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Research Article

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

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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

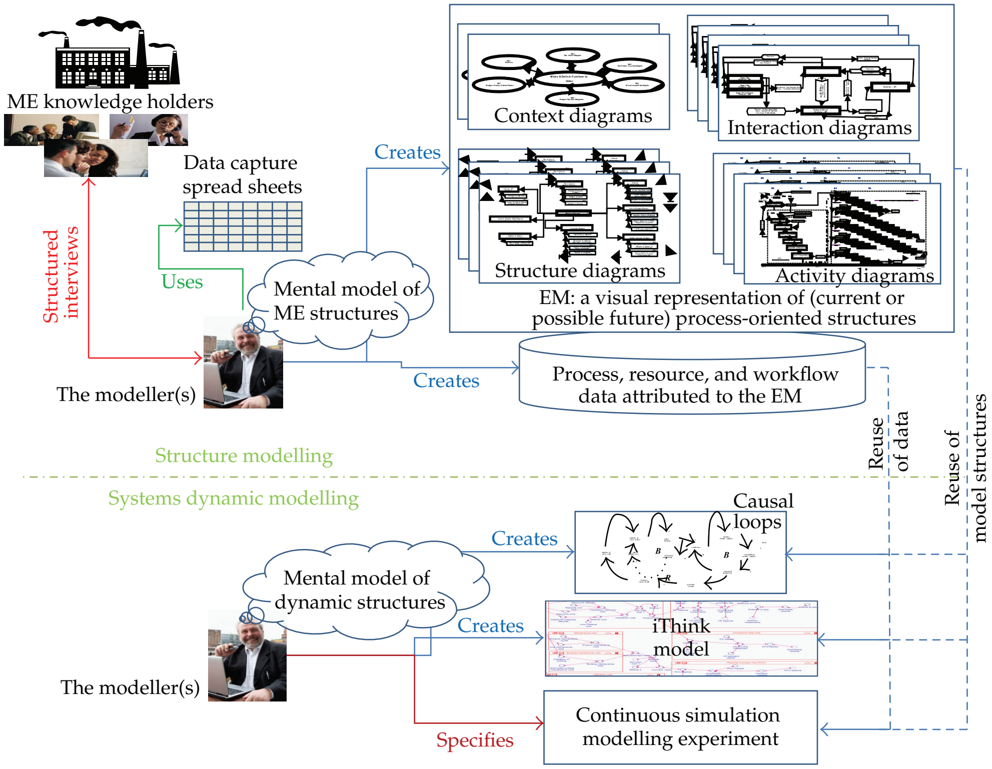

Figure 1: Combined enterprise and system dynamics modelling approach.

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

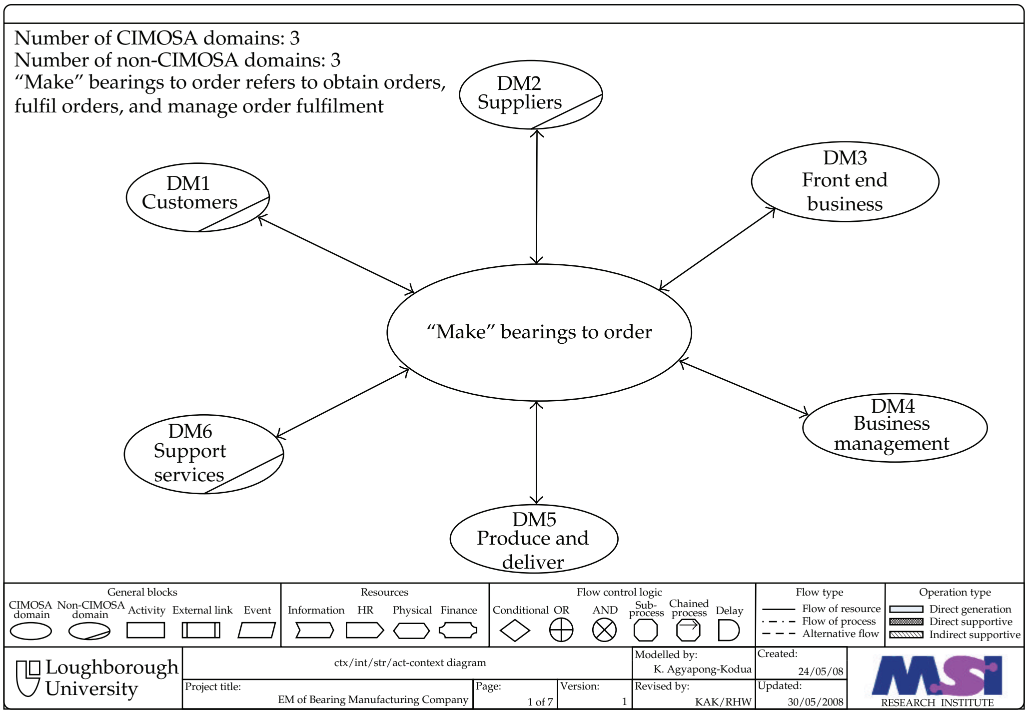

Figure 2: Context diagram of ACAM Ltd.

