

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/245386422>

An approach to modelling dependencies linking engineering processes

Article in *Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture* · May 2003

DOI: 10.1243/095440503322011399

CITATIONS

23

READS

69

3 authors:



Kamran Ali Chatha

Abu Dhabi University

39 PUBLICATIONS 540 CITATIONS

[SEE PROFILE](#)



R. H. Weston

Cranfield University

217 PUBLICATIONS 2,902 CITATIONS

[SEE PROFILE](#)



Radmehr Monfared

Loughborough University

60 PUBLICATIONS 996 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Manufacturing Modelling ltd [View project](#)



Design and implementation of complex supply chains [View project](#)

An Approach to Modelling Dependencies Linking Engineering Processes

K A Chatha, R H Weston and R P Monfared
MSI Research Institute, Loughborough University

Abstract

A multi-perspective modelling method is described which was developed and used to support an international consortium of businesses concerned with realising automobile engine production on a global scale. The modelling method provides a capability to document, communicate and analyse various dependent aspects of multiple threads of engineering activities. Commercially available and specially developed computer modelling tools have been deployed to operationalise the method, and thereby to facilitate (1) the design of dependent activity flows, (2) the resourcing of activity flows by suitable human and technical systems and (3) the control and management of workflows.

The paper outlines requirements of the method with reference to properties of engineering processes that needed to be modelled. A prime focus of attention was on engineering a new generation of component-based manufacturing lines suitable for the ‘mass customisation’ of automotive engine products in production plants around the globe. Key features of the modelling framework are described as are the stages of modelling and the associated use of proprietary modelling tools. Also provided are examples of models generated when using the method and tools.

Keywords: Enterprise Modelling; Complexity; Responsiveness; Business Processes; Workflows

1. General Description of the Problem Domain

Since the late 1990’s an international consortium of automotive companies and their systems suppliers have been participants in a collaborative engineering programme aimed at *mass customising four and five cylinder petrol engines on a global scale (1)*. The programme (known as I4/I5) was founded on the notion that a select group of automotive manufacturers could use a *common base of engine technology and production systems* but would remain competitors with respect to the sale of fully packaged cars at locations around the globe. A small group of partners conceived the I4/I5 programme so that it comprised a number of dependent threads of engineering process, including (1) *product design and rationalisation processes*; (2) *production process design and globalisation processes*; (3) *production machinery design and build processes* and (4) *production facility installation and ‘roll out’ processes*. Through their lifetime (order of four years) these engineering process threads needed to be resourced by a bigger partnership of companies, namely a core group of around ten internationally prominent companies including automotive product manufacturers and automotive production system vendors. Some of the engineering effort of this core group has been supported and documented by researchers at the MSI Research Institute at Loughborough University with a view to (a) understanding and abstracting current best industry practice and (b) proposing and developing enhancement of that practice.

Necessarily each I4/I5 engineering process thread was complex in its own right. This was because of: the dependent nature of the various engineering activities involved (and dependencies between outputs produced by these activities); because of the need to satisfy multiparty (business partnership) desires and concerns; and to co-ordinate the geographically distributed efforts of those parties. Also naturally complex dependencies link engineering activity carried out concurrently in different process threads. For example, product design decisions may impact significantly on the design and implementation of human and technical systems used to achieve production processes, and vice versa.

Many discussions with I4/I5 consortium partners help to qualify aspects of a common industry problem which is centred on current lack of technology provision needed to facilitate: *reasoning about*; and *ongoing maintenance* of dependencies between engineering activities carried out both within and between multiple process threads. This paper reports progress made by MSI researchers in addressing aspects of this problem.

2. ‘Couplings’ between Engineering Process Threads

Members of the I4/I5 engineering programme have rationalised and enabled the shared use of a *common set of car engine components* amongst a small number of automotive manufacturers. Consequently competitive advantage is being gained by consortium members relative to other car manufacturers and automotive system vendors.

Even before the I4/I5 programme it was common practice in the automotive industry to manufacture car engines from five main sub-assemblies namely: ‘cylinder blocks’, ‘cylinder heads’, ‘crank shafts’, ‘con rods’ and ‘cam shafts’. By enhancing this concept, I4/I5 engineering process threads (primarily threads of *engine product design and rationalisation* and *production process design*) sought to develop *a priori* types of ‘industry standard’ engine sub-assembly into a coherent and well defined set of ‘I4/I5 standard’ car engine ‘components’¹. Necessarily constraints needed to be imposed on the degree of customisation (and hence differentiation) between engine products. However, when so doing I4/I5 product designers and I4/I5 production facility designers and developers had to ensure sufficient *product flexibility* and *production flexibility* would be provided so that all needed makes and models of car engine could be produced economically, largely using I4/I5 standard production processes and on a global scale.

It follows that a key deliverable of I4/I5 engineering activity was a new component-based car engine decomposition. This deliverable is illustrated by Figure 1. An essential outcome of the decomposition was that only a relatively small number of engine components need to be manufactured, each with sufficient ‘programmability’ (in the sense that selected ‘features’ of engine components can be changed readily e.g. via standard machining or fixing operations) that they can be ‘configured’ (largely via standard machining, assembly and transportation processes) into customer specified engine types.

¹ In the literature the term ‘component’ is used with different meanings. In this context the term is used to emphasize

New concepts embedded into the developed engine decomposition also led to propagated impact on the design of related *production processes*, *production management processes*, *logistical processes*, and *process engineering processes* realised by the consortium. For example, the reader can observe (at least in qualitative terms) that a standard and shared engine decomposition can enable a reorganisation of production and logistical process streams from the ‘as is’ to the ‘to be’ situations illustrated respectively by Figures 2 and 3. This observation emphasises a closeness of coupling between engineering activity leading to *product modularisation*.

The reader may deduce that the benefits of standardising and sharing engine components arose for three connected reasons, i.e. from improved production process decoupling; production process simplification; and production process standardisation. Figure 3 directly illustrates how a new decoupling point could be introduced into the production flows of I4/I5 manufacturer partners. An outcome of product modularisation and standardising interfaces among components is that the manufacture of engine components is decoupled from the manufacture of other engine components and from the configuration of customer specified car engines. In the I4/I5 case six well decoupled process production threads (or process modules) can be identified. This affords new opportunities to mass produce engine components whilst customising the manufacture of final engine products in smaller (possibly much smaller) batches. The I4/I5 consortium refers to this phenomenon as ‘mass customisation’. In theory at least process decoupling can suit both customer needs (for product variety) and manufacturer needs (for cost effective production).

Production process simplification is also a natural outcome of product modularisation and standardisation, and the process decoupling it enables. Because a relatively small number of standard components can be well defined then the production and logistical activities needed to make and transport these components can be simplified. Particularly because of resultant process decoupling one can surmise that no longer will there be such complex interdependencies linking ‘make’ and ‘transport’ activities.

The reader can deduce that process simplification and decoupling can naturally lead to process standardisation. Now it becomes possible to define sub processes (and associated ‘make’ and ‘transport’ activities) more completely, to communicate process requirements and problems more effectively and to distribute responsibilities (in space and time) for process realisation.

In tandem, therefore, the process of decoupling, simplifying and standardising production and logistical processes can be key to realising complex products on a global scale. What is more it can be presumed that these three outcomes from product modularisation can much simplify engineering projects, processes and activities associated with the design, realisation and change of production processes and facilities. In principle therefore good product and process decompositions are likely to much simplify subsequent process change, process development and ongoing process improvement.

In as complex a case as I4/I5 global production facility development however, it was observed that practical realities mean that it is difficult to quantify propagated effects of decisions and actions taken in one engineering process thread, on decisions and actions taken on associated concurrent engineering or production process threads. Therefore at present the I4/I5 consortium cannot communicate nor reason in a readily

measured way about the effects of such a propagation. It follows that at least to some extent they can only make a 'leap of faith' when designing and implementing new product and production process decomposition. In short any major change is likely to be associated with significant short and long term risks. A natural and likely actual outcome is conservatism, resistance to change and very limited realisation of potential benefits. Regarding the latter point, despite a standardisation agreement on I4/I5 engine components it remains the case that 'as is' engineering processes deployed by the consortium are fairly conventional, costly, long lead-time affairs not designed to be: readily re-instantiated in order to 'roll out' the next phase I4/I5 production plant; nor to cope with late product, process or plant change; nor to cope with uncertain, yet-to-be determined global needs.

3. A Method of Modelling Multiple Processes and Process Dependencies

Engineering and Physical Sciences Research Council (EPSRC) has funded research at Loughborough University which has created and used various multi-perspective models of the engineering and production processes resourced by I4/I5 business partners (1). As successive I4/I5 process modelling studies were carried out a new approach to Multi-Process Modelling (MPM) was conceived. Further its use has been tested and developed up during follow up research study. Essentially the MPM method lends 'structure' to the use of state-of-the-art enterprise modelling concepts and tools. That structure 'organises':

- (1) the ongoing capture of a coherent and semantically 'rich picture' of dependent processes, in such a way that key dependencies can be explicitly represented during process lifetimes;
- (2) the reuse of multiple coherent views of multiple process models and their modelled dependencies for different enterprise engineering purposes.

Literature review and previous experience of the authors showed that no pre-existing multi-process modelling method (and supporting software toolset) was available to satisfy requirements (1) and (2). Consequently MPM method was conceived. Method design and development has centred on an enhanced use of CIMOSA modelling concepts (2) which were found to provide a suitable backbone of representational primitives. Table 1 describes the state of development of the MPM at the time of writing but method developments are ongoing.

