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DEFINITIONS, LIMITATIONS AND APPROACHES OF EVOLVABLE ASSEMBLY SYSTEM PLATFORMS

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Europe, as most other OECD areas, is confronted with major potential opportunities in the decades to come. Although often portrayed as threats, the symptoms being denoted in the European economy are, in fact, part of a shift in knowledge and technology infrastructures created by these trends. These current challenges being faced by manufacturing companies nowadays require production systems to become ever more responsive and agile. This is particularly relevant to micro-products, since manual assembly becomes impossible, rendering outsourcing strategies less effective if not deliberately negative. Furthermore, traditional approaches to R&D in this field no longer suffice to cope with the challenges imposed since these imply new business methods, continuous technological evolution,and the increased tendency towards networks of enterprises.
To meet such demands there is a need for new rapidly deployable and affordable (economically sustainable) microassembly systems based on re-configurable, modular concepts that would allow continuous system evolution and seamless reconfiguration. Furthermore, as will be detailed later, one of the required foundations to sustainable assembly system concepts lies within a new way of thinking and working: a methodology that could integrate the various aspects related to the life cycle of the production systems, with particular focus being placed on the re-engineering phase. This article will present some definitions, clarify the basic approach, and outline the serious requirements being posed by such a paradigm: Evolvable Assembly Systems.

1. INTRODUCTION

Modular assembly systems, standardised solutions, and re-configurable approaches have appeared all the more frequently in recent publications. Such terminology indicates that the R&D community has responded to the industrial demands for a more agile *re-engineering phase* (shaded area, fig.1.0). However, since the underlying problems are holistic, and therefore include many different segments of the production equation, the ensuing solutions have only addressed parts of the problem: management, human, design and supply chain issues are not yet well integrated. As given in the preceding figure, the approach given in this article will focus on the re-engineering phase, which is central to the issue of re-configurability or evolvability. Re-engineering is hereby defined as the modification or adaptation of currently available system solutions to fit the new assembly needs. In this respect re-engineering is of capital importance because, in reality, the major part of producing companies have to deal with planned products and existing production facilities. Ideally, they would like to fit any new product, variant, or volume fluctuation into an existing assembly system with as low costs as possible: the re-engineering phase. To date, this has only been a dream. Therefore, if the equipment cannot easily adapt to changing product & market requirements , the overall flexibility is greatly reduced.

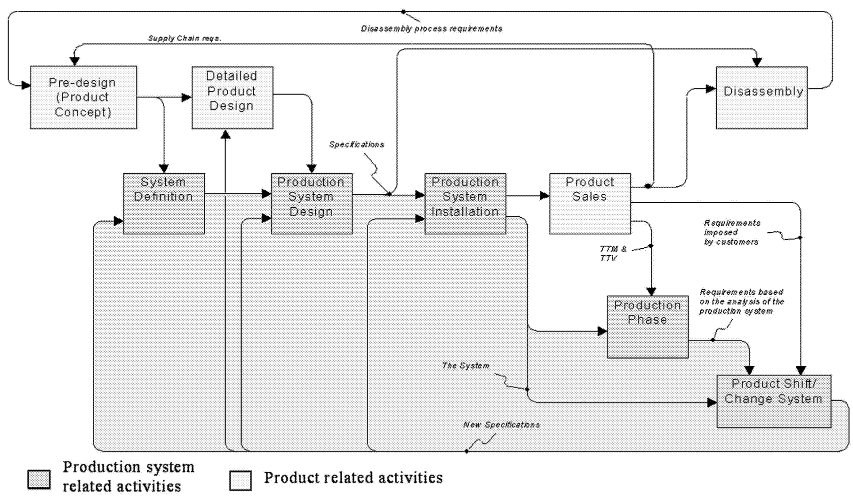

Figure 1 - Simplified View of Product-System Lifecycle

Basically, a radical new way of thinking and working is required: in terms of assembly systems, what is required is not a solution which tries to accomplish all of the envisaged assembly needs within a closed unit (Flexible Assembly systems) but, rather, a solution which, being based on several re-configurable, task-specific elements (system modules), allows for a continuous evolution of the assembly system. In other words, many simple, strictly task-oriented components with standard interfaces are better than few, very flexible but extremely expensive solutions that cannot be integrated within existing systems. The Evolvable Assembly Systems (EAS, [1]) paradigm offers such an approach.

The objective of this article is to clarify the complexity of such an approach, and that it is far more complicated than simply calling a system solution as "modular". Such an endeavour requires a structured approach, and the methods and tools must be collected around a methodology.