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

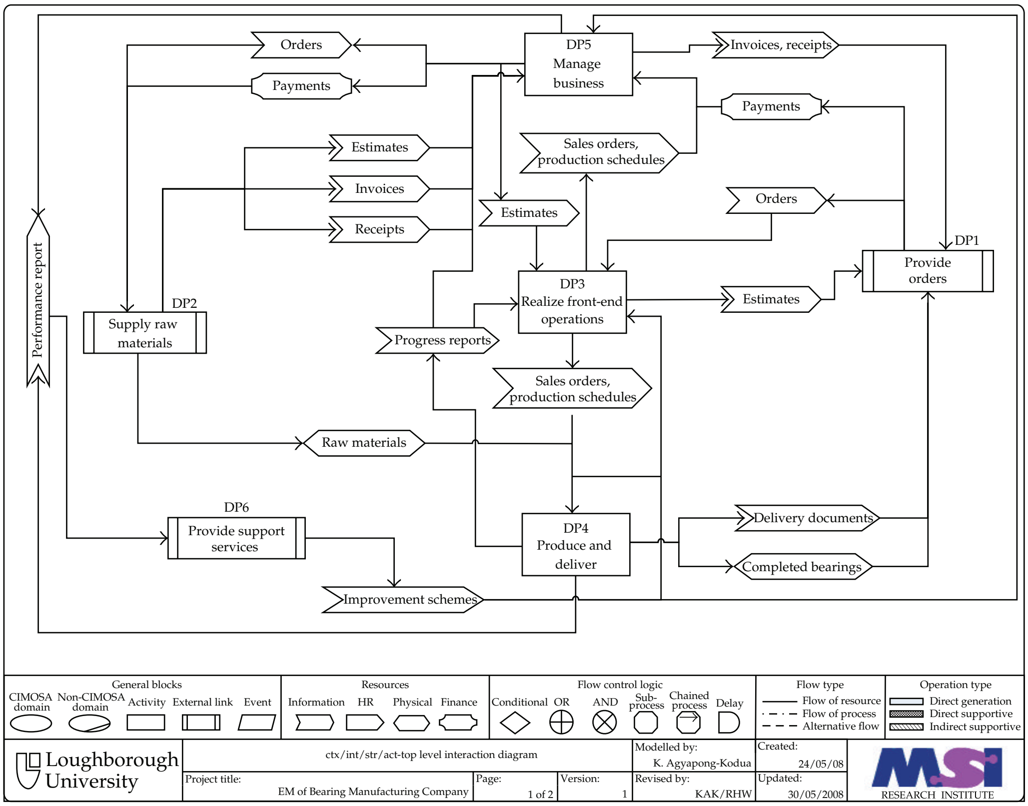

Figure 3: Top-level interaction diagram.

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

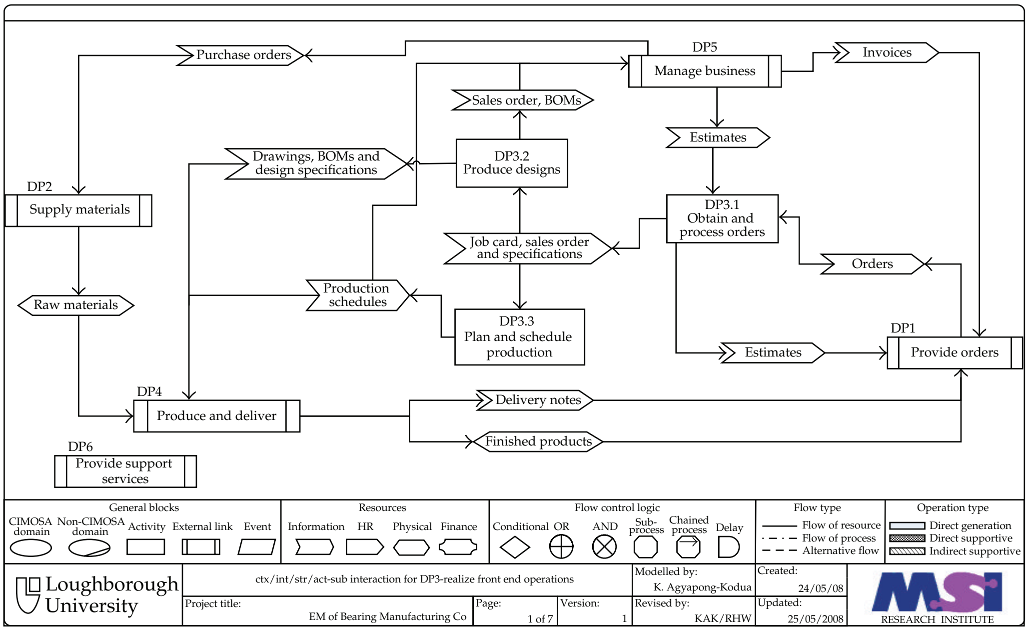

Figure 4: Subinteraction diagram for DP3.