Table 1 Overview of the Multi-Process Modelling (MPM) Method

	Outline Description of Modelling Activities Needed at each Main Step of the Modelling Method	Method & Concepts used to 'Structure' Modelling Activities & Multiple Process Representations	Modelling Techniques & Tools Deployed to Represent & Analyse Modelled Entities & their Interrelationships
Stage 1: Elicit 'As Is' Process Data from Engineering Partners	Elicit and record multiple understandings about current business processes deployed by the engineering partners, with the aim of developing a unified set of process representations that collectively form a static pool of enterprise knowledge that can be reused for various purposes.	A developed approach to documenting alternative views of multiple business processes; held either within the heads of people responsible for different process segments or previously recorded in company documents. Structured interviews (which constitute an integral part of the approach) are organised with reference to the need to populate four kinds of CIMOSA diagramming template.	Various paper based sketches of CIMOSA conformant 'domain processes', 'business processes' and 'enterprise activities' are developed to facilitate knowledge elicitation and multi-process documentation, leading to the population of many modelling templates.
Stage 2: Create and Validate 'Static Views' (or representations) of 'As Is' Processes	Reuse of elicited data to populate and validate multiple 'static views' of 'as is' business processes that collectively and coherently provide a 'semantically rich picture' of relatively enduring enterprise entities and their interrelationships that can be reused by different enterprise personnel in support of their various roles.	Static views captured and populated in conformance with CIMOSA diagramming templates needed to encode 'enterprise requirements'. Thus fragmented process views, at multiple levels of abstraction are organised into 'context', 'interaction', 'structure' and 'activity' modelling templates pertaining to both partnership enterprises and individual partner businesses. Individual and collective validity of the views is rechecked with appropriate personnel.	A structured approach to the use of a combined Powerpoint and VISIO (general purpose presentation software) was developed to facilitate the generation of graphical (non-computer executable) representations of 'as is' static model views, based on the semi-structure use of CIMOSA conformant modelling constructs. Use for this purpose of various specialist commercial tools (such as FIRST STEP, MO ² GO and METIS) was considered but not adopted.

Stage 3: Develop & Validate Dynamic Models Pertaining to Focused Aspects of 'As Is' Processes	Selected aspects of the static representations of 'as is' processes are recoded into computer executable models with capability to simulate process operation and behaviours from some perspective and thereby provide new insights into 'as is' <i>process design</i> , <i>process resourcing</i> and <i>process operation</i> . Initial dynamic model analysis and development is focused on model validation with subsequent analysis on identifying possible constraints arising from 'as is' practice.	Various general CIMOSA modelling concepts (pertaining to ' <i>derivation</i> ', ' <i>generation</i> ' and ' <i>instantiation</i> ') were used to focus and structure dynamic model generation. However use of these concepts and associated CIMOSA decomposition principles needed to be translated into an alternative set of modelling concepts which can be practically implemented using a selected dynamic systems modelling tool.	At the time of writing more than 10 modelling studies have, for different purposes, generated alternative dynamic models using the <i>ithink</i> modelling tool [4], by recoding selected entities and entity relationships previously coded by the static base data. This yields computer executable models that via the application of numerical integration techniques simulates and displays metricated dynamic behaviours in various programmable and interactive forms.
Stage 4: Develop & Validate Dynamic Models of Focused Aspects of Possible 'To be' Processes	Based on knowledge of 'as is' process properties (static and dynamic) new business process scenarios are developed and are run under simulation. This provides metricated analysis of alternative: <i>process designs</i> ; <i>attributions of resources to process elements</i> ; and <i>process operations</i> .	Use of CIMOSA and causal loop modelling concepts help structure 'to be' scenario generation. Use of CIMOSA <i>enterprise activity</i> and <i>functional entity</i> concepts help structure process resourcing activity. These and new modelling concepts needed to be mapped onto modelling concepts and constructs made available by the selected dynamic systems modelling tool.	Causal loop diagramming techniques and the <i>ithink</i> systems dynamic tool are used to 'visualise' and 'simulate' causal effects and the operation of various candidate 'to be' scenarios. This enables conceptual thinking and focused simulation of possible 'to be' behaviours and metricated performance measurement made relative to 'as is' benchmarks.
Stage 5: Focused Deployment and Use of Static & Dynamic Process Models to Control Actual Workflows	One important potential use of 'as is' and 'to be' static and dynamic process models is to manage and control workflows. At this stage of the modelling method selected model fragments (previously captured and validated) are recoded so that they can be executed (in a suitable workflow tool). This allows computer executable models to be linked to the actual process and its resource entities.	CIMOSA decomposition principles and particularly its <i>instantiation</i> , <i>enterprise activity</i> , <i>functional entity</i> , <i>information object</i> and <i>enterprise event</i> modelling concepts are used to partially structure the reuse of previously coded process knowledge into recoded forms (namely <i>control flows</i> and <i>data flows</i>) that need to be enacted by the set of modelling constructs provided by the selected workflow tool.	The <i>i-Flow</i> workflow management tool [3] was selected to operationalise focused workflow aspects of the 'as is' and 'to be' process models previously captured, validated and analysed.

Early stages of MPM method development focused on the capture of a pool of static² data, which incorporated various views of multiple processes so that alternative uses of the information pool can be promoted. A selected base of CIMOSA enterprise modelling and reference architecture concepts was found to provide suitable formalisms to (a) decompose complex systems (of processes) into sub-systems (or many largely self-standing sub-processes) that can be analysed independently and (b) during later stages of analysis and project engineering to recompose sub-systems into a collective whole. More specifically MPM builds upon the use of four types of diagramming template specified within the CIMOSA function view, namely: 'context-diagrams', 'interaction-diagrams', 'structure-diagrams' and 'activity-diagrams'. This set of CIMOSA diagramming concepts and graphical modelling constructs provided effective means of structuring the capture and representation of multiple and coherent static views of I4/I5 engineering process attributes at all needed levels of abstraction.

'Context-diagrams' are used to organise process models into interrelated CIMOSA-conformant and non-CIMOSA conformant domains, the former being domains of concern that need to be modelled (using CIMOSA and other modelling constructs) in conformance with the new modelling method. 'Context-diagrams' are decomposed as required into more detailed (lower-level) 'context-diagrams' until core processes (so called 'domain processes') of concern are identified. Domain processes are then treated essentially as 'independent' processes that exist in order to contribute to domain objectives and deliver quantifiable benefits. Domain process interactions are normally modelled in terms of the exchange of information, human resource and/or physical resources where such an exchange is triggered by specified events. This set of ideas was also found to offer suitable means of attaching business metrics.

Interaction amongst 'sub-domain processes' is represented by 'interaction-diagrams' which also model the exchange of results and resources, triggered by events. Sub-domain processes work together and interact with one another to fulfil the purpose of a domain process. Sub-domain processes can be further decomposed into so called 'business processes' and 'enterprise activities'. CIMOSA 'business processes' are similar to domain processes in that they concatenate enterprise activities and have well defined inputs and outputs. But whereas domain processes can be triggered by only an event, business processes need to be jointly triggered by an event and a call from a domain process. Business process specifications also need an ending status to be defined. Enterprise activities are used to represent elementary function units of a CIMOSA domain. Enterprise activities exist to transform inputs into outputs and they require informational and physical (i.e. human, machine and IT system) resources to realise their function.

Dependencies between 'business process' and 'enterprise activities' comprising a single domain process (and its sub processes) are encoded by 'structure-diagrams' and 'activity-diagrams'. 'Structure-diagrams' are used to formally attribute relatively enduring (or static) organisational relationships that couple the business processes and enterprise activities of a domain process. While 'activity-diagrams' are deployed to formally attribute relatively short-lived descriptions of precedence links between

² In this context the term 'static' indicates that engineering process model capture was focused on representing relatively enduring process entities and entity relationships, this being centered on the normal flow of engineering activity carried out. Such a focus of attention is distinct from that of modeling dynamic (short term) properties of engineering processes such as when modeling specific activity states and state transitions required to make a particular engineering decision.

business processes and enterprise activities. Typically therefore a ‘structure-diagram’ might be used to specify long term heterarchical or hierarchical relationships while an ‘activity-diagram’ might be used to define the order of execution of a set of enterprise activities. The status of precedence links (which may be specified in terms of designated process conditions, actions and events) can determine and/or modify the order in which activities are carried out during process execution.

The diagramming templates were found to provide an effective and practical ways of developing mid to long term views of I4/I5 dependency relationships, that couple complex groupings of processes, activities and resources. The resultant static model, coded graphically by many related template model fragments, can be followed from top to bottom. Thereby it can represent and communicate multiple pictures of dependent processes in a coherent, step-by-step manner at different levels of abstraction.

CIMOSA’s well defined and well structured approach proved capable of elaborating an holistic (but static) picture of I4/I5 that cuts through much of the complexity that previously had inhibited collective understanding and the coherent development and description of more focused concerns within a well defined common context. The capture and subsequent use of a static data pool describing I4/I5 engineering processes has proven effective in identifying, visualising and communicating the purpose of activities and processes and possible roles that might be played by different resource groupings. On the other hand, use of the diagramming templates alone does not provide qualitative means of exercising ‘what if’ thinking. Nor do they directly encode certain real time working concerns, such as about how individuals or dependent processes might alternatively behave in response to changes in process inputs, process flows, operating conditions and so forth.

It was observed that the I4/I5 consortium needed improved multi-process modelling and decision making capabilities in order to (i) gain new insights into current process designs, process resourcing and process operation and (ii) realise metricated analysis of possible alternative scenarios discovered under (i). Therefore stages 3 and 4 of the MPM method (see Table 1) were designed and developed to complement earlier stages of modelling. Here it was decided that MPM development should be based on the combined use of (a) CIMOSA model ‘generation’, ‘instantiation’ and ‘derivation’ principles applied to the static data pool and (b) dynamic ‘*Systems Thinking*’ and the selective use of modelling concepts and mechanisms previously developed by Forrester et al (3). *System Thinking* concepts were adopted because they naturally support the process of generating clear mental pictures about complex systems. They provide means of understanding the effect and strength of *cause and effect relationships* that otherwise may not be readily apparent. When they were used in combination CIMOSA modelling and ‘qualitative’ and ‘quantitative’ versions of systems thinking concepts and computer tools were found to provide effective means of developing and reusing computer simulation models that draw from a pre-established pool of relevant information about dependent processes.

Many different software tools could usefully have been selected and used to simulate dynamic behaviours of alternative process designs and configurations and thereby to lend support for stages 3 and 4 of the modelling method. However modelling method development was focused on enabling an effective use of the dynamic *Systems Thinking* tool *ithink*. The strength of this particular tool was perceived to lie in its ability to help visualise process behaviours and process dependencies in a way that

can unify views and concerns of different stakeholders. Being essentially a tool for solving sets of differential equations that describe interrelated physical process behaviours, it provides excellent behaviour simulation capabilities at an aggregated level. It was found that a developed use of the tool can provide effective support for hypothesis and new policy testing associated with ‘could be’ and ‘to be’ multi-process scenarios. However the tool was found to have limited ability to support detailed aspects of process and human and IT system design, hence there was also an observed need to develop the use of other commercial simulation tools within the context of the MPM method.

