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Recipe-based Integrated Semantic Product, Process, Resource (PPR) Digital Modelling Methodology

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Abstract

Virtual engineering methods based on digital modelling and simulations have potential to improve analysis and performance of manufacturing systems. Current generation digital modelling techniques in view of systems design and life cycle modelling attempts to integrate aspects of product, process and resource requirements. Despite these advances, to facilitate rapid design and provide support for the selection of processes and resources, there is the need to semantically model and integrate product-process requirements with resource capabilities. This paper therefore presents a 'recipe-based' approach to modelling based on ontologies with capability to rapidly define and select resource systems meeting product and process requirements.

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1. Introduction

To remain competitive, the next generation of manufacturing systems has to be flexible, scalable and knowledge-based to be able to adjust and operate effectively under changing market and technological conditions [1]. To meet these requirements, there is a need to be able to model and effectively simulate the life cycle of manufacturing systems under different scenarios [1, 2]. Achieving this in a systematic way will require the design and implementation of technologies and techniques of suitable content (semantic) support [3-6]. In addition to this, appropriate contextual description of knowledge (ontology) is reported to be a major contributor for success [7, 8]. Recent advances in digital systems modelling and product life cycle engineering have led to the development of conceptual 'digital factory' platforms [9-11], data integration mechanisms [9-12], new programming logics and knowledge driven reconfigurable systems [13, 14], hardware and adaptive components [14], Plug and Produce Multi Agent Environment [15, 16], semantics architecture and modelling [6, 17], collective systems adaptability based on swarm intelligence and other data mining/ artificial intelligence techniques [2, 18].

A review of the above literature and state of the art techniques shows that:

- Most previous bodies of research were focussed on the development of hardware and control systems which could cope with varying degree of flexibility.
- Major emphasis was laid on programmable logic controllers (PLCs); hardware configurations, data mining and integration algorithms
- Significant achievement included the definition of fundamental ICT requirements for digital modelling of factories
- There is still the need for the specification of new ontological modelling frameworks for knowledge capturing, integration, analysis, reuse and systems interoperability
- There is also the drive towards extension of PLM modelling tools to include new concepts for

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manufacturing systems evolvability and computational algorithms for optimising manufacturing systems.

Falling on previous research findings by the authors and their colleagues [6, 17, 19], this paper adopts a 'recipe-based' digital modelling approach for defining product and process requirement and integrating them with the capabilities of resource systems, thereby achieving a unique way of reducing product, process and resource knowledge gap. The authors have applied this methodology to support the selection of candidate processes and resources in an SME based in the UK.

It was noted that the methodology had capability to reduce product design lifecycle and transform current approach to manufacturing systems modelling

2. State of the art review and requirement specification for digital modelling in support of systems integration

The need for advances in rapid digital modelling techniques and systems integration has been expressed in a number of leading research themes. This was the basis for research projects such as the Fast Ramp-up and Adaptive Manufacturing Environment-FRAME [20], Instantly Deployable Evolvable Assembly Systems-IDEAS [19, 21], Plug and Produce Multi Agent Environment-PRIME [22], Evolvable Ultra-Precision Assembly Systems-EUPASS [23], Evolvable Assembly Systems [24], Cloud manufacturing [25], Self-resilient reconfigurable assembly systems [26] and Knowledge driven configurable manufacturing [13]. Other substantial published bodies of research exist in the broad domain of digital manufacturing and systems integration as automatic and adaptive control [14], holonic manufacturing systems [27], computational algorithms for optimising systems [15, 16, 18], collective systems adaptability based on swarm intelligence [15], co-evolution of products, processes and production systems [2].

Parallel to these developments are other enterprise modelling architecture and framework developed through CIMOSA (Open System Architecture for CIM), Purdue Enterprise Reference Architecture (PERA), Generalised Enterprise Reference Architecture and Methodology (GERAM) and lately, the Virtual Factory Framework (VFF).

Despite the advances in research in the domain of digital modelling of manufacturing systems, practical challenges exist when implementing integrated 'intra or inter information systems', mainly because most of the time, systems are designed without detailed consideration of levels of integration required in enterprises (product-process-equipment interconnections), file transfers and formats needed, levels of manipulations required, specifications and representations utilised or required in different systems and organizations.

