in Table 2.

The designed purpose of using the domain table is to explicitly list and describe issues, bottlenecks, and potential improvements for any CIMOSA conformant domain (which is an entity or part of an entity selected for in-depth modelling and analysis). These issues will be shown in a structured way by maintaining these under specific categories, namely, information, material, human, and financial. Table 2 illustrates domain processes “DPs” which can comprise “sourcing,” “making,” “delivery,” “returning,” and “planning” processes, as defined by the SCOR model [16]. Business processes “BPs” are subprocesses of a DP. For example, for a specific making domain process, BPs could be machining, inspecting, and packing processes. With the use of the domain table forming an integral part of enterprise modelling, the subsequent use of causal loop diagramming and simulation modelling can be systemised, when analyzing a complex supply chain.

Hence, it is assumed that a synergistic use of enterprise modelling, causal loop diagramming, and simulation modelling, with their key integration aspects realised and explicitly defined by the domain table, can usefully support the analytical design of complex

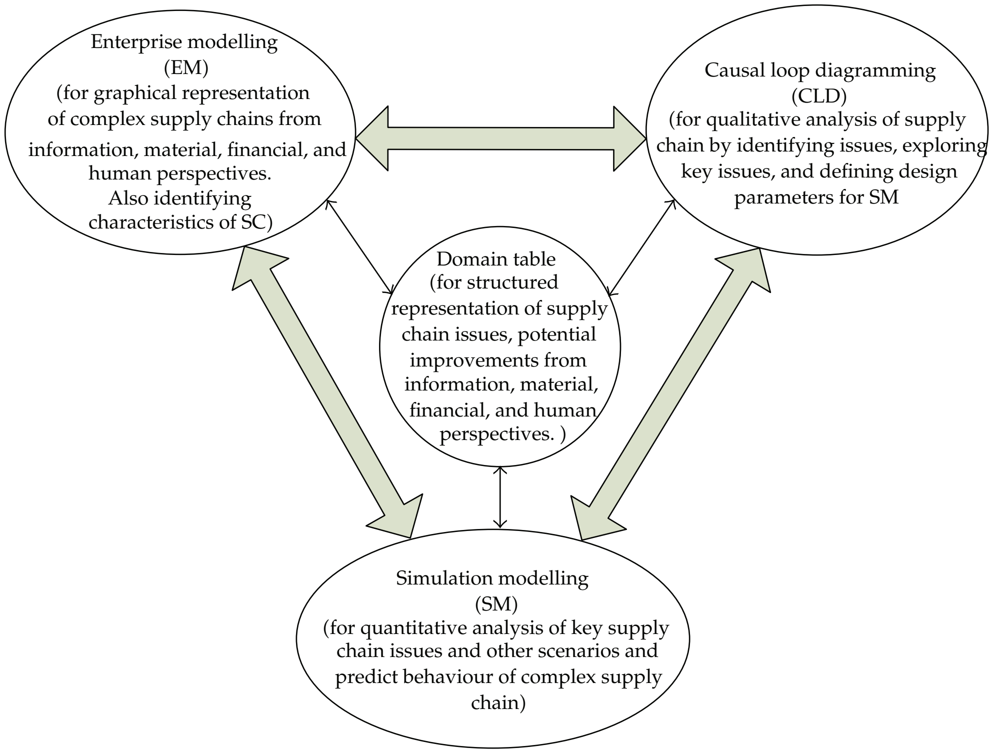


**Figure 4:** The integrated methodology for analytical design of complex supply chains.

supply chains. This constituted an enhancement of the modelling methodology previously proposed by Chatha and Weston [46] and Weston et. al. [47], and by so doing focused integrated modelling on supply chain analysis. The integrated methodology for analytical design of complex supply chains developed via this line of reasoning is conceptually represented by Figure 4.

A brief description about the role of each element of the integrated methodology for the analytical design of complex supply chains (shown in Figure 4) and an overview of synergistic aspects expected from achieving integrated modelling are presented below.