2. DEFINITIONS

Modularity has been widely acclaimed in recent publications [2], in fact, it has become a goal in itself, much in the way flexibility was a few years ago. In simple terms, any assembly system which has one module for a given assembly process, cannot be termed as modular: e.g.- a manipulator module, a transport module, and a feeder module, all part of a "modular" system in which no other alternative modules may be interconnected for new or different operations. The misuse of terminology, however, is only counter-productive, since the end-users will only be deceived if the goods are not delivered. In common terms, the modularity denoted to date only refers to a local, mechanical interoperability of a very restricted set of units. The so-called "modules" are often functionally (high-level) specific units with a dedicated, in-house interface. The problems reside in:

- the very weak link between the functionality being enclosed within the "module" and the assembly processes to be accounted for, in detail.
- the non-existent set of classified, formalised assembly processes accounted for by each "module".
- the local, limited, and not well-defined standard being used for the interface.
- the instability of the processes or sub-process being handled by the "module".

In order to counter such misconceptions, a more widely accepted definition of module and modular must be attained. The same may be said for the terms standardised or standardisation, which lie at the core of the misunderstanding of modularity. Even though fairly succesful standards have been derived at in-house level, they may not be regarded as true standards or modular systems since they have not succeeded in becoming as widely used as intended.

These problems with terminology clearly underline the need for a more concerted effort in forming the correct taxonomies and ontologies for this branch of technology. A platform for discussion may be found in the common definitions of these terms[1]:

Module : any in a series of standardized units for use together: an assembly system unit which covers a classified set of formalised assembly operations.

Modular : constructed with standardized units (modules) for flexibility, interconnectability, and variety in use within a specified class of operations.

Standard : An acknowledged degree or level of requirement.

Evolvable : The capability to develop, or arise through, evolutionary processes.

Evolutionary: A gradual process in which something changes into a different and usually more well-adapted form.

[1] Derived from the Merriam-Webster Dictionary; http://www.m-w.com/cgi-bin/dictionary?book=Dictionary

The core issue behind this drive for evolvable or re-configurable assembly systems should be that micro-assembly is *process-driven*; that is to say that the product design may not be miniaturised without serious consideration of the assembly processes that will be required, since a scaling down of existing assembly systems is *not* viable. Therefore, the required micro-assembly processes, which are unstable and practically invisible, dictate a large range of constraints upon the possible product designs (at this stage of events). Hence the need to develop process-oriented concepts, as given by the Evolvable Assembly Systems paradigm [3]. Another important aspect brought forward is that the key issue within any re-configurable system resides in the manner in which the solution caters for the assembly process knowledge. The modularity achieved by such an approach is consequently based on the careful classification, structuring and formalisation of assembly processes and sub-processes.

In order to achieve such solutions, and create a more robust approach, the E-Race[2] project and Assembly Net[3] community have attempted to define the terms and conditions required to attain Evolvable Assembly Systems. Since the endeavour requires the collection of applicable methods, ontologies, and architectures, the formation of a methodology is given the highest priority, which includes control architectures and multi-agent technology [4]. The next sections will now delve into a proposed paradigm, and the article will attempt to clarify the complexity of applying such scientific paradigms into applicable solutions, and the requirements generated.

2.1 The EAS Concept

The proposed EAS vision, first proposed in 2002 [3], aims to provide the business vision, the methodologies and the underlining technologies and educational foundations for developing new rapidly deployable, modular and re-usable, ultra-precision assembly systems that will allow complex, micro-scale products to be successfully assembled in Europe on a competitive and sustainable cost basis. The EAS concept principles have been embraced by the Assembly-Net, E-Race projects, as well as the 6th framework Integrated Project called EUPASS- Evolvable Ultra Precision Assembly Systems. The term evolvable was chosen to pinpoint the creation of a new paradigm and to differentiate this approach, and ensuing methodology, from others: EAS actually embraces two concepts: evolvability and process-oriented systems.

Note that the term *evolvable* is herewith used as an *attribute* of the concept that is to include the modularity aspects within it. Summarising the EAS concept:

- The focus of the EAS approach is on the processes involved within assembly (perspective: entire product lifecycle) rather than on flexibility, technology, or automation issues.