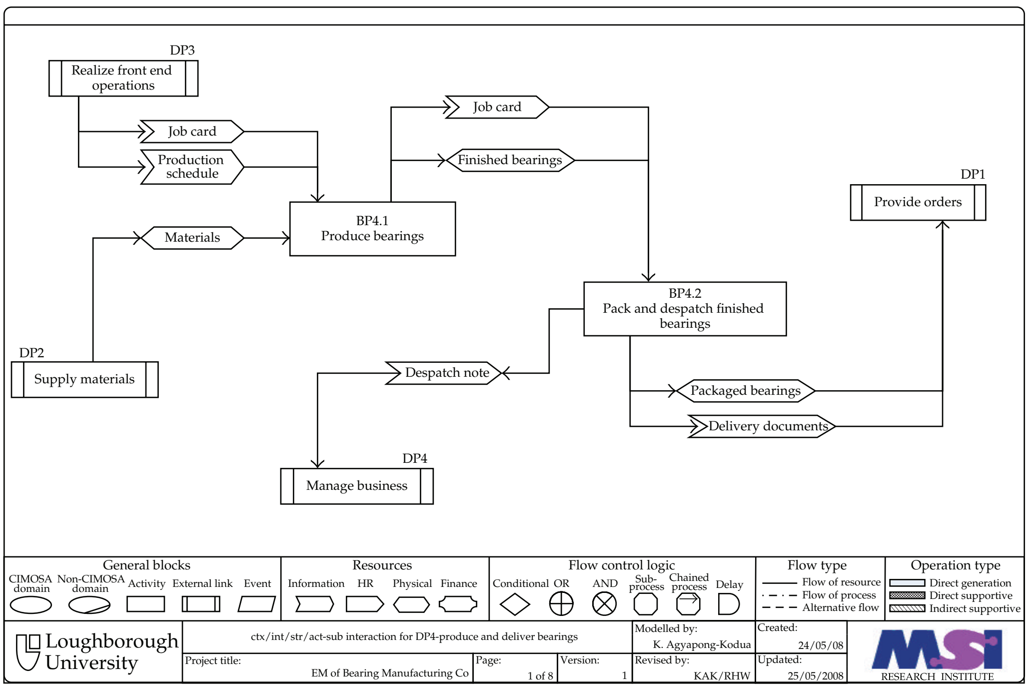

Figure 5: Subinteraction diagram for DP4.

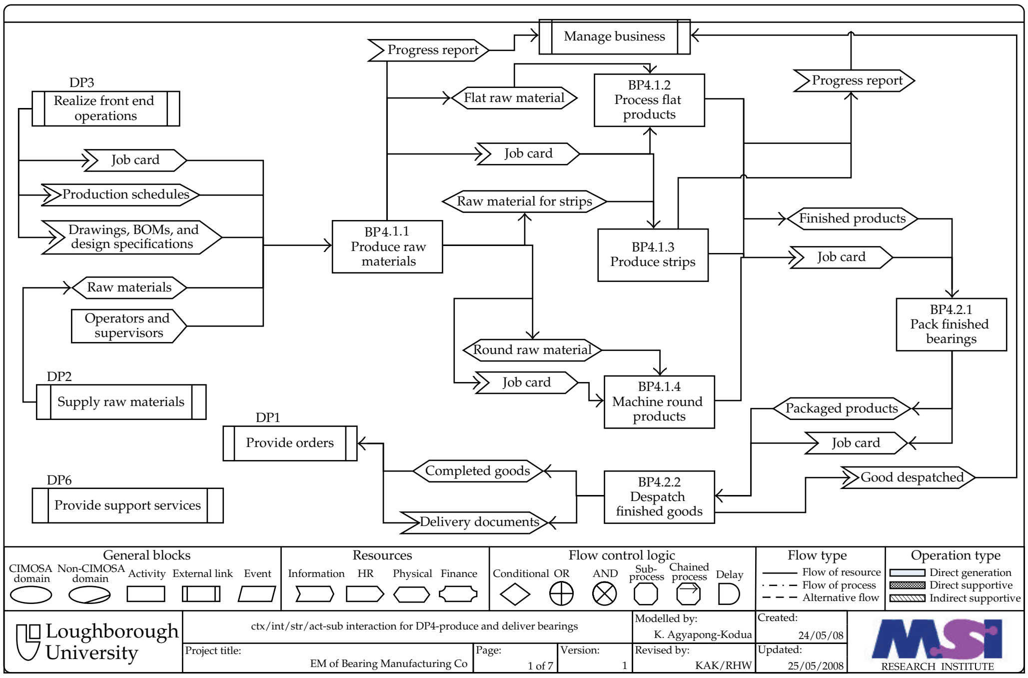

Figure 6: Sub-sub interaction diagram for BP4.1 and BP4.2.