To address these, Lin and Harding, 2007 [28], noted that there is the need to implement a semantically consistent standardized terminology (ontology) across Organizational boundaries. Some useful applications of ontologies in simplifying and maintaining consistencies in communications as applied in Knowledge Engineering can be found in [29], Manufacturing and Supply Chain Systems Engineering [7, 28], manufacturing systems and distributed planning [6, 28, 30].

Despite these advances, the communication requirements for rapid designing and prototyping of digitised manufacturing systems still remain a challenge. Earlier research works by the authors and their colleagues [6, 9] have shown that models for efficient design, control and management of digitised virtual factories require [12]:

- Explicit characterization of data with their relations at a semantic level.
- Support for inter–document references (cross-references) to ensure proper referential consistency.
- Efficient modelling and management of distributed data
- Efficient integration of different knowledge domains (Factory, Building, System, Resource, Process, Product, Strategy, Performance and Management).

Also observed from the authors' previous research work was that:

- There is still the need to define and appropriately model product, process and resource requirements and integrate these requirements with suitable solution sets. This is considered necessary because after studying the causes of failure of some businesses, one of the major factors for business failures was 'differences in semantics and business rules between different applications that were never intended to collaborate'[6]. It has also been reported that the lack of appropriate and common semantic language for capturing high level product, process and equipment requirements relevant for the design and testing of new manufacturing systems have led to the failure of many engineering projects [30].
- Existing digital modelling approaches largely depend on the skill of different designers who do not necessarily work collaboratively or coherently, leading to very expensive product and systems design life cycles. Current generation tools although with integration capabilities, do not provide enough intelligence to 'selectively design' products or systems. For example, process and resource systems designs are not fully integrated with product designs and vice versa, hence product designs are not fully cognizant of existing process and resource capacities, capabilities and competencies. As a result, decisions are not concurrent and lead to potential errors in system designs.
- Current digital modelling tools especially, the resource systems toolkits provide modelling constructs that enable modelling manufacturing systems in context but are less advanced with respect to:
    - Explicit specification of resource sets: (human, machines and IT systems) and integrating the capabilities of these resource components into a unified resource system

meeting product, process design requirements.
    - Adjusting virtual resource systems dynamically to changing process requirements
    - Computer executing semantically selected resource systems and their behaviours in real production environments.
- More critically, the causal impacts of products, processes and resource (PPR) changes are not mapped on each other hence the implication of changes on PPR cannot be fully depicted in current digital modelling tools.
- Currently (as evidenced widely in literature and confirmed during the authors previous publications), there exist many 'partial domain product, process and resource models' but seldom are these usefully interconnected semantically. Where they are, these are not readily reusable and testable; indeed currently there is a lack of overarching principles or concepts, methods and techniques that interconnect domain architectures in ways that facilitate design and life cycle engineering of manufacturing systems that will enable specific manufacturing organisations (which may have different purposes and be of many types and sizes, and operate in distinctive environments) to compete with world class performance.

Addressing the gaps mentioned above will require:

- A unified enriched modelling methodology with reusable overarching scientific principles supported by current ontological thinking and virtual engineering technologies that can design and enact a coherent platform for unifying and custom fitting 'systems requirements' (product-process-resource) with 'systems solutions'. By so doing, systems solutions can be conceived quickly and its needed qualities tested in relation to current and future operational scenarios.
- Explicit characterisation of product, process and resource data with their semantic relationships
- Support for inter–document references (cross-references) to ensure proper referential consistency.
- Efficient modelling and management of distributed data to support the realisation of inter-document references.
- Efficient integration of heterogeneous data from different knowledge domains (Factory, Building, System, Resource, Process, Product, Strategy, Performance and Management).

To help realise the above requirements, the authors have developed a recipe-based digital modelling methodology which relies on:

1. Capturing product-process-resource (PPR) requirements;
2. developing a 'library of recipes' (solutions);
3. Semantically integrating PPR requirements with pre-populated solutions;
4. Conducting further simulation and analyses for optimal performance.