Other needed I4/I5 decision making concerns were observed that related to (a) the specification and development of human and machine systems, with capabilities, capacities and qualities to resource ‘as is’ and ‘to be’ engineering process designs and (b) the specification, management and control of actual instances of I4/I5 engineering workflows. Much of the previous MSI modelling research reported in the literature has centred on (a). In this respect previous I4/I5 modelling studies have sought to determine how the introduction of a new generation of component-based engine assembly machines would impact on future I4/I5 engineering processes [1]. With respect to (b), improved engineering workflow management and control of I4/I5 project work was needed to reduce the impact of overly long machine design and build lead-times, and the impact of late change to machine designs on machine engineering processes carried out by vendor partners. To address this, and similar workflow management and control problems, the multi-process modelling method was further extended as outlined in Table 1. At a fifth stage of modelling, CIMOSA concepts related to model instantiation were used to lend structure to the capture and description of workflow models that can be enacted by an ‘off the shelf’ workflow management tool, namely the *i-Flow*TM tool (4).

Process enactment tools other than *i-Flow* could have also been chosen. However, the *i-Flow* tool was perceived to possess well developed capabilities to achieve distributed management and control, based on the use of Internet enabled systems integration services. In particular it provides capabilities needed to achieve runtime connectivity between distributed processes, and particularly engineering processes used by I4/I5 vendor partners to design and make engine assembly machines. The *i-Flow* tool is a distributed client server, web-enabled, workflow application development tool that was designed to manage co-ordination aspects of business processes. It provides a set of modelling constructs designed to represent and enact representations of certain aspects of enterprise activities, relationships linking activities, attributes of personnel assigned to activities, the order in which process steps should take place and relevant data needed for each process step. Thereby processes can be designed using *i-Flow* templates which are used to define properties of a sequence of *i-Flow* activity nodes and behaviour nodes, having some defined finality. Specified nodes can then manage and control real processes and their resources using Internet enabled services.

4. Illustrative Use of MPM

It is only practical within journal publication constraints to briefly illustrate a few of the modelling steps and model views that can be usefully generated and reused when using the new multi-process modelling method. The following subsections are designed to illustrate the concepts in action, rather than to provide a comprehensive

picture of results achieved from I4/I5 process modelling or to illustrate the magnitude of modelling efforts involved when using the MPM method.

4.1 Sample Static Models of I4/I5 Engineering Processes

A sample use of the four types of static modelling template is illustrated by Figures 4 through 8. The sample is taken from a much bigger set of templates used to model dependent engineering processes used currently to design and manufacture engine assembly production machines. Each template is essentially a fragment of the complete model of I4/I5 engineering processes and codes selected aspects of that model graphically in terms of CIMOSA defined standard modelling constructs. The CIMOSA graphical modelling constructs made available are illustrated in template keys. Attributed labels and text descriptions particularise the use of these standard constructs.

Figures 4 and 5 are two examples of the use of context-diagrams. Figure 4 illustrates the 'Overall Project Domain' for the New Engine Project. One domain process of concern within this Overall Project Domain comprised an organised set of engineering activities that collectively lead to the 'Production/Assembly (of) Machines'. When modelling, this set of engineering activities became known as the 'Produce Engine Assembly Machines (PEAM)' domain process. This domain process is shown in the context diagram illustrated by Figure 5. The Figure shows that the 'Produce Engine Assembly Machines' domain process was itself decomposed into sub-domains related to concerns of 'customers', 'machine builders', 'component builders' and 'technology vendors'. Models of these sub-domains needed to interact according to attributed CIMOSA rules. It was determined that I4/I5 modelling studies related to the 'Produce Engine Assembly Machine' domain process only required detailed modelling of 'customer', 'machine builder' and 'component-builder' sub-domains. When creating CIMOSA models, these sub-domains were treated as dependent domain processes. This means that it was assumed that the 'technology vendor' sub-domain was sufficiently decoupled from consortia decision making (and therefore other sub-domain processes) that it was not necessary to carry out detailed modelling of technology vendor activities.

A sample 'interaction-diagram' is shown in Figure 6. This graphically represents interactions between dependent domain processes specified previously by templates shown in Figures 4 and 5. In the case of modelling I4/I5 engineering processes multiple instances of multi-level sets of interaction diagrams needed to be produced in order to sufficiently well define interactions that occur between the various 'end user customers', 'machine builders' and 'machine component vendors' involved in I4/I5 engineering projects. The modelled interactions are those necessary to achieve interworking between domain process and sub-domain processes, so that collective domain objectives are achieved.

Figure 7 shows a sample 'structure-diagram'. This fragment of the overall static model identifies, structures and organises the business processes and enterprise activities that collectively comprise a single domain process, in this case those activities for which Machine Builder 1 is responsible. In this case the modelled domain process comprises a structured grouping of business processes (namely 'concept design', 'design review', 'detailed design', etc) which in turn comprise sub-business process (for example 'concept design' comprises 'station layout' and 'advance planning') and enterprise activities (these being listed in Figure 7 with reference to parent business processes). After 'organising' BPs (business processes)

and EAs (enterprise activities) in this way they can be further structured in accordance with the MPM method by attributing a sequence to them. Such a sequence is designated graphically by means of arrow-headed lines indicating those BPs and EAs that follow each other. In the I4/I5 engineering process modelling studies the use of structure diagrams was found to prove powerful and effective, providing a technique for coding up, validating and visualising process information elicited from I4/I5 partners.

The use of CIMOSA activity-diagrams was also found to prove highly effective. Figure 8 shows a sample I4/I5 activity-diagram. This represents flows associated with some of the EAs and BPs specified in Figure 7.

Very many CIMOSA diagramming templates needed to be created to facilitate the holistic, albeit static, representation of dependent I4/I5 engineering processes. To capture knowledge required to model I4/I5 processes, approximately four man months work was carried out to extract information from companies' experts and their documentations. Further one man month was required to structure the information in CIMOSA compliant templates and another one man month for consistency checking and validating the models in consultation with the collaborators' engineers. This constituted a considerable modelling effort (order of 6 man months work), partly because at the time when the static model was captured no sufficiently comprehensive and conveniently available computer modelling tool was available to support multi-process model development, documentation and change. Some (mainly) research prototype tools had previously been created for such a purpose but all available alternatives considered were found to have technical or practical limitations. Therefore general purpose graphical modelling software is being developed for this purpose.

Despite the effort involved, the process of eliciting, validating, visualising and updating the static pool of templated multiple process data has proven effective. It has provided a rich and coherent source of data about a number of interrelated I4/I5 engineering processes. The data pool has been reused and developed up in a series of modelling studies that serve various purposes.

4.2 Sample Dynamic Simulation Model

During stages 3 and 4 of the multi-process modelling method an underlying purpose of modelling is to better understand the nature of domain processes and their interdependencies from viewpoints of concerned parties. These new understandings should lead during stage 3 to a measured assessment of the effectiveness of current practice and in stage 4 to assessments of benefits and risks of alternate practice. Specific I4/I5 engineering process modelling studies carried out by MSI personnel confirmed the complex and time dependent nature of process dependencies, showing how decisions made and action taken by a responsible party in one segment (or sub-domain) of a domain process can significantly influence the magnitude and distribution of costs and lead-times associated with partner roles in engine assembly machine design and build projects. This exemplified the need for a multi-process simulation capability. To satisfy that need new simulation methods were developed based on the combined use of CIMOSA and *Systems Thinking* concepts.

The static data pool (coded via CIMOSA graphical templates) provides source knowledge about how current sequences of I4/I5 engineering activities require resources, information flows, control flows and material flows in order for them to

generate suitable process outputs. Also coded within that data pool are trigger event and ending statuses that call and terminate process interactions. However, cause and effect model concepts and graphical modelling primitives used to model systems in *ithink* require quite distinctive ways of visualising and representing processes and particularly are centred on multiple differential equation solving to exhibit complex system behaviours. *Systems Thinking* does not define specific process semantics such as domain processes, business processes, enterprise activities etc. Nor does it enforce CIMOSA decomposition rules such as a need for separated modelling of process requirements and resource and related system solutions. Rather it facilitates the use of very general modelling constructs which include: variables, links, loops, stocks and flows. The *ithink* modelling tool offers three levels of modelling abstraction to support the efforts of model users and model developers. It follows that CIMOSA and *System Thinking* concepts are complementary but that high levels of skill and human intuition are needed to convert information coded into the static data pool into effective simulation models and dependency scenarios that can be executed using the *ithink* tool.

Figure 9 shows an example process segment represented at the Interface Layer of the *ithink* tool, which corresponds to a part of the I4/I5 process represented by the activity diagram of Figure 8. This layer of modelling is designed to provide a high level view, suitable for senior managers or middle managers who may have financial responsibility for sanctioning process and systems engineering projects.

Figure 10 shows a sample of enterprise activities and their relationships described at the *ithink* Model Construction Layer. This model segment details a segment of BP222 (see Figures 7, 8 and 9 related to ‘as is’ Concept Design sector of the *machine design and build process* deployed by Machine Vendor 1. The purpose of the Model Construction Layer is to facilitate the roles of system and process modellers as they build, run and develop alternative dynamic models.

Consider a segment of the ‘as is’ sub-domain process, ‘product design engineering’, specified previously by the Activity Diagram of Figure 8. This model segment concerns three business processes, i.e. Concept Design-BP222, Design-Review BP223 and Detailed Design-BP224. This model segment is also part of wider scope domain process that was previously modelled at the Interface Layer of the *ithink* tool. Figures 10 and 11 show model fragments representing some of the Concept Design-BP222 enterprise activities. Model segments like this can be executed (using dynamic simulation techniques based on numerical integration) by the *ithink* tool thereby enabling dynamic behaviours to be predicted and analysed. However, a process is only generated when a coherent group of activities are concatenated. Therefore there arises a need to formalise the concatenation of activities so that inputs and outputs can be passed between them. Two ways of achieving this were developed. An example snapshot of how activities are concatenated is shown in Figure 11.

The *ithink* tool does not provide means to enact a process, in the sense that it cannot link to, and interact with, the real world system it models. However it does provide means to predict behaviours of modelled processes providing various ways of interacting with process model developers wishing to analyse and compare behaviours of alternative process designs. Figure 12 shows a sample of simulation results obtained when executing the models shown in Figures 10 and 11. Various simulation

parameters can be adjusted and *ithink* provides a so called *flight simulator* to allow process and systems designers to interact effectively with dynamic simulations.

The *ithink* simulation models of I4/I5 engineering processes have proven very effective. They have helped both academic and industrial partners to learn about and communicate multi-disciplinary behavioural aspects of ‘as is’, ‘could be’ and ‘to be’ processes. By so doing they have helped to specify requirements of related human, machine and IT systems.