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

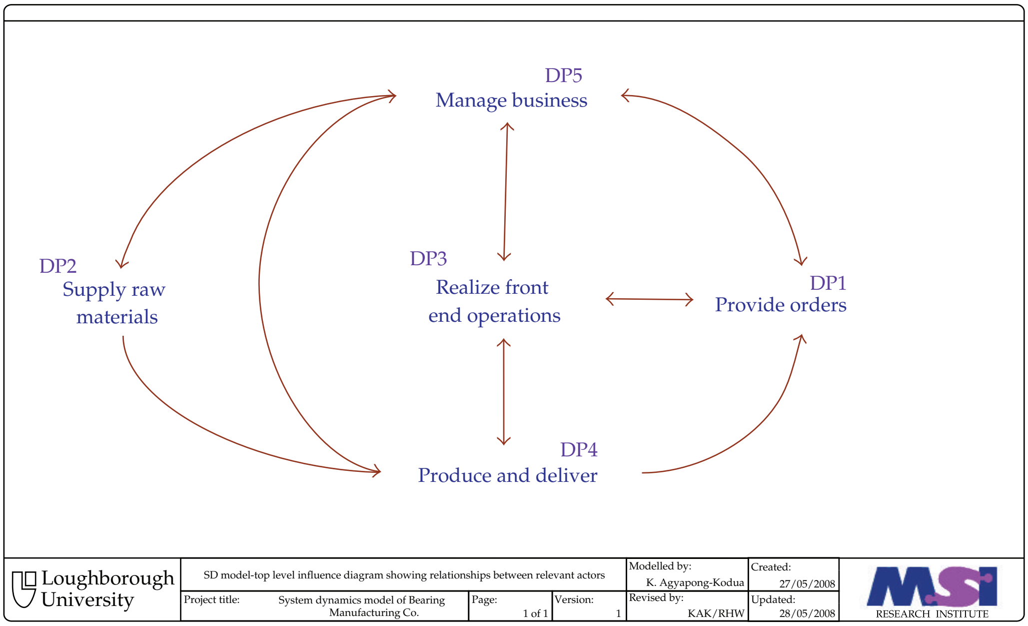

Figure 7: Top-level causal structure of domain processes.

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

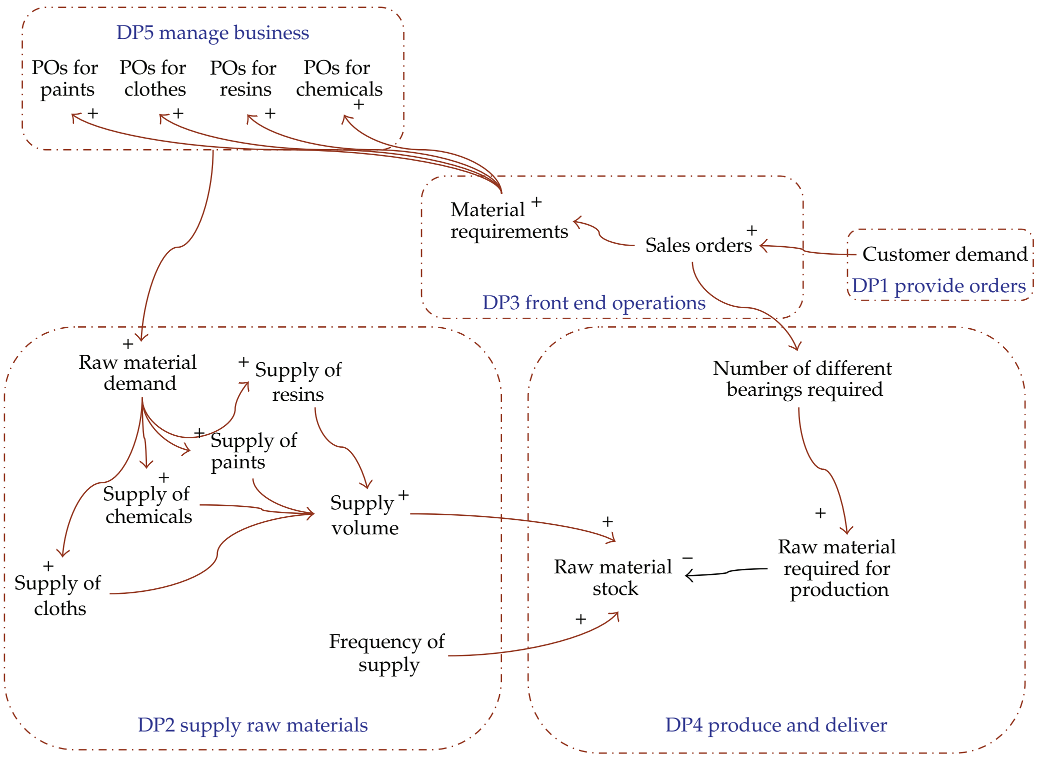

Figure 8: Initial CLM illustrating factors affecting raw material stock.

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.