3. The recipe-based semantic modelling methodology

The recipe-based modelling methodology rests on the fact that relevant knowledge exist in specific domains which can be reused to promote learning and reduce design cycle times. For example, a product model has embedded process knowledge which can be extracted and used to produce first hand process model. Also process models have implicit resource knowledge which can be used as the basis for creating resource models. An ability to synchronise these bodies of knowledge will influence next generation approach to manufacturing systems modelling science. This will help reduce the amount of effort required for planning and designing new products, processes and resources. This is the thinking behind the recipe-based semantic modelling methodology for manufacturing systems design. Basically, the concept relies on the derivation of a library of 'pre-defined product-process configuration recipes' which can semantically be matched to a set of production resource requirements, so that based on semantic rules, logics and appropriate matching of 'concepts', possible solutions can be pulled from existing databases of recipes and their associated modelling libraries.

A manufacturing system recipe refers to predefined 'patterns of resource solutions' matching product and process requirements of a given production system. The basic idea behind enacting such an approach is to provide current and future designers with abstract descriptions of reusable components (or building blocks) of manufacturing systems and also allow them to select among predicted suitable sets of resource systems (people, machines and computers). This is considered important because when manufacturing systems' requirements change, the resource systems can dynamically be reconfigured to meet the new requirements. To a larger extent, recipes of manufacturing systems solutions comprise various systems of layouts, people, production and assembly machines, utility systems and computers which are often configured based on different organisational structures, constraints, demand, and data so that they function appropriately to meet product-process requirement. This is achieved through a common high level semantic language which acts as a communication backbone between product, process and resource sets of data. They dwell on models and methods required to enable the convergence of meaning across the life cycle of virtual system development.

To achieve this, ontologies based on ObjectLogic in the OntoStudio modelling environment are created. Reasoning mechanisms are embedded on the ontologies through the application of the OntoBroker reasoner. The specific steps for realising the recipe-based approach are:

- Describe concepts related to products, processes and resources (Product, process, resource ontologies)
- Integrate product, process and resource ontologies by defining their relationships, rules and characteristics. At this stage, the capabilities and competencies of resource systems are modelled independently and

matched with the product-process requirements. This allows the selection of candidate processes and resources during product modelling. This allows the transfer of selected processes and resources into a 3D digital modelling environment for in-depth simulation and analysis.

- Query the ontologies to derive results from the reasoner
- Verify the results with domain experts.

3.1 *Product ontology*

The Product Ontology defines the conceptual framework underpinning the recipe-based approach to product specification. The key concepts in this ontology are the definition of the physical building blocks which make up a product and how they are connected to each other. The Product Component concept represents all the physical entities within the product domain which constitute a product or part of it. The role of a Product Component is context specific and can only be attributed to a Product Component in a specific scenario. A Product Component can either be a 'Product, Subassembly, Product family, Component, or Attachment' within the product domain (see Figure 1).

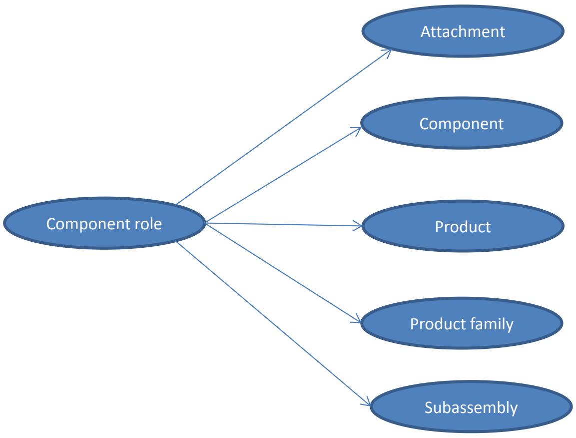

Fig. 1. Product Component description

The same Product Component could act, for instance, as a 'Product' for its manufacturer or a 'Component' for someone who integrates it into an Assembly.

The following definitions are applied:

- A product is a material, piece part, or assembly that has been manufactured to be sold to a third party.
- A subassembly is an assembly with the intention to be used as a physical interlinked object inside another assembly. Subassemblies are usually used to structure the order in which a product is being assembled.
- Components are the objects that make up an assembly from the view point of an assembling system. They can either be individual monolithic machined parts or complex subassemblies of their own that come from a source outside the assembling system in question.
- An attachment is a piece part or material that is used to join two components together. Examples of *Attachments* include: rivets, screws, solder paste, adhesives, etc.

