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Research Article

Model Driven Integrated Decision-Making in Manufacturing Enterprises

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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

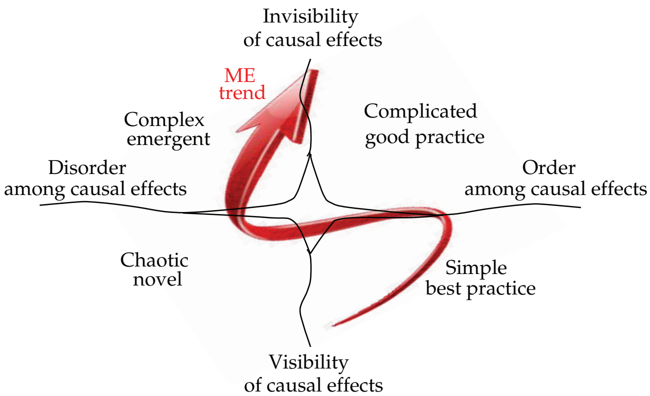

Figure 1: An interpretation of causality in MEs (after [14]).

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

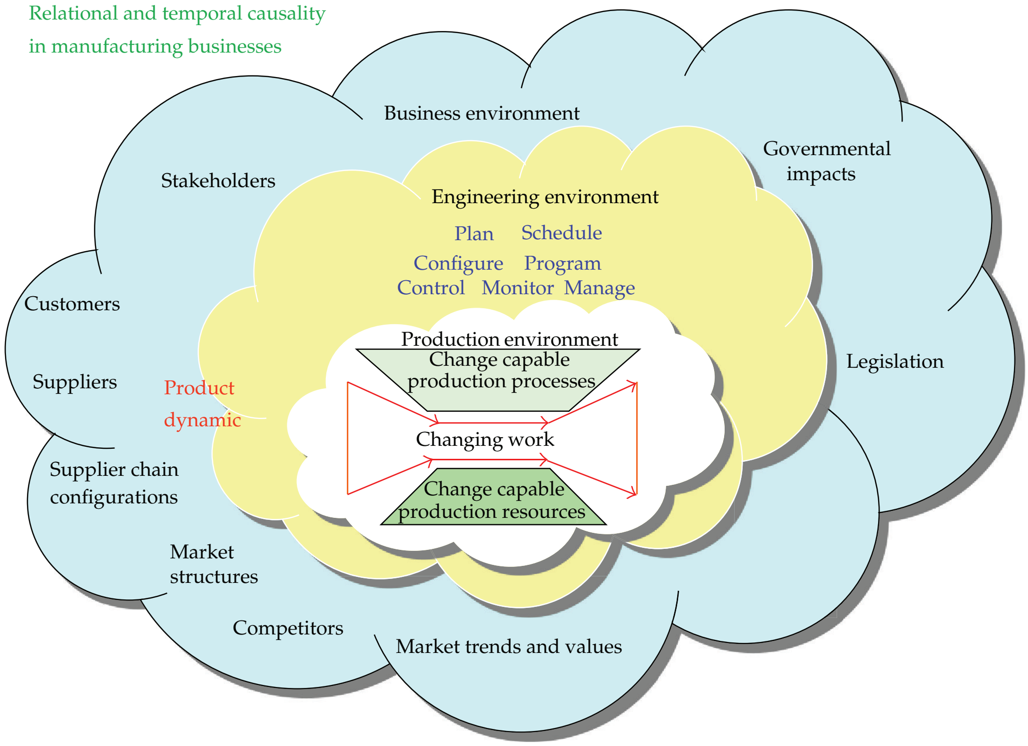

Figure 2: Some common examples of causally related variables.

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 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 Product complexity: low to medium Product variance: high Lead-times: short to medium Product cost: medium	Key concerns of company: major cash flow problems because of late contract fulfilment apparently arising mainly from poor assembly system behaviours 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 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) 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 Product complexity: low Product variance: high Lead-times: short to medium Product cost: low to medium	Key concerns of company: excessive inventories and contract delays leading to significant cash flow problems 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 Research/consultancy approach taken: three-level modelling of various ME system behaviours set within a common specific case structural model of the organisation
AEM 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 Product complexity: high Product variance: low Lead-times: medium to long 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 Hypothesise sources of the problem: disjunct between manufacturing operations, tactical and strategic	Project aim: decision/information support and integrate 3 levels of manufacturing planning 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 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 Product complexity: very high New product variance: very low Lead-times: long 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 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 Research/consultancy approach taken: simulated behaviours of targeted systems set within a common specific case structural model of the ME's supply chain