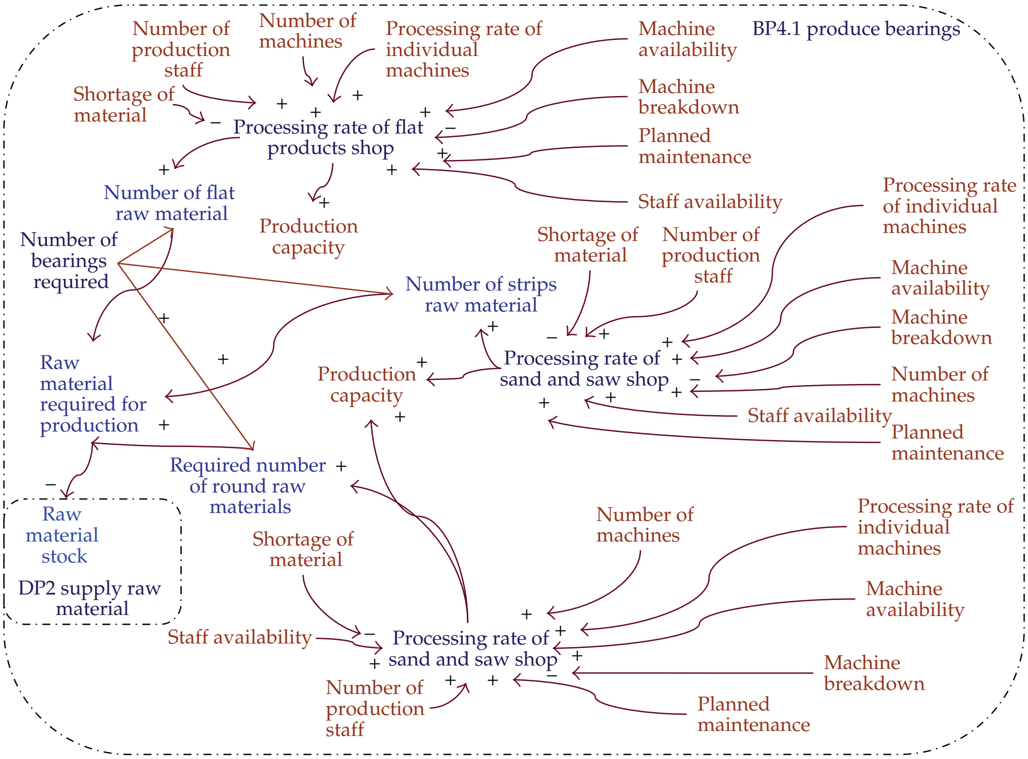

Figure 9: Initial CLM for bearings production (BP4.1).

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

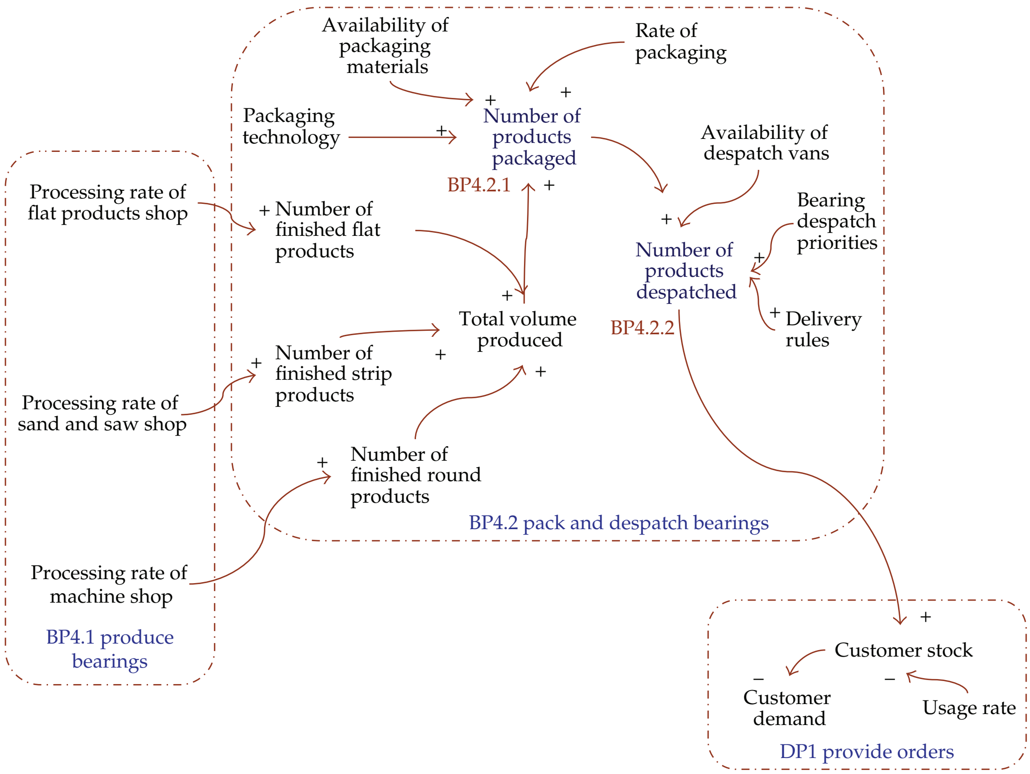

Figure 10: Initial CLM for "pack and despatch bearings" (BP4.2).