3.2 *Process ontology*

The Process Ontology defines the conceptual framework underpinning process definition and modelling. The 'process' bridges the gap between the product(s) that need to be realised and the manufacturing system that creates them. The fundamental notion is that it is possible to define the required process characteristics from the product specifications and also define available process capabilities offered by existing resources. The product based requirements need to be turned into one or more possible processes which in turn provide the basis for the design of the required production system.

All concepts in the process domain are considered to be descendants of the *ActivityType* and *ProcessTypes* concepts. *Processes* are only the complex *Activities* which are composed of several lower level *Activities*. The following definitions apply:

- An Assembling Process is the collection of lower level assembling activities with the purpose of facilitating the assembling of an assembly or subassembly. Secondly, the process hierarchy is regulated through four high level types of Activities: MultiTasks, Tasks, Operations, and Actions.
- A Multi Task is a high level Process which defines the overall order in which different Assemblies, Subassemblies, and Components are being put together.
- A Task is a Process which facilitates a clearly definable portion of work towards the completion of a product. A Task is composed of a set of Operations. Tasks are normally carried out by either workstations or transport system.
- An Operation is a Process which facilitates a state change of entities that are part of a product within the scope of a specific Task. An Operation is composed of a set of Actions. Operations are normally carried out by Equipment Units.
- An Action is a fundamental Activity which can be performed by an Actor without directly causing a state change to a product related object. Actions are not Processes. They define the smallest building blocks of the process hierarchy and are normally carried out by Equipment Devices.

3.3 *Resource ontology*

The resource ontology represents 3 sub concepts:

1. Systems configuration layout
2. Equipment type and
3. Human resource

The system configuration layout concept describes various possible layout types. The equipment and human resource concepts consist of the potential equipment and human resource types, capable of fulfilling the requirements. The capabilities of the concepts related to the production system ontology are described in their 'attributes'. The connections between different concepts are expressed in 'relations'.

3.4 PPR capability integration

In the semantic model, the capabilities of processes and equipment are detailed in their 'attributes'. Attributes basically describe the characteristics of specified concepts. Through the 'relations' aspect of the ontology, processes and equipment with specified attributes can be 'linked' to specific product requirements. Thus in the creation of ontologies, the resource ontologies are connected with other product and process ontologies. The integrated ontology is achieved by linking the product, process and production system ontologies through their relationships, rules and logics. This is represented by Fig. 2.

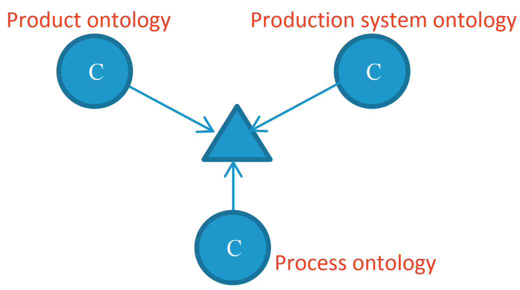

Fig. 2. Integrated ontological concepts

4. Case application of recipe-based methodology

The case study relates to a SME based in the UK designing and producing wrenches meeting customer specifications. Brief instances of product, process and resource ontologies for the case company is shown in fig. 3. The product has ontological descriptions such as:

ProductHasSubassemblies,ProductHasCode, ProductBelongsToFamily,ProductHasParts, ProductHasName, ProductRealisedByProcesses

Similarly, the Process ontology has: ProcessHasName, ProcessHasActivities, ProcessRequiresResourceCapabilities, ProcessResourcedBy, etc.

4.1 Example results from PPR integrated ontology

Following the modelling logic and integrating with case company internal databases, the ontologies aided the generation of relevant product, process and resource knowledge. As shown in figure 4 (highlighted red), the results which were generated by querying the ontologies are shown for product type Wrench 7" and its parts; wrench 7" and its associated processes, and resources for bending operations in the company.