4.3 Example Use of Process Models to Control Actual Workflows

Suppose following stages 3 and 4 of modelling a case for process improvement has been made and a suitable project budget has been agreed. Dependent upon the nature of the needed process change, alternative uses can be made of the new process understandings coded by the static data pool and by ‘as is’, ‘could be’ and ‘to be’ simulation models. Importantly aspects of these multi-process models can be used to inform the design of (new or changed) human and IT systems, so that modified enterprise activities or activity relationships can be appropriately resourced. In the case of I4/I5 process engineering projects, many new and old distributed systems (comprising people, IT systems and manufacturing machines) were needed to organise and realise the many complex engineering activities carried out by the business partners. Common types of needed process change included: (i) the introduction of new systems, (ii) the replacement of existing systems and (iii) improvement to the integrated operation of existing and/or new systems.

Stage 5 of the multi-process modelling method was conceived and developed primarily to satisfy process change cases of type (iii). Here concept and tool development was centred on the use of the commercially available workflow management tool *i-Flow*TM. This was capable of enacting process models so that a ‘programmable co-ordination structure’ could be flexibly imposed around the real execution of multiple IT systems, i.e. the *i-Flow* workflow management tool would provide a ‘groupware mechanism’. Previous commercial use of this particular workflow management tool had been confined mainly to financial and related business application areas. However one thread of MSI research investigated the potential new application of this tool in manufacturing and engineering domains.

Because their intended purpose and scope of use is different, naturally there are marked differences between the modelling constructs and modelling templates available during CIMOSA, *ithink* and *i-Flow* modelling of processes. Therefore the MPM method needed to ensure that their capabilities are used coherently, thereby enabling multiple uses (and reuses) of encoded knowledge during the lifetime of multiple, dependent processes. Here it was observed that *i-Flow* modelling templates and constructs can be used effectively to model workflow aspects of either domain processes or business processes. However they needed to be triggered in accordance with CIMOSA rules. Therefore for example, when an *i-Flow* template is initiated by another *i-Flow* template, then the initiated template must be a business process.

Figure 13 illustrates a snapshot of an *i-Flow* template that was created from knowledge previously encoded into Figures 8 and 11. The *i-Flow* tool provides three user interface ‘panes’, namely: an ‘exploded drawing pane’ (right hand side of Figure 13); a ‘browser pane’ (top left of Figure 13) which lists templates, processes and activities that may be sorted or filtered based on a number of criteria; and a thumbnail

view (bottom left of Figure 13) which shows the ‘context’ of the exploded view. Above the start node appears a horizontal bar containing different types of Node Icon, i.e. ‘Activity Node’, ‘Conditional Node’, ‘Control Flow Node’, etc. Selection and joining of these nodes results in simple or complex activity sequences. *i-Flow* defines templates as being reusable process definitions. They contain the entire structure of a process. However they are not active. Rather they are static entities used to define common process properties and behaviours (including the standard ordering of activities). They also provide a static view of links between activities and their associated information and human resources.

Therefore *i-Flow* templates can re-encode some of information previously defined using CIMOSA templates into a form which leads to process enactment. *i-Flow* uses the Java Script language to define rules that can: define local variables, import/export data variables, do simple arithmetic functions, delay process initiation or conditionally start a process. Various ‘Timers’ and ‘Emailing Facilities’ may be used to exert time control over processes.

Process designers can use a number of node-types to represent processes. Those types can be grouped into two categories: ‘Activity Nodes’ and ‘Behaviour Nodes’. These nodes may be used in various ways to model aspects of enterprise activities previously coded within CIMOSA templates. Particularly they allow dynamic aspects of processes to be detailed in such a way that process model execution can be linked to real groupings of activities carried out by human and IT systems.

As an example consider the ‘concept design process’, which was one of the I4/I5 business processes previously modelled by using both CIMOSA templates and the *ithink* dynamic systems simulation tool. Suppose now that this CIMOSA business process needs to be remodelled using an *i-Flow* template, so that aspects of instances of the actual operation of the concept design process (and its elemental enterprise activities and the functioning of its contributor human and IT systems) can be co-ordinated more effectively than that previously achieved at the site of a vendor of engine production machines. Figure 14 illustrates how the constituent activities of this process are modelled by *i-Flow* activity nodes and behavioural nodes.

If there are different types of enterprise activity, all have to be modelled by the same *i-Flow* ‘Activity Node’ modelling construct. However the state of these nodes can be colour coded by the *i-Flow* tool. When a node is being designed it is coloured ‘Teal’ but it changes colour for different states like accepted, declined, suspended, etc. ‘Roles’ to which enterprise activities are assigned can be shown in an ‘apparent upper field’. *i-Flow* ‘Roles’ consist of a list of resources that come under a category and where each resource item listed has the capability to do the enterprise activity. By such means enterprise activities may be assigned to a specific person, department or organisation.

Figure 15 illustrates how *i-Flow* was used to model activity nodes and behaviour nodes of the ‘concept design’ business process in a templated fashion. When all templated activities have been defined, the Templates can be stored as a static model. To work with the template, an instant of that template needs to be generated. The *i-Flow* tool considers a process to be *dynamic enactments of template instances that provide a real time link between a ‘designed process’ and a ‘real process’*. When a process instance is generated, the system clock starts ticking for this process and the first activity becomes active and is assigned to the designated assignee. Four types of

'User Interface' are provided here for stereotypical roles of 'Development Manager', 'New Process?', 'Task Manager' and 'Server Administrator'.

For our example, when the 'concept design' template is saved, its name and a unique identifier appears in the 'browser pane'. When an instance of this template is created a process becomes active. This is indicated via colouring, as illustrated by Figure 16. The status of a process (and its activities) is monitored via the 'Development Manager' user interface: designated colour schemes (green, blue and yellow) inform process owners about specific activity states. i-Flow allows multiple processes and activities to run concurrently. Whenever a new process is instantiated from a template it appears as an active process in the organiser pane.

5. Observations and Conclusions

Foregoing discussion serves to illustrate the high levels of complexity involved when engineering significant product and process change. This is particularly true when multiple companies collaborate in order to influence and/or dominate product markets worldwide. Improved understandings about the nature and operation of product realising processes, that typically will need to cross conventional organisational boundaries, can illuminate the likely propagated impact of different types of change (e.g. product, process, resource, change, etc) on the interests of concerned stakeholders (manufacturers, vendors, engineers, managers, etc).

Experience gained when seeking to better understand I4/I5 product, process and machine engineering work of a global consortium has demonstrated the importance of being able to reason about multiple threads of activity (i.e. multiple processes) and about dependency links that couple these threads. By being able to reason about these dependent threads from various viewpoints of concern to stakeholders, it becomes possible to predict (a) benefits and risks associated with new ways of achieving the same ends and (b) how the adoption of these new ways will impact on the provision (lead-time, cost and quality) of engineering functions.

This set of observations formed the basis of a rationale for developing a new multi-process modelling (MPM) method which seeks to systemise the collective use of best in class available enterprise modelling concepts and tools. Key features of the developed method have been described, as was the rationale for choosing a five step approach which unifies the use of different kinds of modelling template and modelling construct through different life phases of process engineering projects. The purpose of the first two steps of the MPM method is to 'cut through' problem complexity issues and to develop a well decomposed, well defined set of static process models that can be reused. Currently these two stages of model development are only supported by limited capability modelling tools but new capabilities are being sought so that process model sets can be captured and modified more effectively and quickly and with increased guarantee of modelling coherence.

The third and fourth stages of the MPM method are centred on the use of a multi-process simulation capability. Here causal relationships are modelled in both qualitative and quantitative forms. This leads to computer executable models that can predict likely benefits, cost and risks associated with various types of product and process change. Here the simulation models need to be recoded based upon the reuse of process understandings previously coded using CIMOSA templates and modelling constructs. Although this recoding process has proven complex and time consuming, collectively the CIMOSA templates can provide a context for more focused process

simulation work and much of the base data needed to model alternative multi-process arrangements with sufficient clarity and accuracy. In the case of I4/I5 engineering process simulation work this has informed the design of new processes that (1) reduce lead-times and costs associated with changing engine assembly machine designs, (2) more effectively attribute human teams to groupings of engineering activities, (3) attribute benefits and risks associated with engineering component-based engine assembly machines and production lines, (4) specify design and make activity sets that can be managed and controlled effectively via workflow tools.

The fifth stage of the MPM method is centred on facilitating the use of a commercial workflow tool, particularly in support of co-ordinating multi-partner, multi-process engineering activity carried out by vendors of engine assembly machines. Once again significant complexity was found to arise when using the tool to transform base static data into computer models that can be enacted. The MPM method helped systemise this process, and thereby enabled detailed process modelling and process enactment with a broader and well defined context of enterprise needs.

Ongoing research in MSI seeks to further develop and deploy the MPM method. This will deliver new results for I4/I5 partners and provide further case study findings that will be used to test capabilities and qualities of the method. One such avenue of testing will seek to determine the ‘extent to which’ and ‘ease with which’ dependency types can be adequately represented and reused.

As new case study work is carried out alternative commercially available modelling tools will be selected and their systematic reuse facilitated. Where necessary, prototype modelling tools will be created that help maintain coherence between multiple-process models and/or semi-automate the process of creating, storing and changing modelled templates during their useful lifetime.