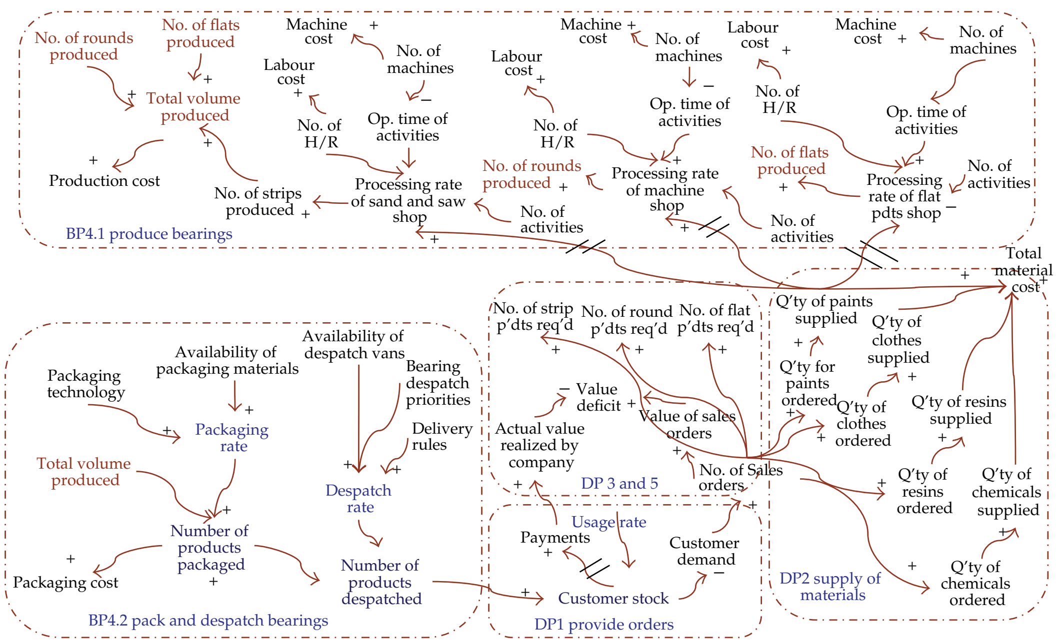

Figure 11: Extended CL model.

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

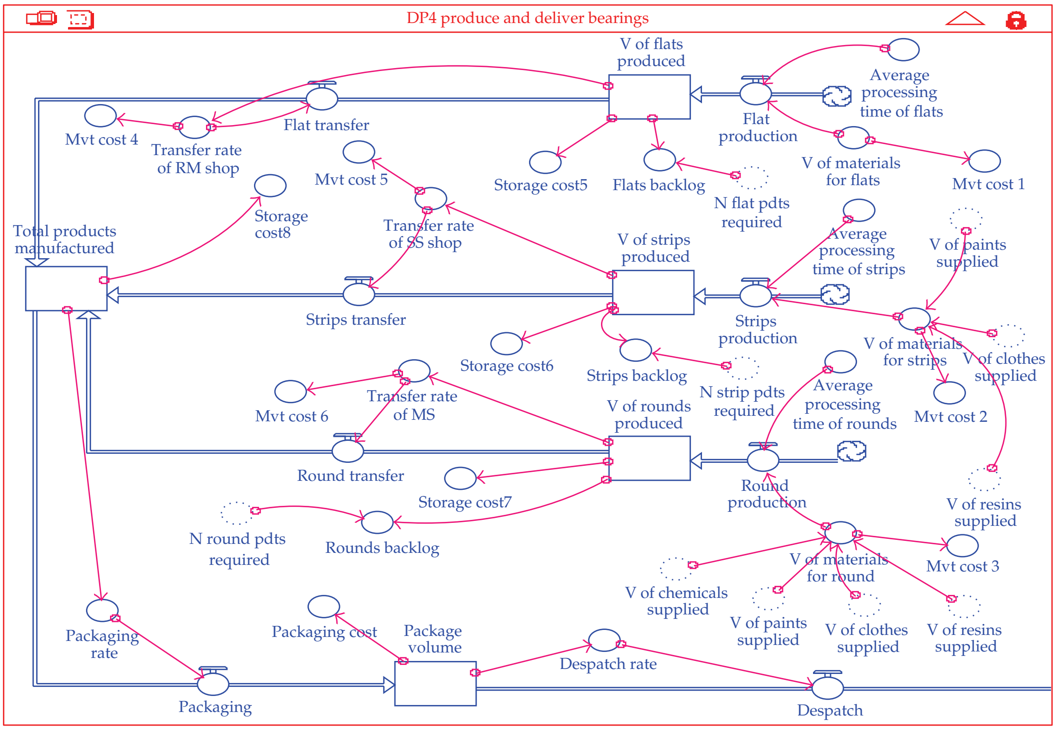

Figure 12: iThink model of DP4.