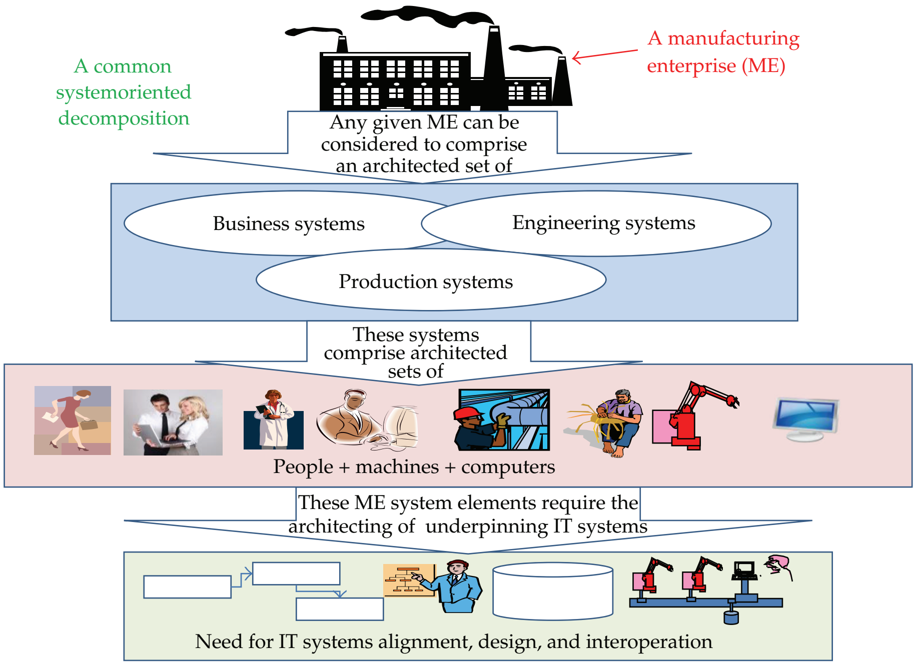

Figure 3: A conceptualisation of the system of systems deployed by the four example case study MEs.

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

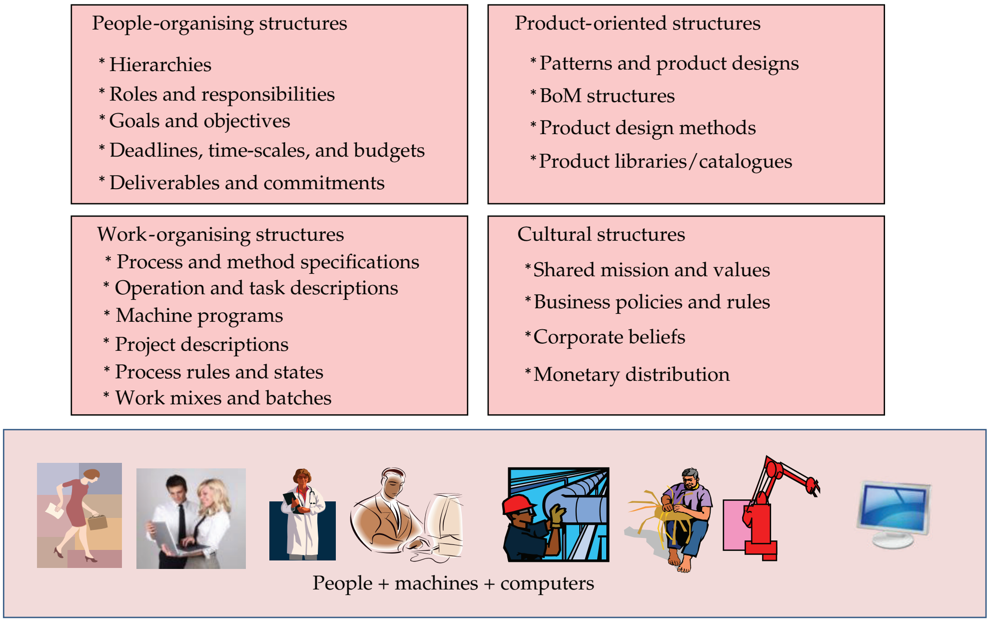

Figure 4: Common organising structures deployed in the case study MEs.