6. References

1. Harrison, R, West, A.A., Weston, R.H. and Monfared, R.P. “Distributed Engineering of Manufacturing Machines”, *Journal of Engineering Manufacture*, Part B2, Vol. 215, pp 217-231, March 2001.
2. ESPIRIT-CIMOSA Standards, 1993, CIMOSA: Open System Architecture for CIM, Springer-Verlag.
3. i-Flow User’s Guide, 2000, Fujitsu Software Corporation, 3055 Orchard Drive, San Jose, CA 95134-2022, USA, URL: <http://www.i-flow.com/>
4. High Performance Systems, Inc.,(2002), “ithink: Software Version 7”, 45 Lyme Road, Suite 300, Hanover, NH 03755. URL: <http://www.hps-inc.com>

List of Figures

Figure 1: I4/I5 Product Decomposition and Rationalisation Achieved by the Consortium

Figure 2: 'AS IS' Process De-coupling-prior to I4/I5 product decomposition

Figure 3: 'TO BE' Process De-coupling-consequent on I4/I5 product decomposition: towards LEAGILE manufacture

Figure 4: Overall context diagram for New Engine Project

Figure 5: Context diagram for Production/Assembly Machines

Figure 6: Interaction diagram for Production/Assembly Machine Interactions

Figure 7: Structure diagram for Cross Huller - Product Design Engineering Domain Process

Figure 8: Activity diagram for Company X - Product Design Engineering (Admin/Doc/Commission)

Figure 9: Sector Frames and Bundled Flow and Bundled Connectors, representing business processes at the Interface Layer

Figure 10: Model construction layer in *ithink* software tool

Figure 11: A snapshot of business processes interacting with each other

Figure 12: Simulation result of Check Anomalies Activity

Figure 13: A snapshot of *i-Flow* software tool showing general environment and a template being designed

Figure 14: Defining template properties

Figure 15: Activity node properties as provided by *i-Flow*

Figure 16: An active concept design process as shown in development manager interface

Cam, Crank, Con Rod, Head, Block

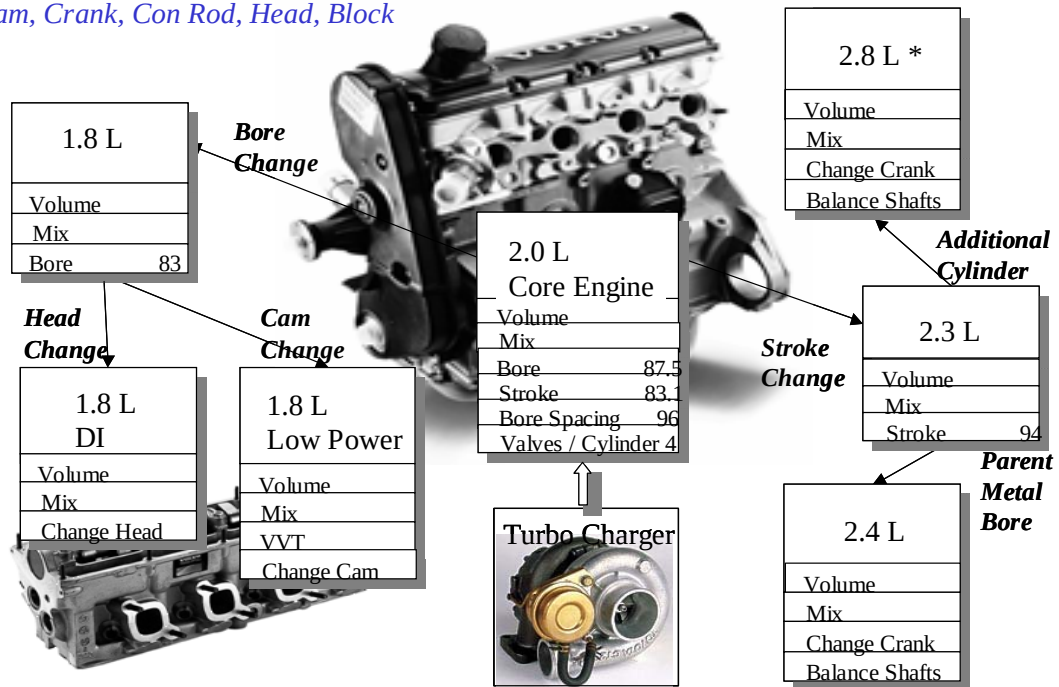


Figure 1 I4/I5 Product Decomposition and Rationalisation Achieved by the Consortium

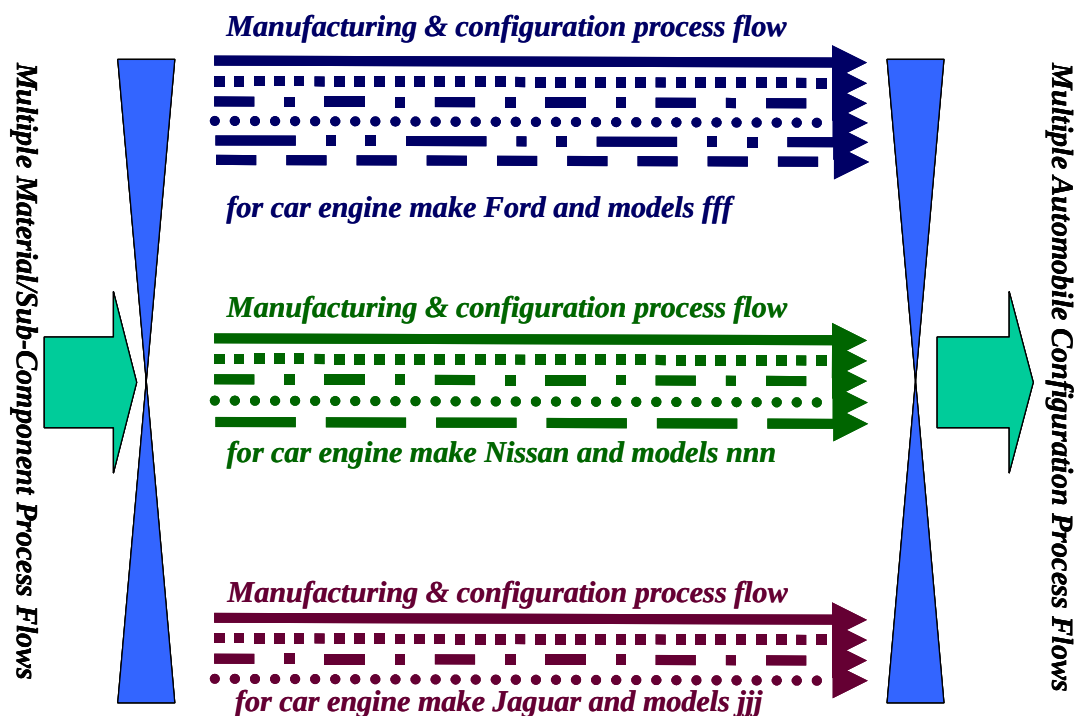


Figure 2 'AS IS' Process De-coupling-prior to I4/I5 product decomposition

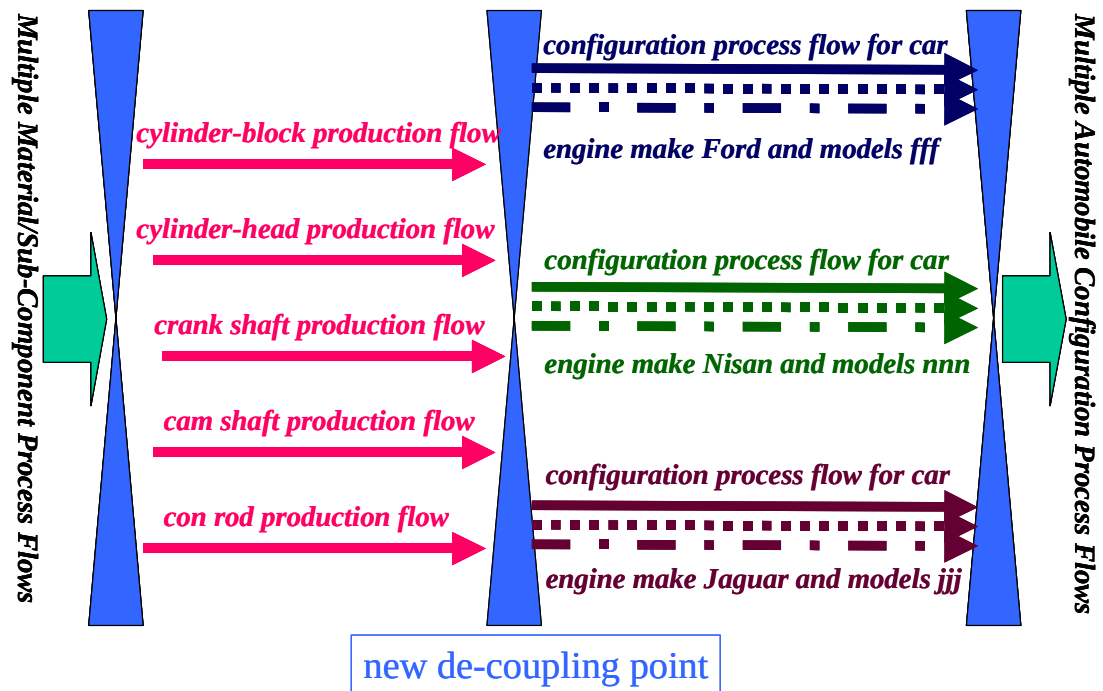


Figure 3 'TO BE' Process De-coupling-consequent on I4/I5 product decomposition: towards LEAGILE manufacture