(i) Standard CIMOSA enterprise modelling constructs are implemented via the MSI graphical approach to enterprise modelling in order to facilitate the creation of holistic enterprise models of complex supply chains. This enables the explicit and graphical definition of “big picture” models of supply chain configurations, so as to capture the knowledge of relevant ME personnel in the form of relatively enduring structural dependencies between supply chain entities. These supply chain models are holistic because they can capture end-to-end supply chains at required levels of abstraction needed to support various kinds of supply chain engineering decision making. Hence, this kind of “big picture” EM will become a source of understanding about different supply chain entities/actors, different processes included in the entities, interaction of the processes with in the entities and outside the entities from various perspectives of information, physical (material), finance and human, structure of processes associated with the entities, and flows of the processes from customer order to the supply of desired product/service in a given supply chain. Further, the "big picture" EM will become a source of explicitly modelled understandings that can help to unify the use and indeed reuse of the other selected modelling technologies listed into Figure 3.

(ii) Following which the domain table will be fleshed out for specific case supply chains, to capture attributes of issues related to selected domains identified during CIMOSA-based enterprise modelling. These tables will cover data from different perspectives associated with information, physical (material), financial, and human entities which are used for enterprise modelling of the CIMOSA conformant domain(s).

(iii) The causal loop diagramming (CLD) technique is then used to understand and represent causality associated with specific supply chain dynamics. CLD is used to explore the likely impacts of key causal effects related to the issues represented in the domain table. The resultant causal loops will provide a source of qualitative exploration of supply chain dynamics under different uncertain conditions within the context defined by enterprise modelling. Also causal loops are used for designing parameters associated with needed simulation experiments which subsequently are used to quantify supply chain dynamics related to key issues of concern to that enterprise.

(iv) Simulation modelling will be used to quantify and visualise dynamic supply chain processes and different flows through supply chain entities. The key issues identified by the causal loop diagrams will be focused with a view to quantification using simulation modelling. Also, much of the structural relationships linking the entities encoded into simulation models will be inherited from the EM. Business processes or enterprise activities related to the key issues will be found from the domain table. When designing and developing the simulation models, CIMOSA-based graphical models will be used to view specific process segments found from the domain table. Simulation model design parameters will be deduced from a study of the causal loops. Design parameters will include variables and performance parameters relative time-based behaviours of which need to be quantified during simulation modelling experiments. Simulation modelling will be performed by using computer-based simulation modelling tools. Either a discrete event simulation (DES) or a continuous simulation (CS) or both can be used. The selection of the simulation technology depends on the problem to be simulated. For example, simulations at a high level of abstraction in support to make policy level decisions for complex supply chains like selection of suitable paradigm in complex supply chains, size of inventory required in case of a selected paradigm, inventory turnover for selected paradigm and, CS can be used. For problems where in-depth details are required to be modelled and the implementation of the policies are required to be tested for different small segments of the whole supply chain, DES can be used.

## 4. Research Approach Adopted to Case Study Test the Integrated Methodology for Analytical Design of Complex Supply Chains

A systematic use of the integrated modelling methodology for the analytical design of complex supply chains is presented in Figure 5, which was devised and subsequently