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-

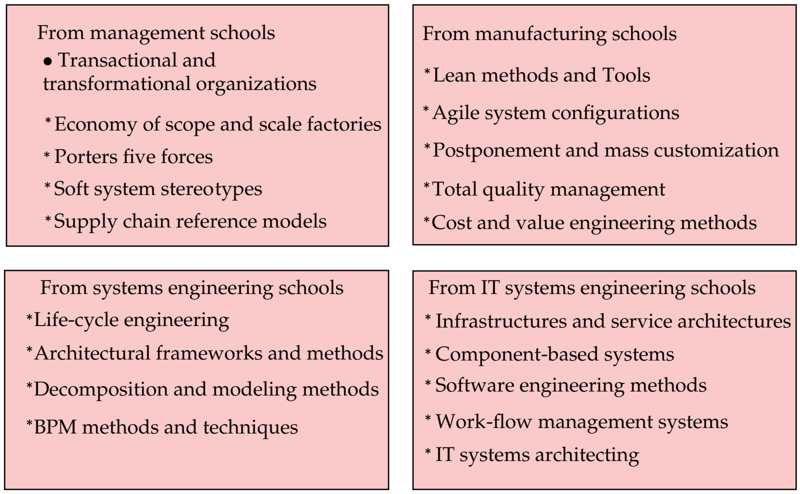

Figure 5: Interdisciplinary perspectives on patterns of structural elements used by MEs.

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

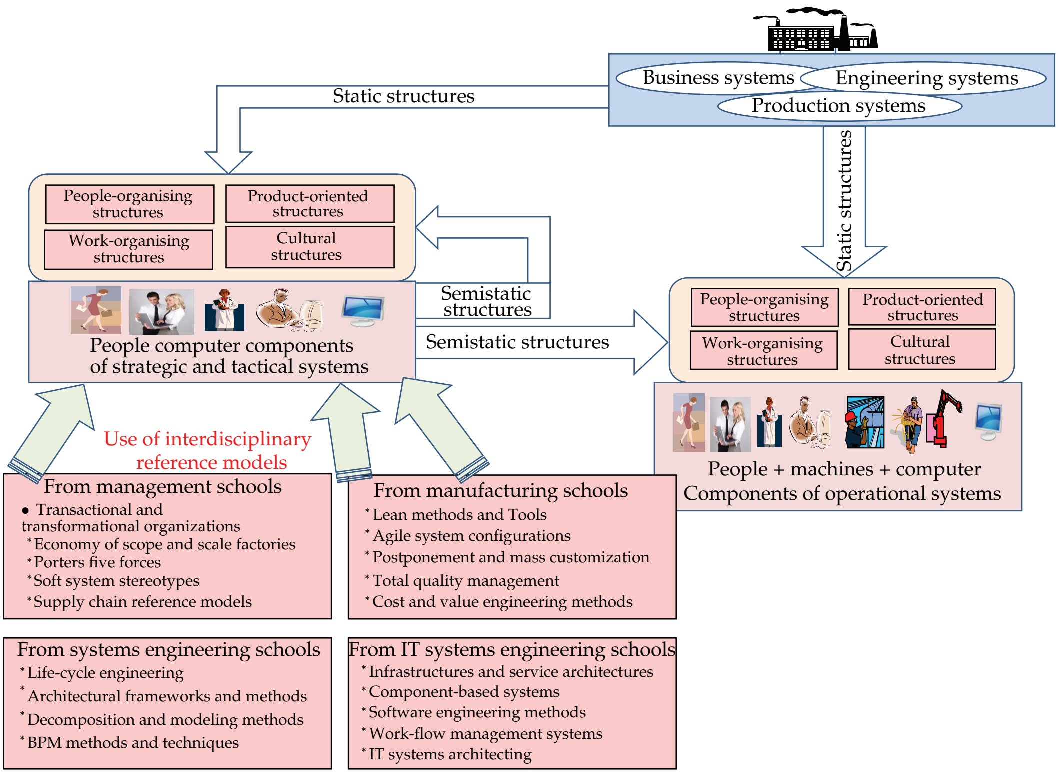

Figure 6: Use of interdisciplinary reference models by strategic and tactical teams in the case study MEs.