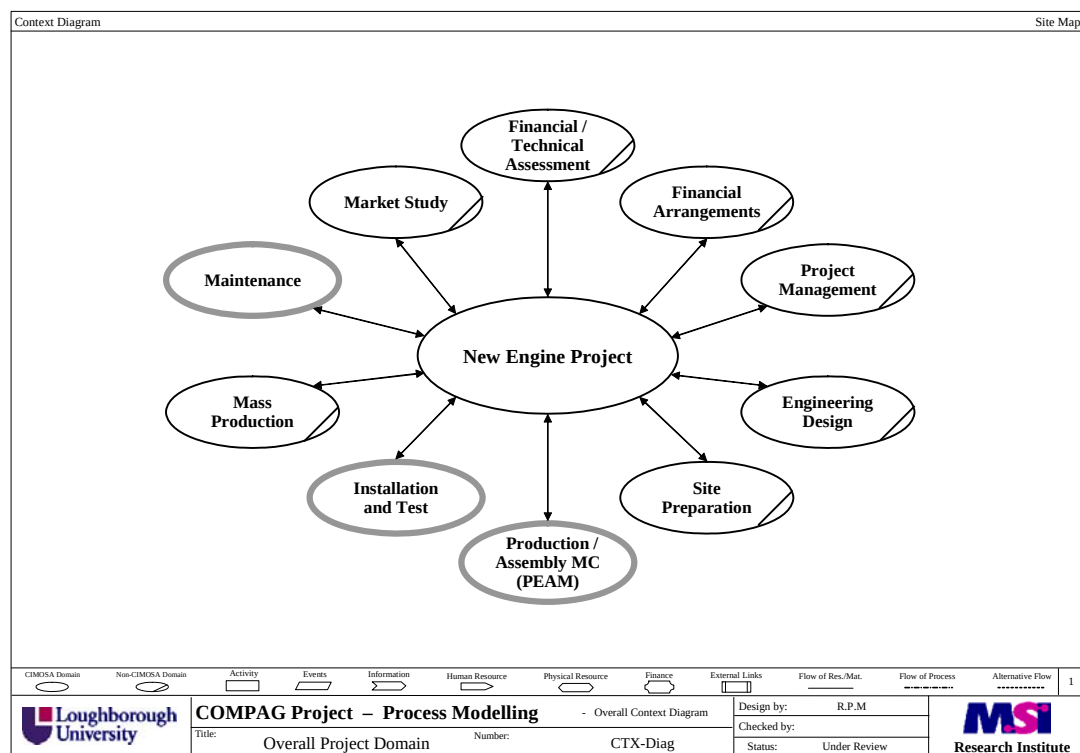


Figure 4 Overall context diagram for New Engine Project

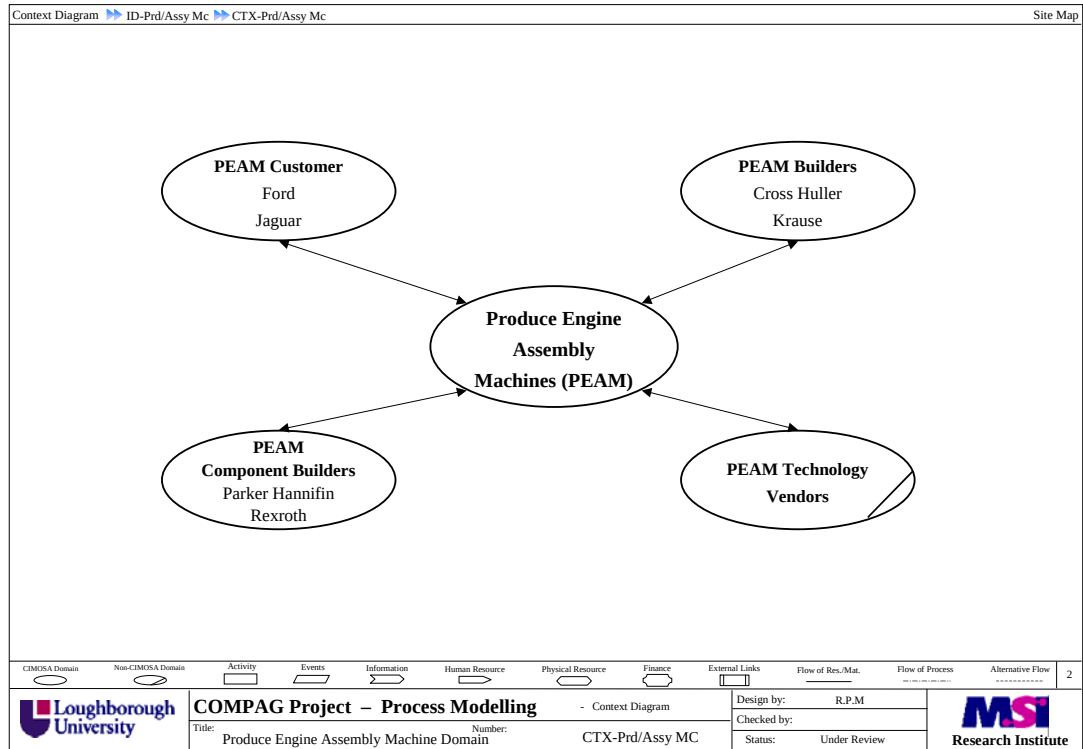


Figure 5 Context diagram for Production/Assembly Machines

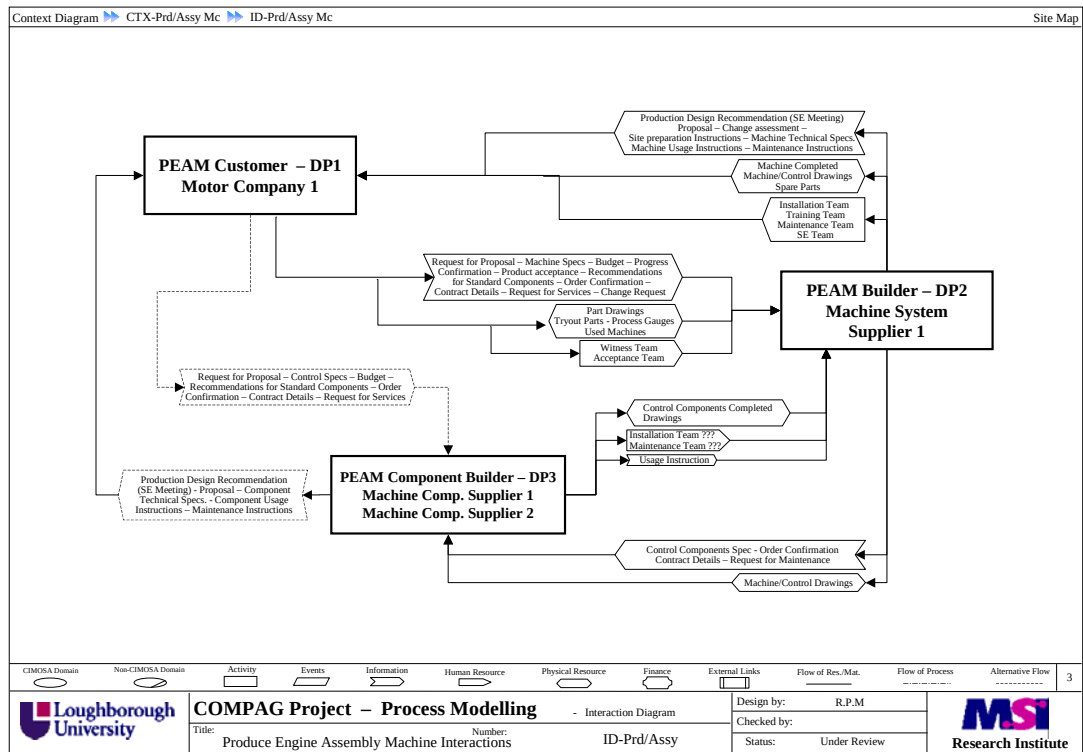


Figure 6 Interaction diagram for Production/Assembly Machine Interactions

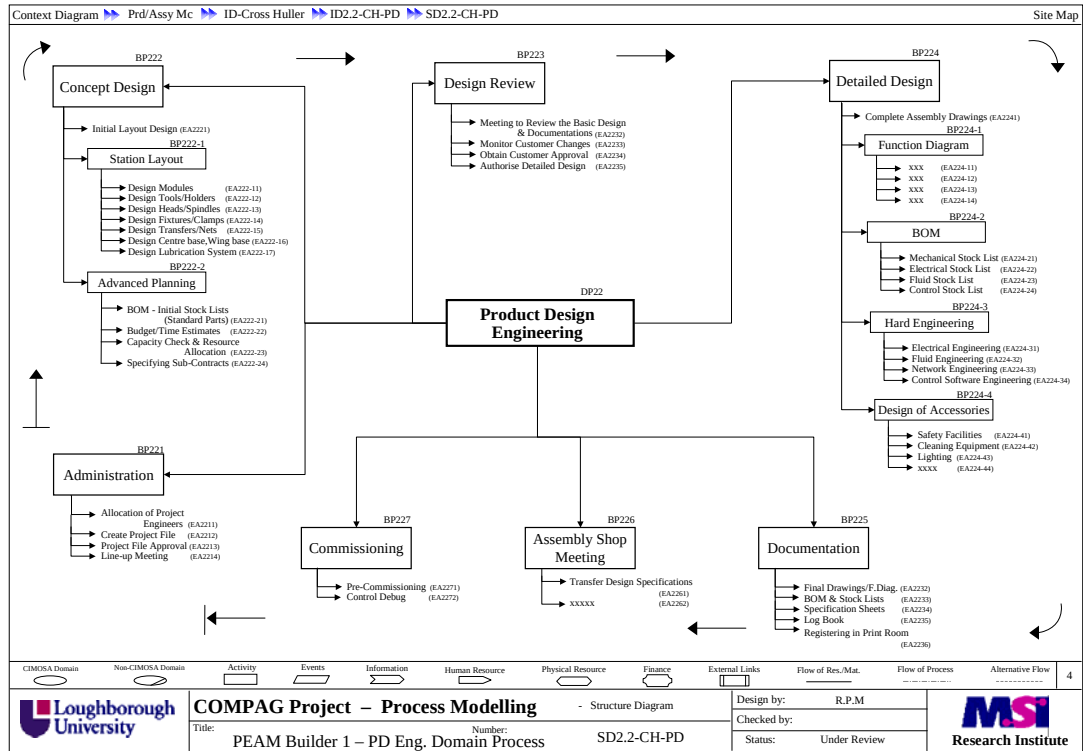


Figure 7 Structure diagram for Cross Huller - Product Design Engineering Domain Process

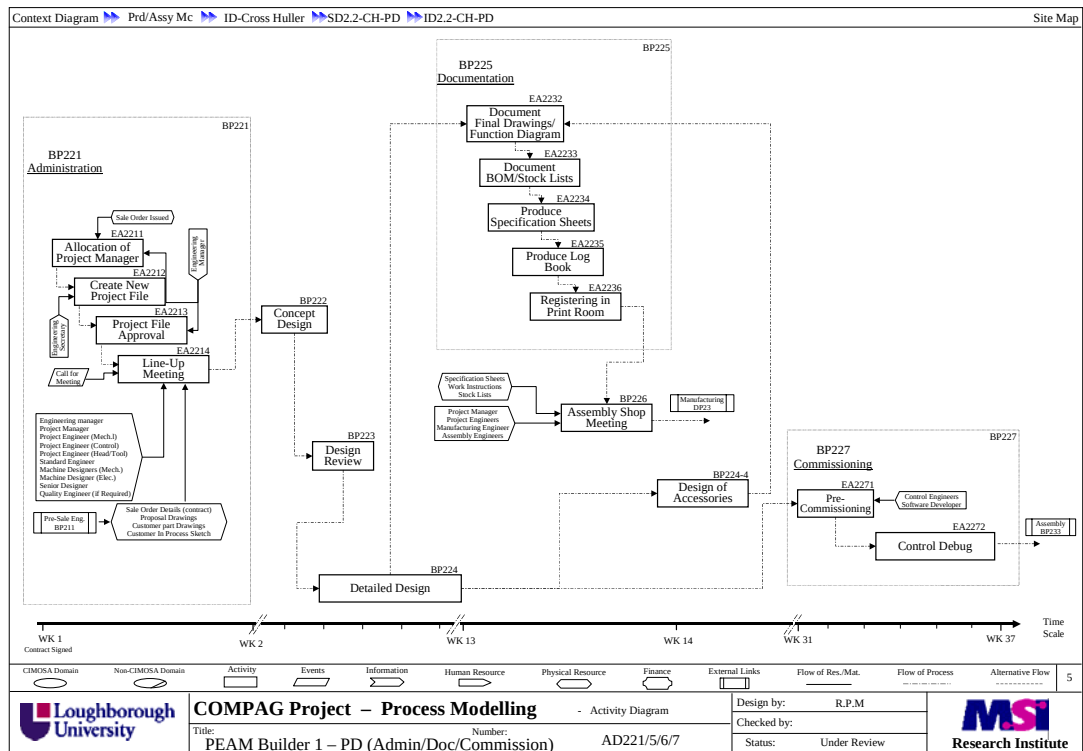


Figure 8 Activity diagram for Company X - Product Design Engineering (Admin/Doc/Commission)