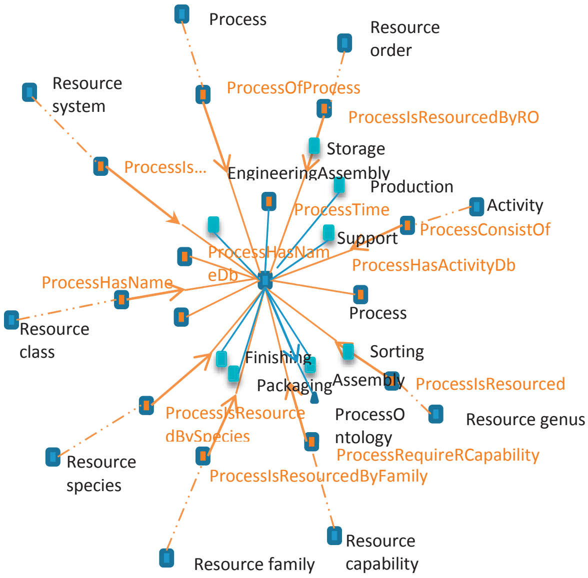

Fig 3. Process ontology for case company

5. Conclusion

This paper focussed on demonstrating how product, process and resource ontologies can be integrated so that based on their semantically described capabilities, queries on various aspects of product, process and resource design can generate relevant knowledge set for onward simulation. This shows therefore that structural models and their encapsulated data can be re-used via the use of suitable 'in context' semantic models of types outlined in sections 3 and 4.

It follows also that resource systems can be semantically modelled so that their capabilities can be matched with product and process requirements. The full semantic description of product-process requirements can be found in [6].

The methodology has strength in integrating several data sources and based on appropriate mapping logic, to assign resources matching product-process requirements. As a result, it allows the synergistic use of various kinds of mental, structural and dynamic systems model which facilitate complexity handling and lead to better and faster dynamic analysis of manufacturing systems models. This helps reduce the product design lifecycle.

Integrating product with process capabilities and resources is uniquely important for engineering and manufacturing applications since dedicated manufacturing systems and customer facilities can be modelled such that alternative design decisions can be experimented before committing physical resources.

Result for Query ‘2. Product/part realised by processes’ [DatabaseExtension,_copernicoProduct] -11 result(s).

?Produts1_products_id	?Produts1_products_ProductName	?Processes1_Processes_ProcessName	?Part1_parts_id	?Proc
46	“Wrench: 7\¯¯	¯Coining¯	47	<http
46	“Wrench: 7\¯¯	¯Dipping oil¯	47	<http
46	“Wrench: 7\¯¯	¯Drilling¯	47	<http
46	“Wrench: 7\¯¯	¯Flashing¯	47	<http
46	“Wrench: 7\¯¯	¯Hardening¯	47	<http
46	“Wrench: 7\¯¯	¯Milling¯	47	<http
46	“Wrench: 7\¯¯	¯Normalising¯	47	<http
46	“Wrench: 7\¯¯	¯Rough Glazing¯	47	<http
46	“Wrench: 7\¯¯	¯Shotblasting¯	47	<http
46	“Wrench: 7\¯¯	¯ Shotblasting ¯	47	<http
46	“Wrench: 7\¯¯	¯Stamping_1¯	47	<http

Results for query “1. Product has Parts” [DatabaseExtension_copernicoProduct] – 5 result(s)

?Produts1_products_id	?Produts1_products_ProductName	?Part1_parts_id	?Parts1_parts_PartName
46	“Wrench: 7\¯¯	58	¯Screw: ¼” Whitworth¯
46	“Wrench: 7\¯¯	47	¯Hook: 15mm dia EN9, length: 80-81 inches¯
46	“Wrench: 7\¯¯	50	¯Frame: 6.1/2”x12g strip¯
46	“Wrench: 7\¯¯	53	¯Wedge:15mm dia EN9¯
46	“Wrench: 7\¯¯	56	¯Rivet: 11/16 x 7G¯

Results for query “3. Processes realised by Machines” [DatabaseExtension_copernicoProduct] – 2 result(s)

?bending_machines1_bending_machines_machineName	?bending_machines1_bending_machines_machine_available	?Processes1_Processes_ProcessName	?processes
“Bending Machine 2”	true	“Bending”	
“Bending Machine 3”	true	“Bending”	

Fig 4. Process ontology for case company

6. Further work

Further work includes the linkage of relevant product, process and equipment requirements with solution databases and needed modelling tools to form a complete manufacturing systems recipe library. This will become the backbone to lots of next generation manufacturing systems modelling tools. Also the authors and their colleagues are currently working on the development of graphical user interfaces (GUI), which will now interrogate the semantic model and provide user friendly results at multiple levels

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