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

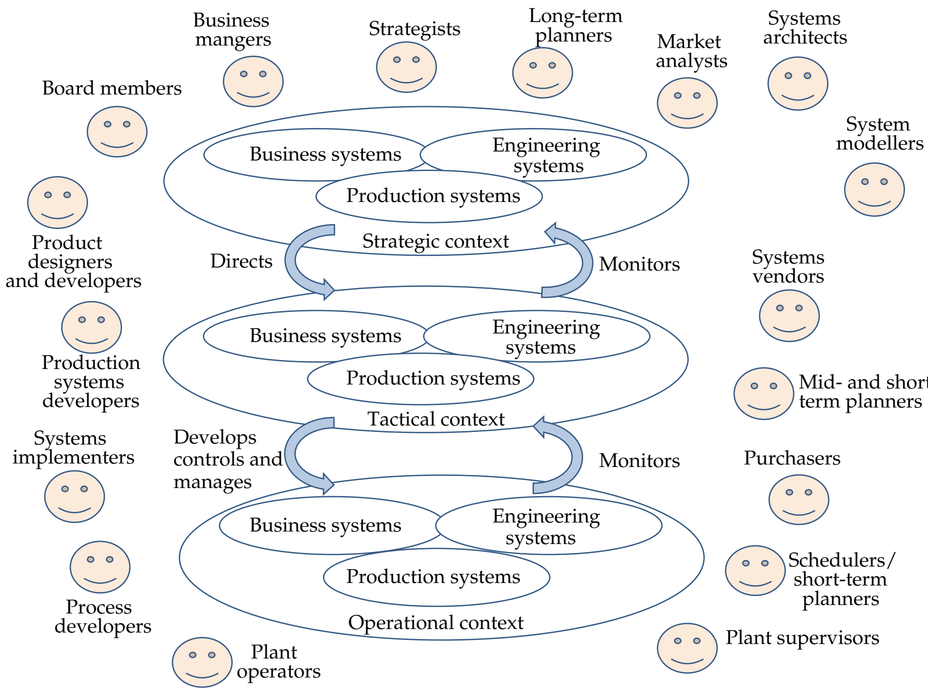

Figure 7: Common decision making roles observed in the case study LMEs.