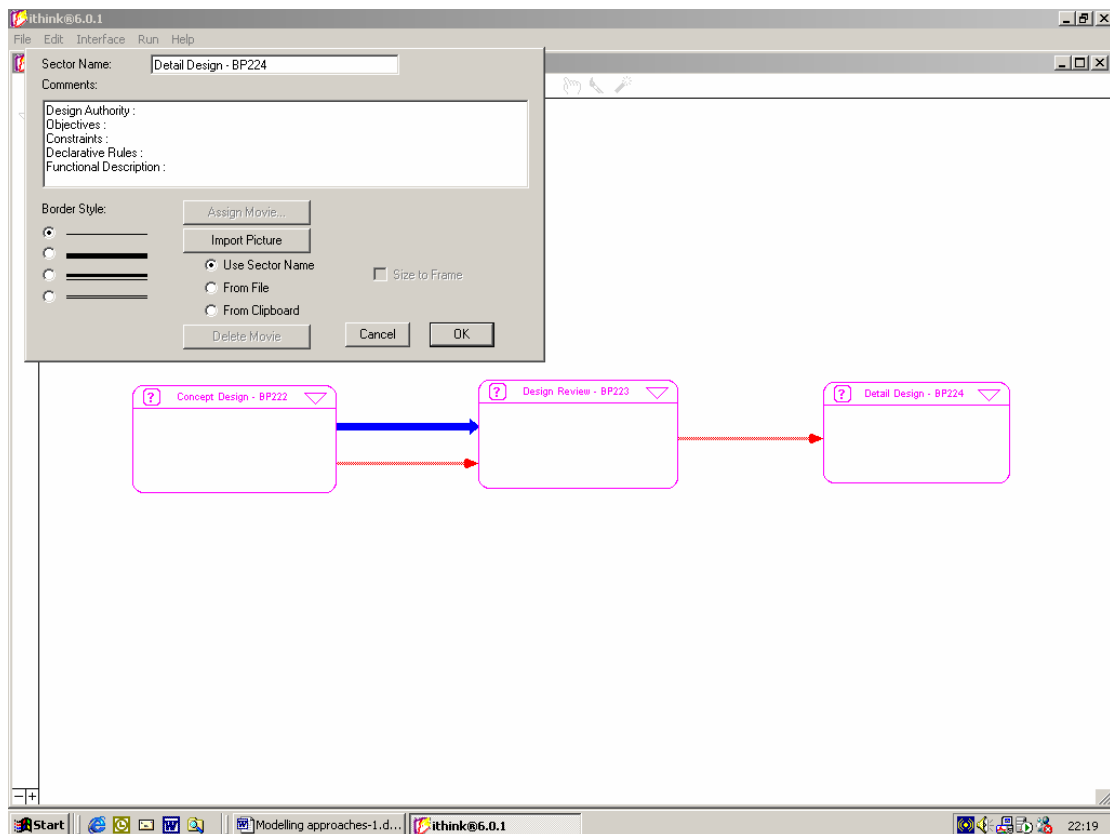


Figure 9 Sector Frames and Bundled Flow and Bundled Connectors, representing business processes at the Interface Layer

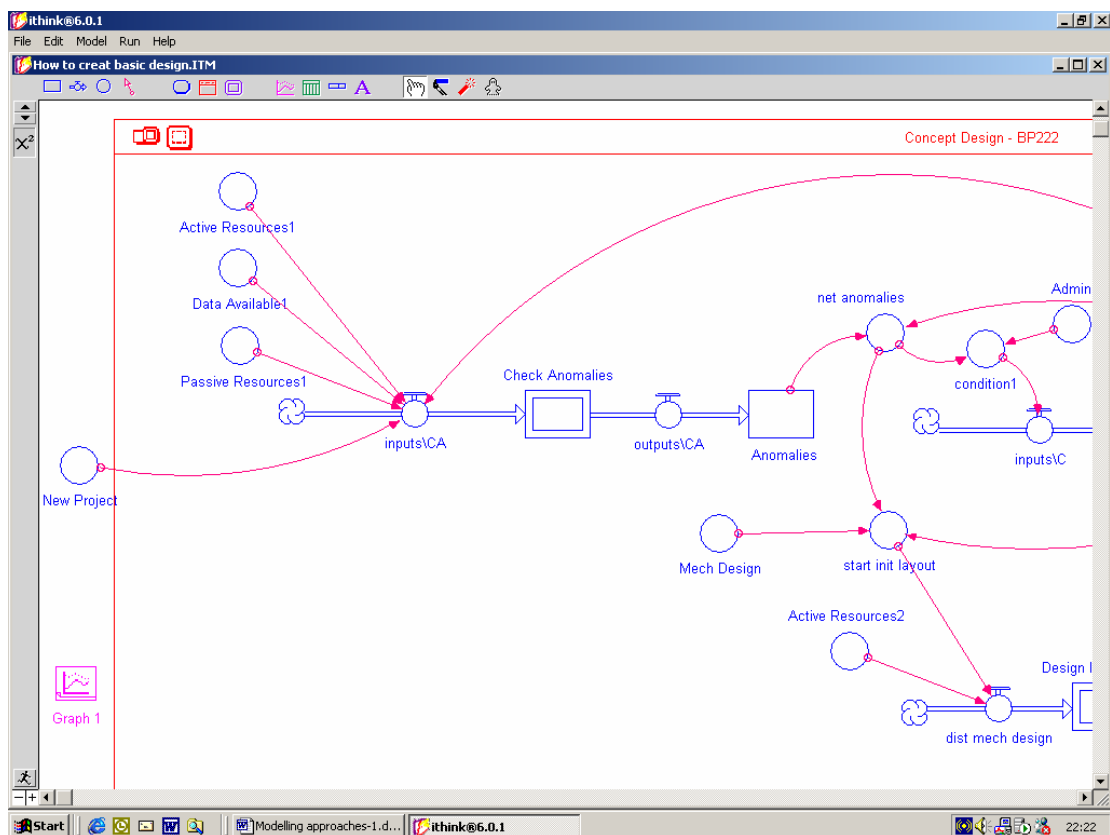


Figure 10 Model construction layer in ithink software tool

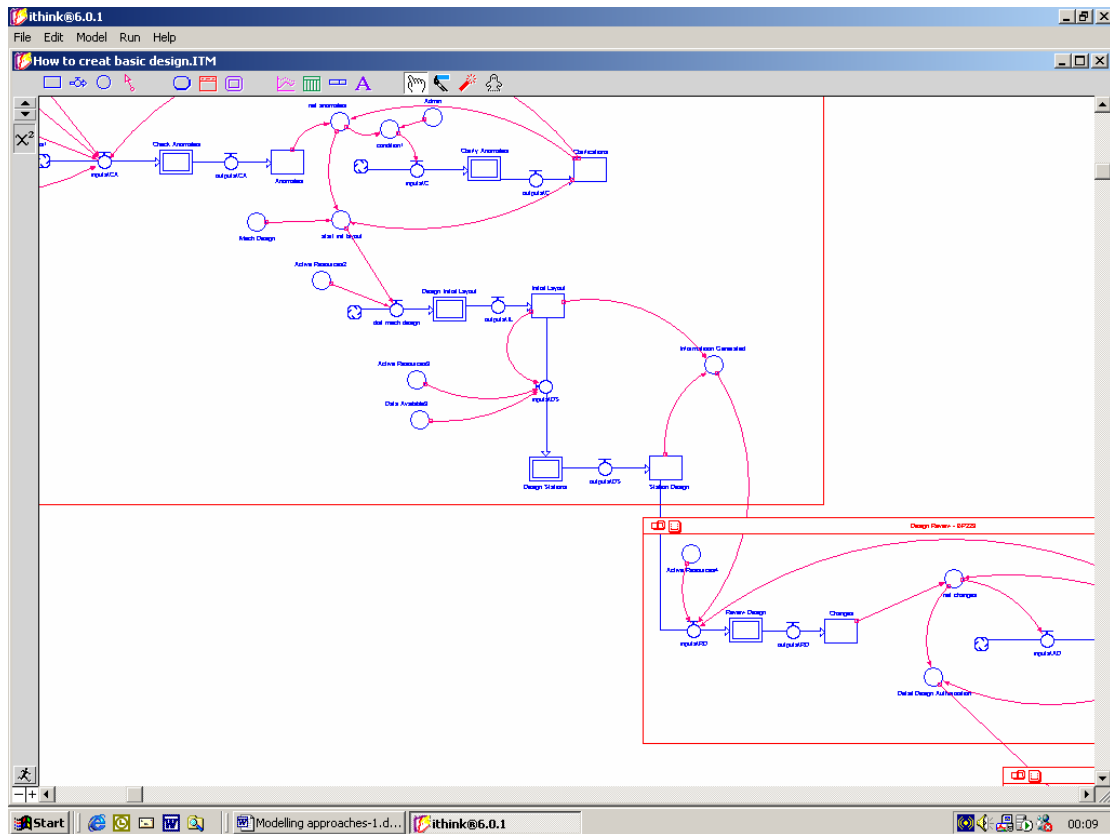


Figure 11 A snapshot of business processes interacting with each other
Note: For a readable version of this model readers are advised to contact the first author.