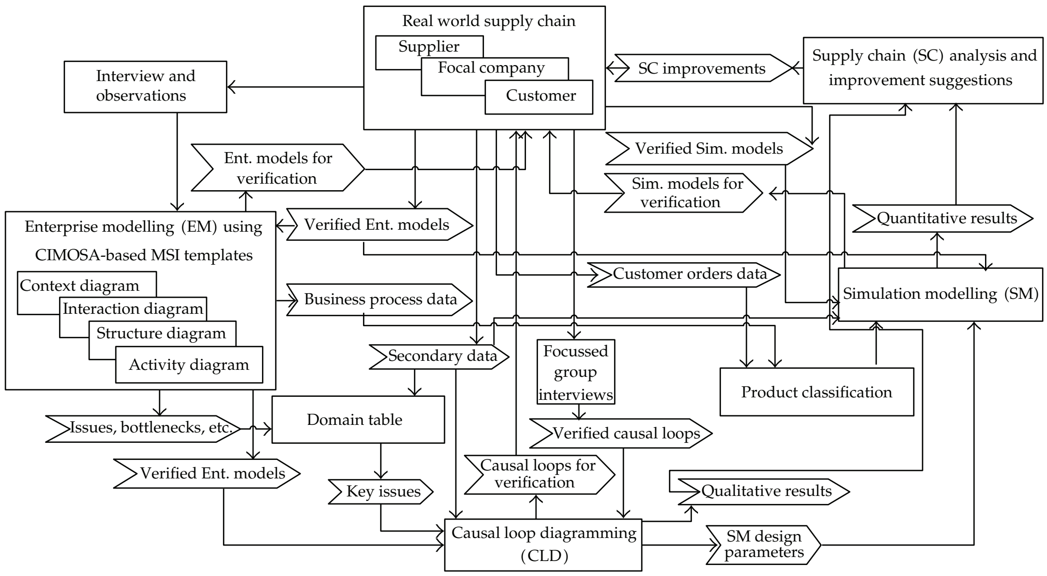


**Figure 5:** Research approach to using the integrated methodology for analytical design of complex supply chain.

deployed when modelling the supply chains of two real case MEs. This figure illustrates that when creating an enterprise model of a real world supply chain, specific data about the organisational structures currently used needs to be elicited by conducting focussed group interviews of relevant knowledge holders of the supply chain and via shop floor walk-through and observations made by the modeller. The model so constructed will be in the form of multiple instances of four kinds of diagrams (namely, context diagrams, interaction diagrams, structure diagrams and activity diagrams) which are populated with specific supply chain data. The validity of the enterprise model developed in this way needs to be verified by relevant knowledge holders. Following which supply chain problem issues can be discussed with relevant ME personnel, and the knowledge gained can be related to organisational structures depicted by the developed enterprise model. Secondary data related to those problem issues can be used to populate the domain table with a defined focus for later supply chain dynamic modelling. Verified enterprise model and key issues encoded into the domain table then provide key inputs for the development of causal loop diagrams. To verify the validity and focus of causal loop diagrams, focussed group interviews with the supply chain knowledge holders need to be carried out. Outcomes of the causal loops are qualitative results about key causalities that will likely impact on specific supply chain behaviours along with key design structures and parameters needed to develop one or more simulation models. At this stage, an “in context,” “fit for purpose” simulation model can be conceptually designed, then implemented, by using the big picture captured by the enterprise model along with outcomes from causal loop modelling and by gathering related facts and figures about the operations of the supply chain. The behaviours generated by the simulation model(s) also need to be verified by the supply chain knowledge holders. Via simulation, known behaviours of current supply chain configurations can be replicated (such as in response to known scenarios of operation), and possible future behaviours of new supply chain configurations and/or new operational scenarios can be predicted. In this way quantitative testing can underpin scientifically based analysis and design of complex supply chain and investment risks can be much reduced.

A list of instructions which should be followed when applying the proposed methodology is documented into Table 3. This table includes guidelines for the application of each step of the methodology, the data collection method recommended for each step, and expected outcomes as a result of the application of each step.

## 5. Novelty and Potential Benefits of the Integrated Modelling Methodology for Analytical Design of Complex Supply Chains

The integrated use of EM, CLD, and SM along with the synergistic application of the domain table constitutes a new systematic way of analysing and designing complex supply chains, which considers both structural and behavioural view points in a coherent fashion. The novelty of this systematic approach stems from three main things: (i) its synergistic use of modelling concepts implemented via the domain table, which glues together the use of alternative modelling technologies in complex supply chain domains to provide an explicit description of issues, bottlenecks, and potential improvements, (ii) it constitutes a new combination of EM, CLD, and SM techniques which can be systematically applied, and (iii) it is targeted at the focused field of supply chain analysis for which no previous analysis methodology of equivalent coverage existed.

The first author's Ph.D. thesis describes in two real case supply chains the virtual testing of the "Design and realisation of an integrated methodology for the analytical design of complex supply chains" [7]. It is recommended that the reader wishing to apply the methodology in a supply chain for which they are responsible should study the case study models developed and described in that thesis.

## 6. Conclusions

The main aim of this research was to "to develop an integrated methodology for analytical design of complex supply chains." The capabilities envisaged for this methodology were as follows.