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

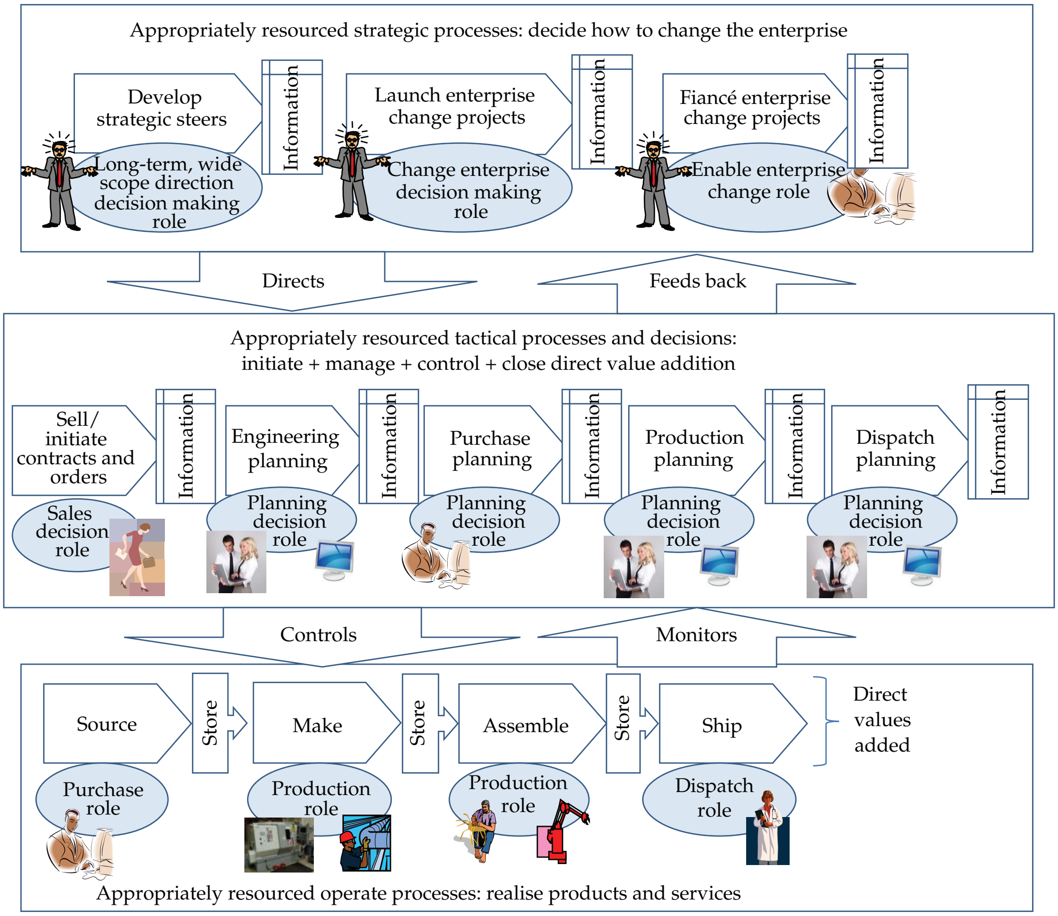

Figure 8: Commonality observed in the distribution of decision making roles in the case study LMEs.

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

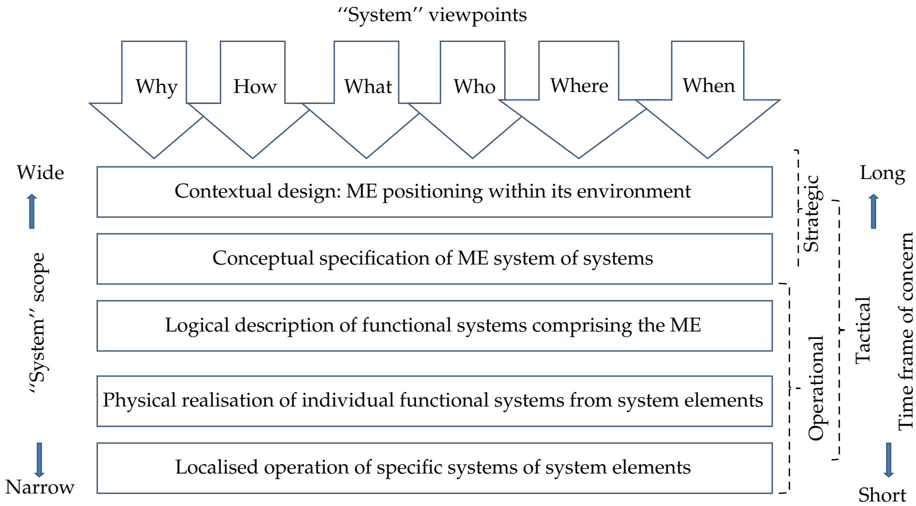

Figure 9: Common decomposition ideas in ad hoc use in the case study MEs to simplify individual decision making roles.

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

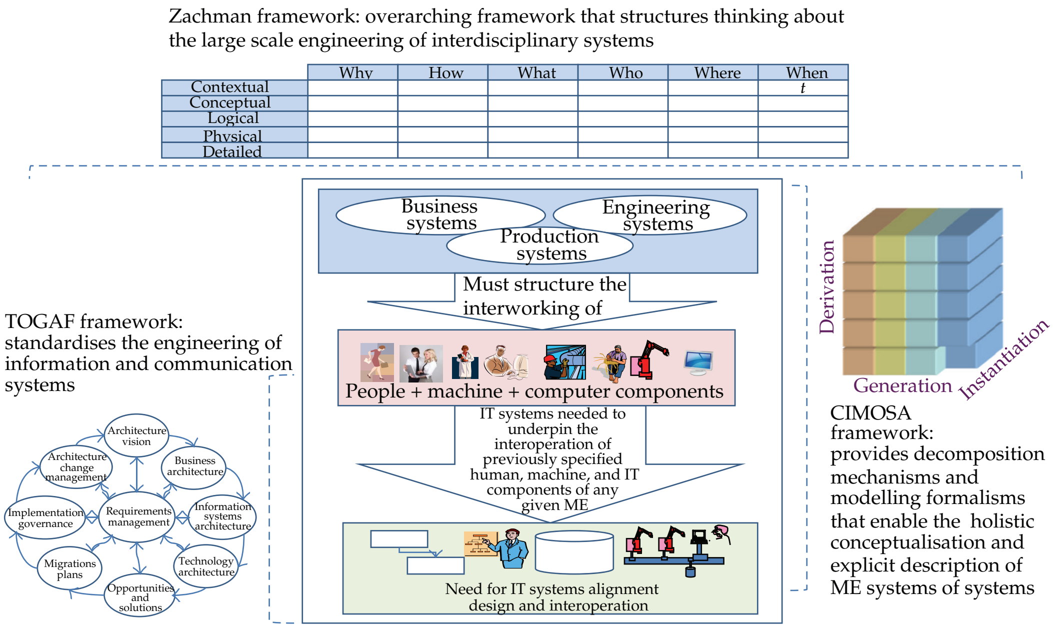

Figure 10: The model-driven framework developed to life-cycle engineer ME architectures, based on a unification of Zachman, CIMOSA, and Togaf ideas.