Figure 12 Simulation result of Check Anomalies Activity

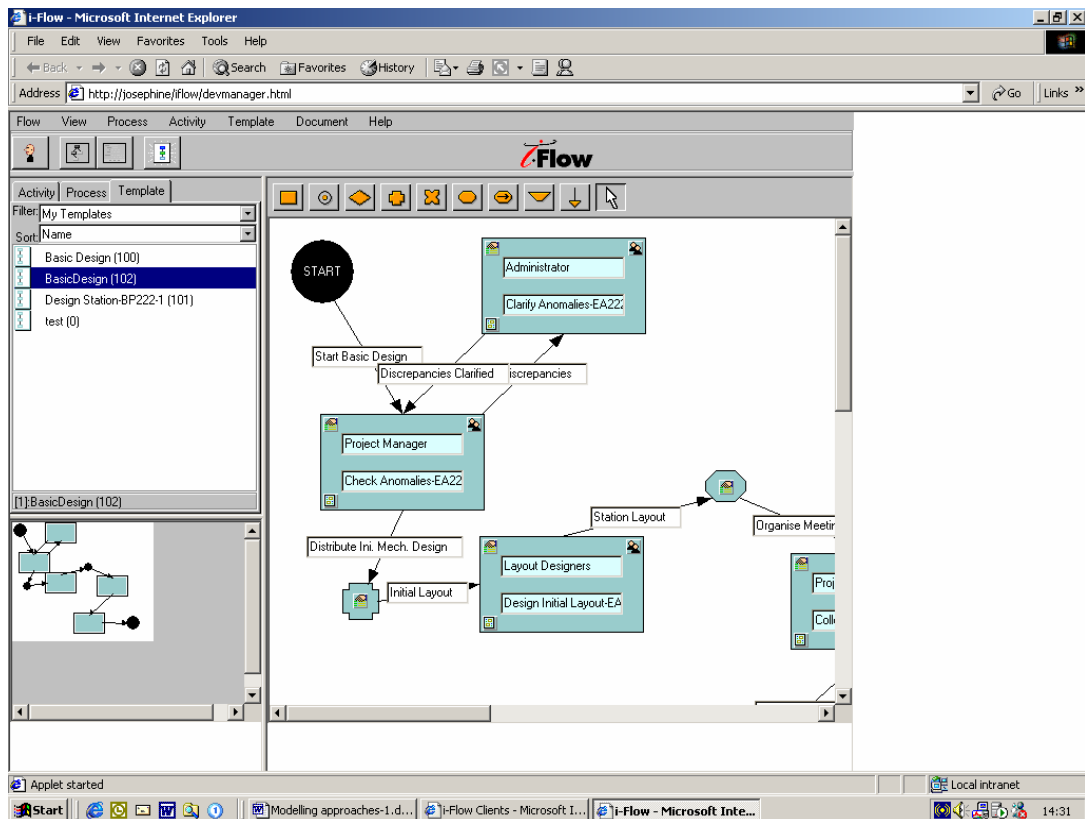


Figure 13 A snapshot of *i-Flow* software tool showing general environment and a template being designed

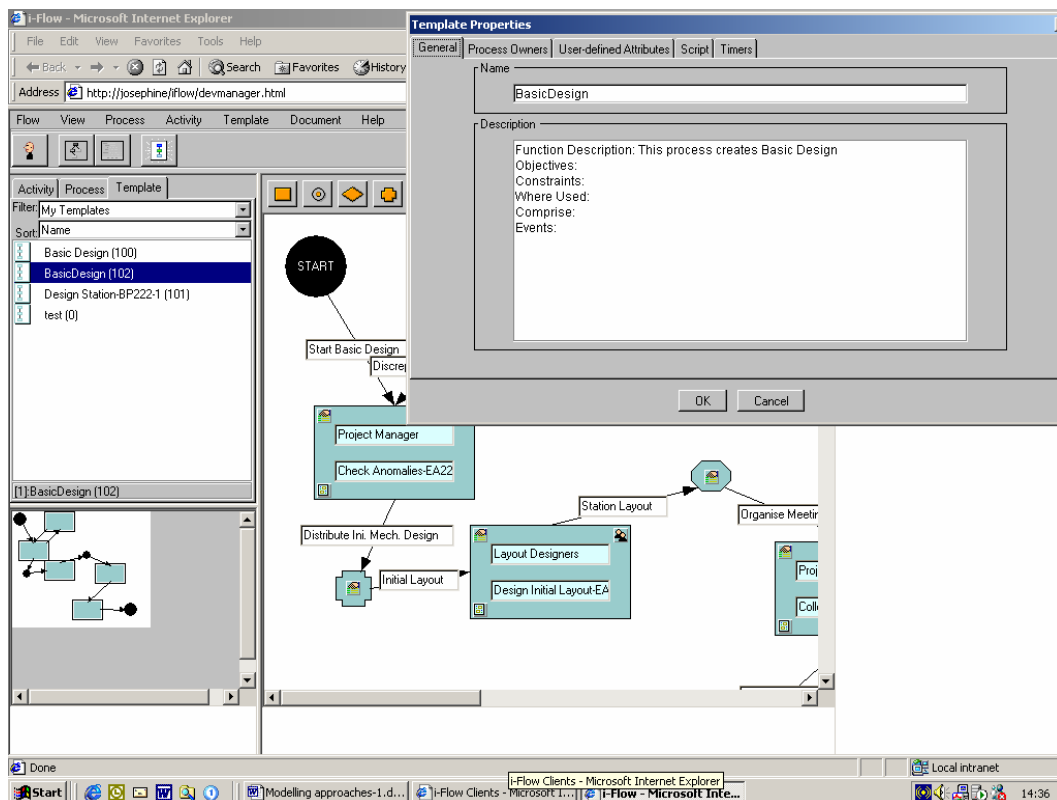


Figure 14 Defining template properties

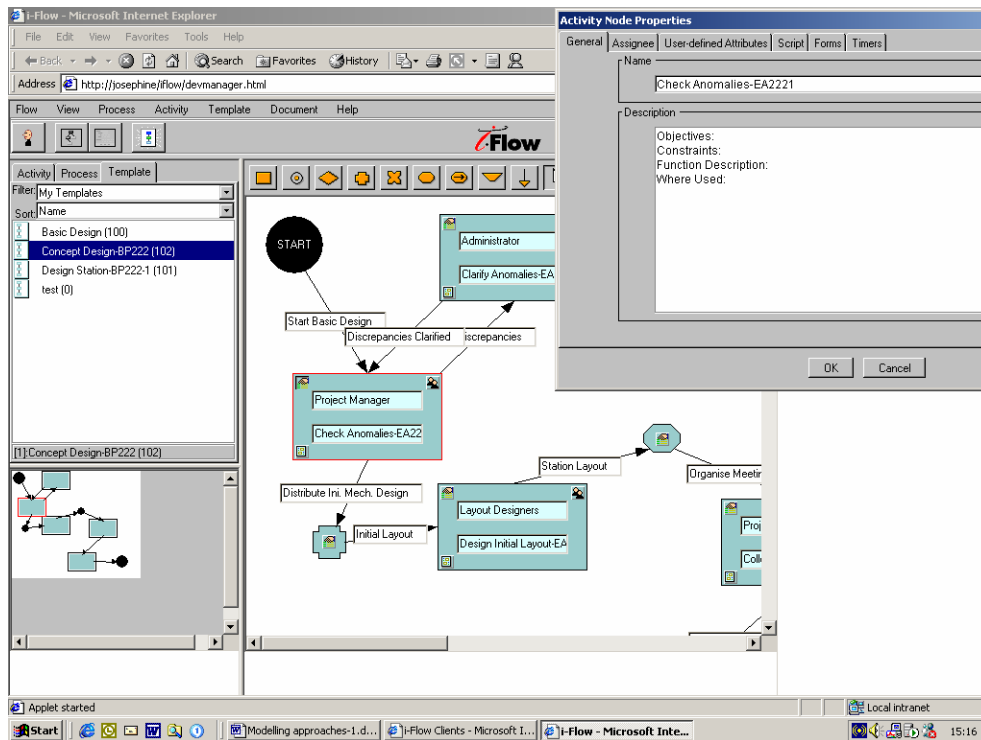


Figure 15 Activity node properties as provided by i-Flow

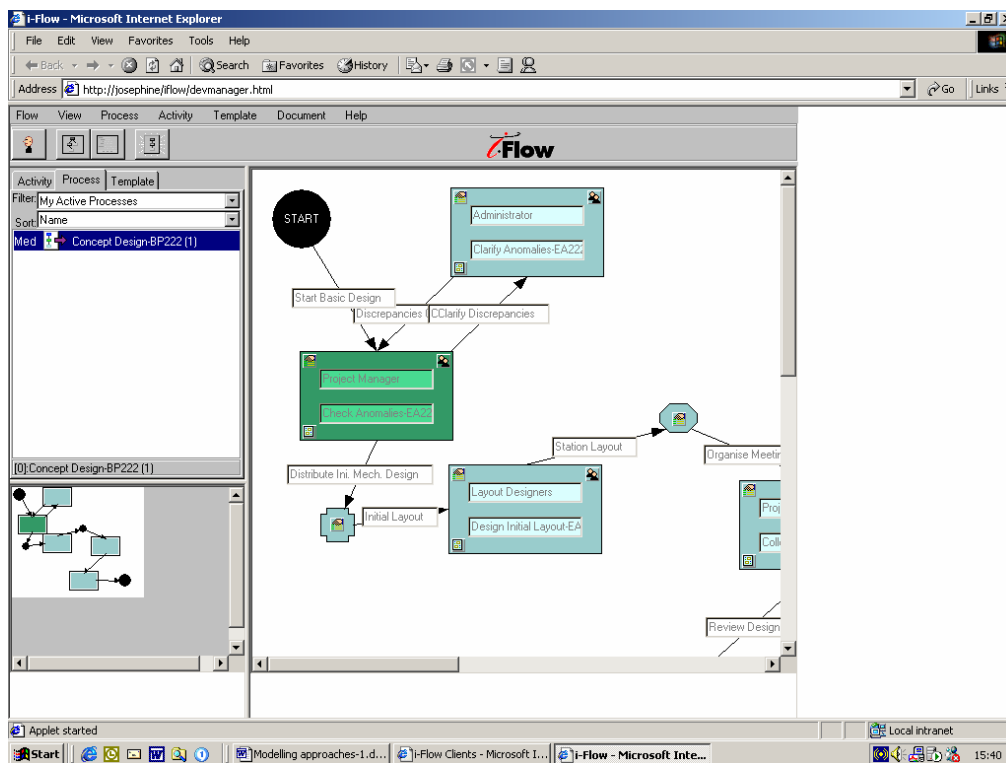


Figure 16 An active concept design process as shown in development manager interface