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

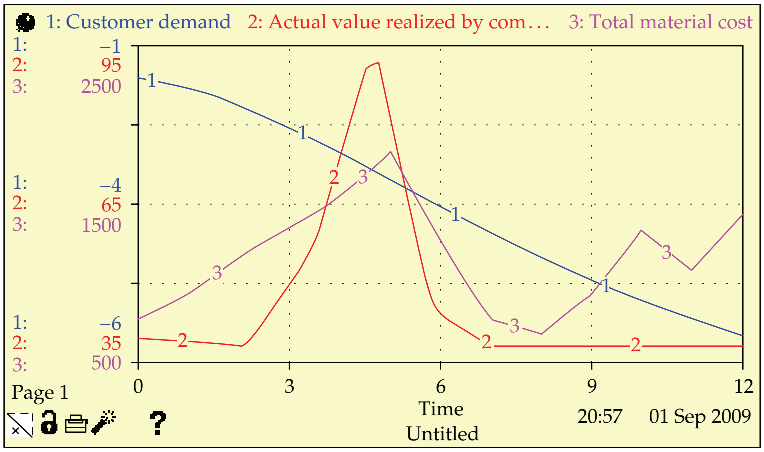

Figure 13: Results showing the impact of customer orders on value realization.

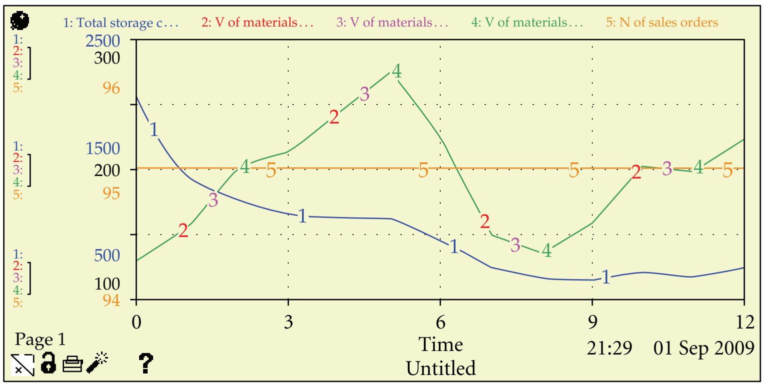

Figure 14: iThink model results for supply of materials.

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.

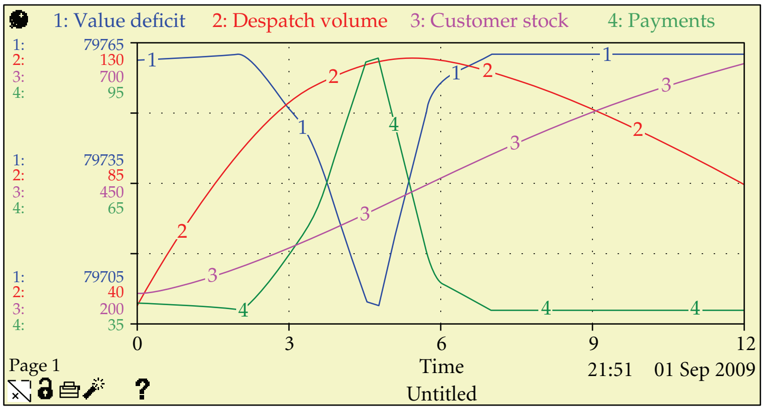

Figure 15: Effect of variables on payments.