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

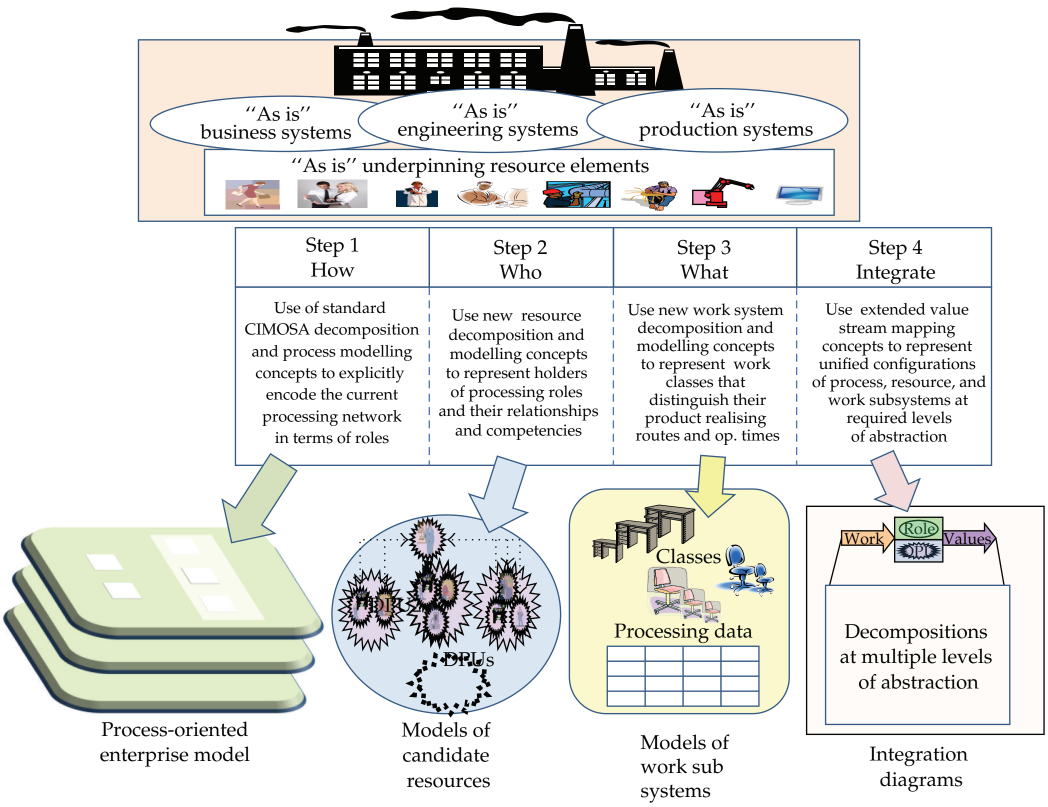

Figure 11: Conceptualisation of the "structural" modelling steps for modelling alternative ME systems of systems configurations.

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

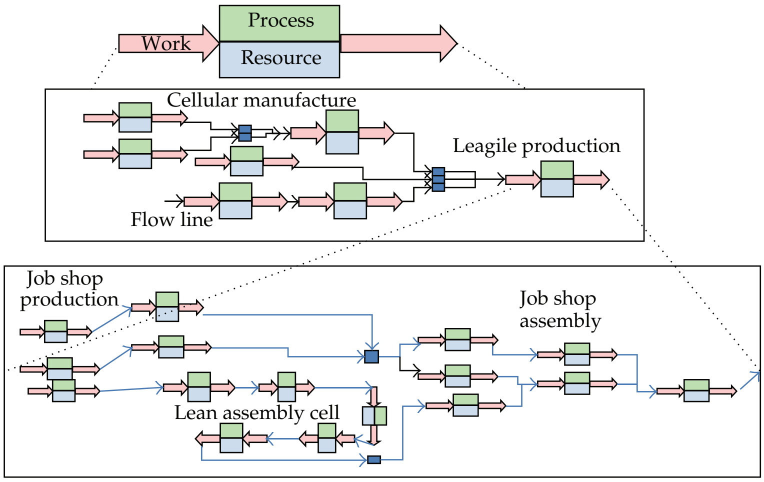

Figure 12: Example of multilevel representations of structural decompositions of systems visualised by using integration diagrams.