(i) To graphically represent and explicitly describe key characteristic properties of complex supply chains.

(ii) To analytically explore dynamic properties of complex supply chains, so as to provide analytic means of reasoning about impacts of uncertainty in complex supply chains, such as those introduced due to changes in demand, supply, make, delivery, and return processes.

(iii) To quantify and predict behavioural aspects of complex supply chains due to observed impacts of uncertainties and to assess possible risks potential uncertainties should arise.

Previous existing integrated modelling methodologies were also reviewed that were previously designed to integrate the use of different modelling techniques in other manufacturing system domains. Analysis of the reviewed work showed that no integrated methodology suitable for modelling complex supply chains which can fulfil the set of capabilities required to analytically design complex supply chains. Based on the required

**Table 3:** Guideline for the application of the integrated methodology for case complex supply chain.

| Steps of integrated methodology | Step description | Guideline for application | Data collection method | Expected outcome |
|---|---|---|---|---|
| Enterprise modelling | Create enterprise model for graphical representation of the focussed enterprise and its complex supply chain | (i) Use the four CIMOSA-MSI enterprise modelling graphical templates and populate these with data of the focussed enterprise and its complex supply chain<br>(ii) Verify the enterprise model from the related knowledge holder in the complex supply chain<br>(iii) Use the verified enterprise model for graphical representation and static structural analysis of the complex supply chain | (i) Introductory visits and shop floor walk-through of the focal enterprise<br>(ii) Semistructured focussed group interviews of complex supply chain knowledge holders<br>(iii) Participant observations | Verified enterprise model in the form of "Context diagram," Interaction diagram," "Structure diagram," and "Activity diagram" representing big picture of processes of the focal enterprise and its complex supply chain |
| Domain table | Create the domain table for explicit description of the issues of focussed enterprise and its complex supply chain | Use the standard template of the domain table and populate it with the data about observed issues of the focussed enterprise and its complex supply chain | (i) Data collected for creating enterprise models<br>(ii) Some secondary data like quality and performance records | A domain table explicitly representing issues of the focussed enterprise and its complex supply chain |
| Causal loop diagramming | Create causal loop diagram(s) to understand dynamics about some important issues of complex supply chain | (i) Construct causal loop diagram(s) for some important issues of the complex supply chain<br>(ii) Verify the causal loop diagrams from the related knowledge holder in the complex supply chain<br>(iii) Use verified causal loop diagrams for qualitative analysis of complex supply chain and define KPI's for performing simulation modelling | (i) Information and understanding already conceived focussed group interviews, and participant observation of complex supply chain knowledge holders | Verified causal loop diagram(s) created for some important complex supply chain issues, exploring and presenting dynamic issues of complex supply chain related to the issues and in a way defining KPI's for simulation modelling |
| Simulation modelling | Create simulation model to numerically quantify important issues of complex supply chain and predict future behaviour of the complex supply chain in that case | (i) Construct simulation model for the related process segment of the complex supply chain<br>(ii) Validate the simulation model from the relevant knowledge holders of the complex supply chain<br>(iii) Use the validated simulation model for the numerical quantification of the complex supply chain issues and predict future behaviour of the complex supply chain | (i) Complex supply chain process information presented in the "Activity diagrams"<br>(ii) Key performance indicators presented by the causal loop diagramming<br>(iii) Some secondary data like process duration, work flows, resource utilization, and availability | Validated simulation model for a related process segment of the complex supply chain, which can be used for the quantitative analysis of the important issues of complex supply chain |

capabilities, an integrated methodology for analytical design of complex supply chains is developed. To use the methodology, a graphical approach is illustrated and a detailed step by step guideline is presented which include guideline for application of each step of the methodology, data collection method for each step, and expected outcomes as a result of application of each step.

The integrated modeling methodology for analytical design of complex supply chains is case tested for supply chains of two case enterprises, that is, a UK's leading Point of Purchase (POP) equipments manufacturing enterprise, namely, Artform International and a service enterprise providing parking and valeting service at a UK airport. Results of both case studies show usefulness of the integrated modelling methodology to analyse selected issues of the supply chains and thereby help in suggesting changes in supply chains design.

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