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

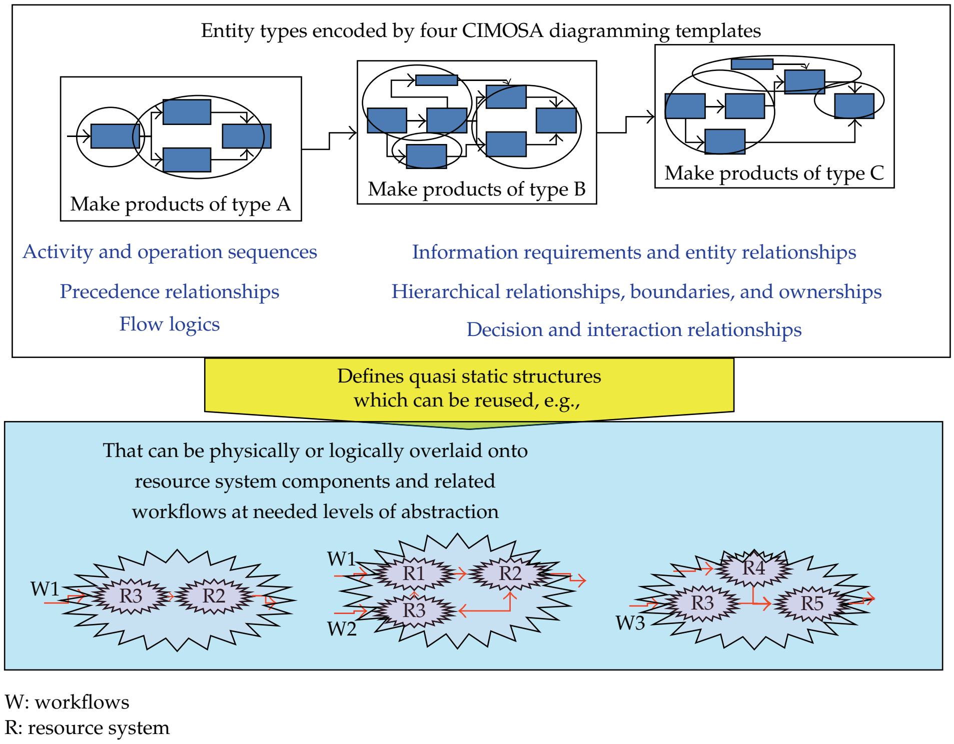

Figure 16: Entity types encoded in structural models.

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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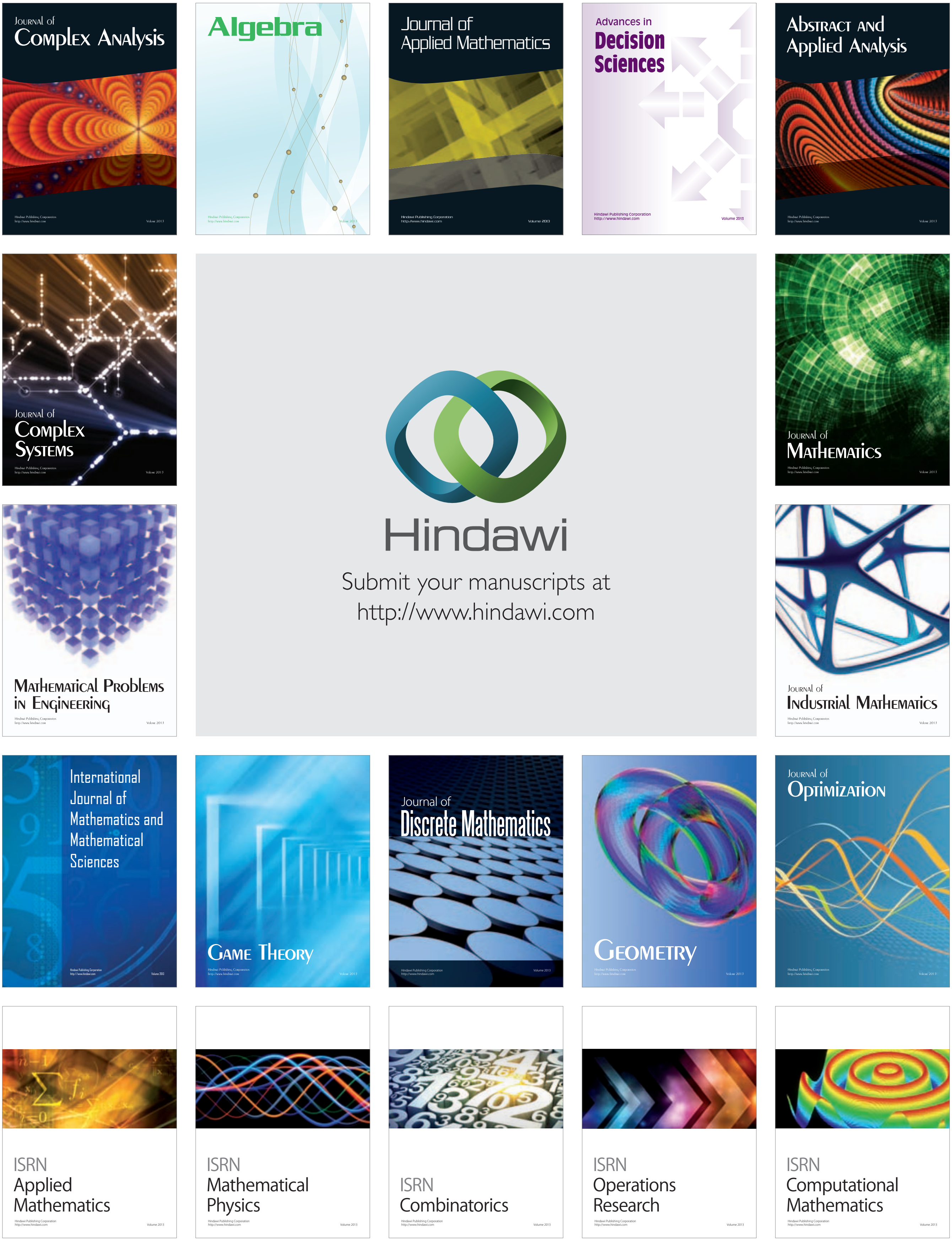
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