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-

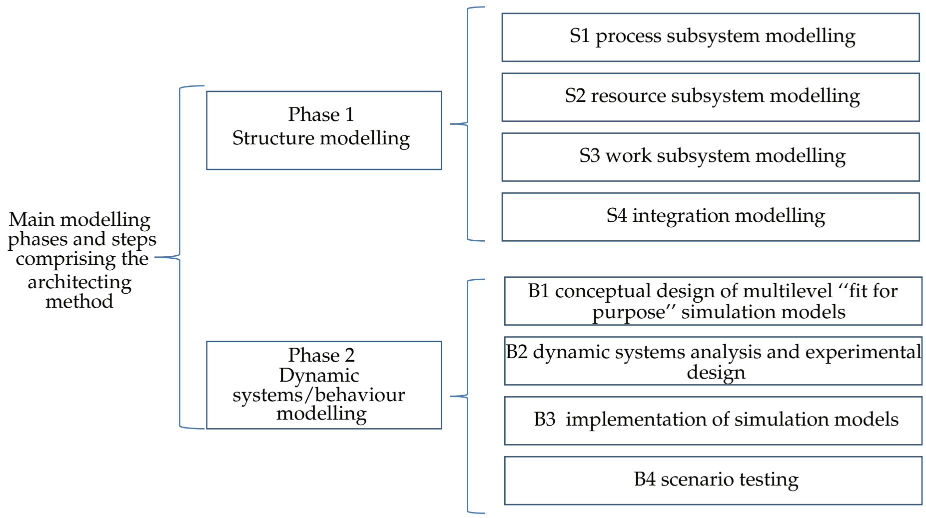

Figure 13: Combined structural and behavioural steps of the model-driven method.

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

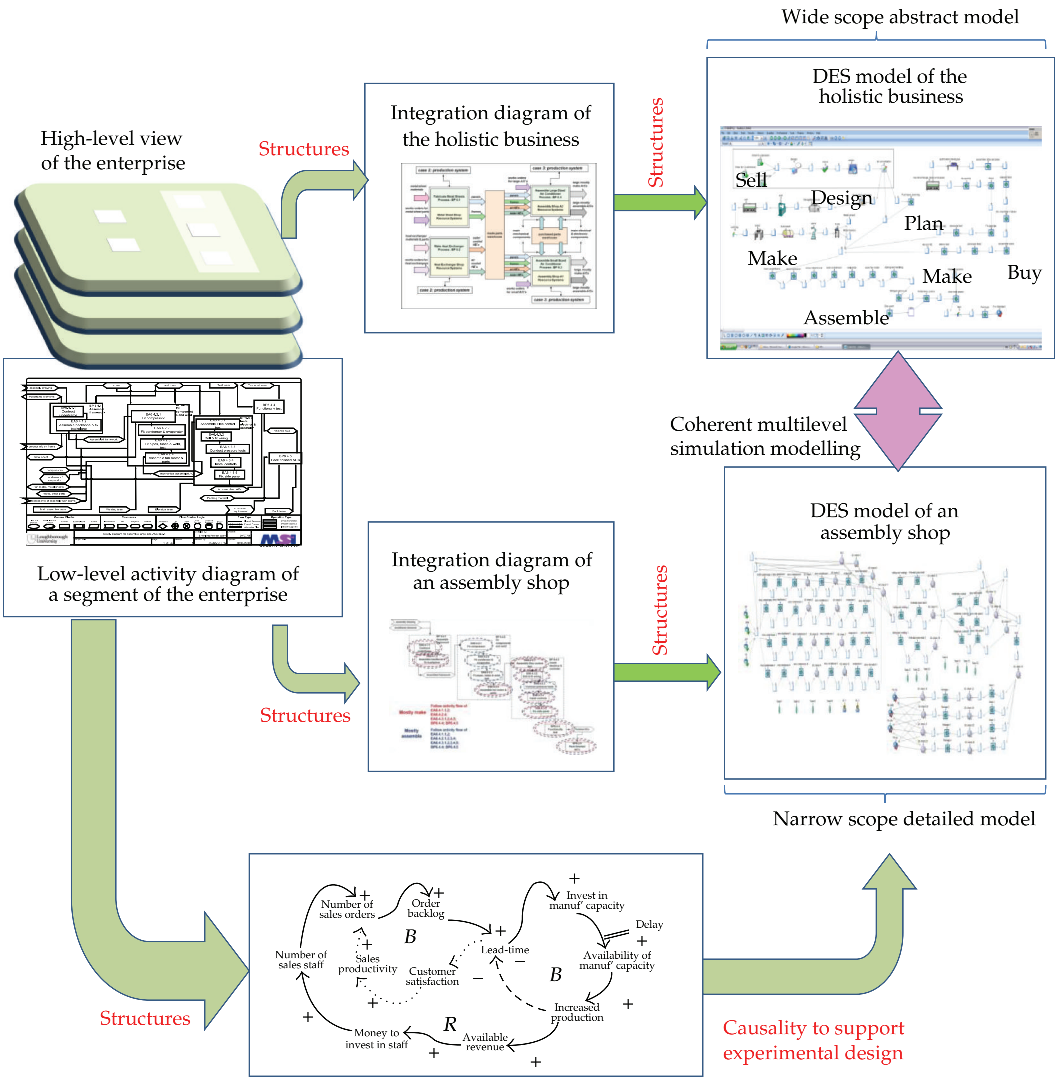

Figure 14: Conceptualisation of common behavioural steps of the modelling method.

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 multilevel 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),

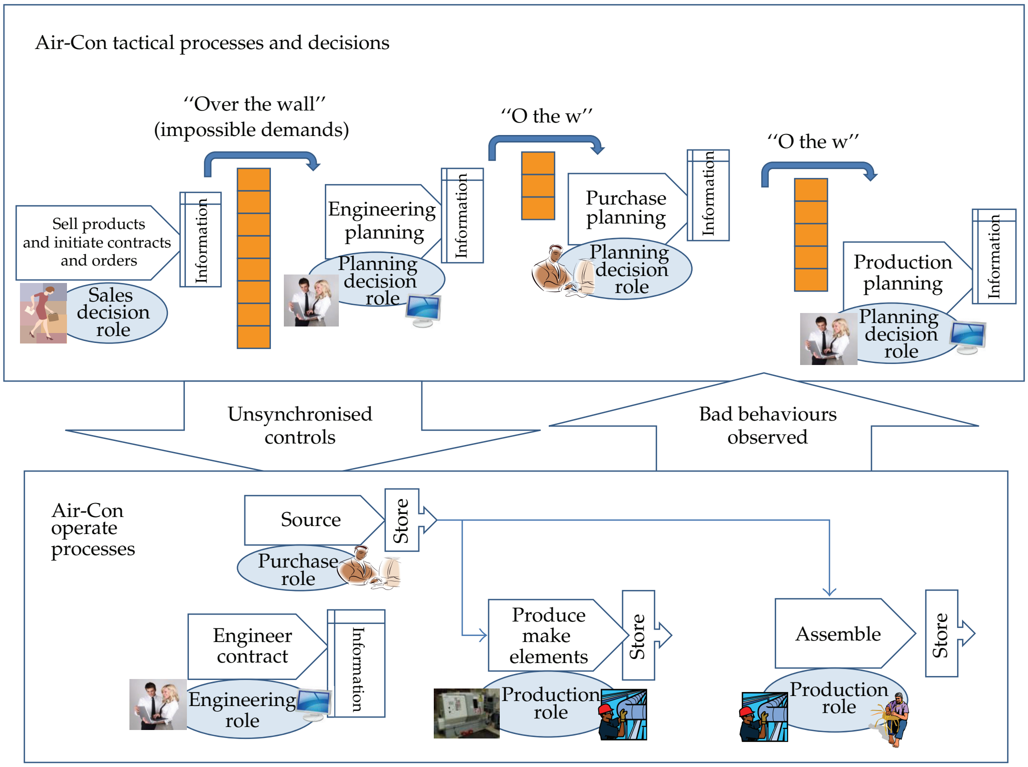

Figure 15: Conceptualisation of Air-Con decision making problems.

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

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