[2] E-Race, Eureka Factory (E!-2851-Factory)

[3] *EU Growth Thematic Network on Precision Assembly Technologies for Mini and Micro Products (Assembly-Net, EU GIRT-CT-2001-05039)*

- EAS implies that theoretically very flexible, multi-purpose cells will be replaced by a highly flexible concept consisting of several targeted but not, in themselves, flexible components.
- the focus is not on short to medium-term product changeover scenarios, but on long-term sustainability of the company's capability to maintain in-house assembly.
- EAS focusses on the assembly processes and their classification, stabilisation and formalisation. This is to attain true modularity rather than mechanical interconnectability.
- EAS intends to integrate all activities within a product lifecycle into a single methodology.
- EAS introduces re-engineering as part of the system life-cycle.

Another very important aspect of the EAS is that it introduces the idea of evolution rather than adaptation. Survival-of-the-fittest, legacy systems, and conceptual mutations will have to become part of the EAS scenario, which will discriminate against ineffective solutions to the benefit of innovative ones. This is only possible if the engineering community accepts that the product design and production systems departments can no longer be assumed to be two independent entities or activities. The essence of the EAS concept will include two main components, which will have to be grouped to attain the desired equation:

1. Functional issues, such as process-oriented assembly systems;
2. Quality attributes, such as found within the EAS paradigm.

Work is currently being finalised within dedicated projects, and will be detailed in forthcoming publications. The difficult issue here is to derive the essential variables for correlating the two components given above. The Required Functionality will be a function of the functional components, whilst the Evolvability attribute will be a function of the quality attributes. A non-linear relation will probably ensue. The task is being developed at present, in which the Quality Attributes and Functionalities are being detailed. The point is to try and validate, for example, that the requirements posed by the EAS one is trying to build will be given by a certain level of modularity, which, in turn, will provide a quantifiable level of quality.

2.2 A Potential Application

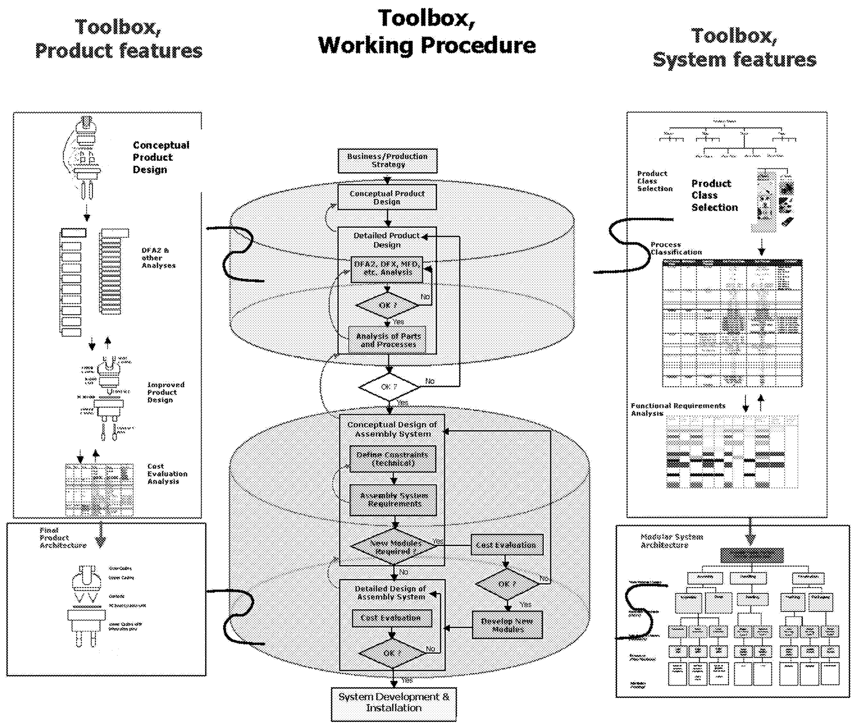

Figure 2 - Working Procedure and Toolbox details for the EAS Approach

The approach could result in a radically new and elaborate working procedure for assembly system developments. The working procedure given as an example reflects the life-cycle given in figure 1.0, and is a step-by-step procedure from fundamental business & production strategies to final product design and ensuing assembly system. As given in this figure, the development toolbox resulting from the application of the EAS methodology may include product-related actions and system-related actions. The shaded areas represent the phases within the working procedure during which the toolbox is most relevant.

It is clear that the EAS toolbox will inevitably require the incorporation of several methods. It will also require the development of structured architectures, knowledge acquisition routines, and data validation schemes. Therefore as it stands, this figure only represents a theoretically possible application. The next section will try to clarify the steps needed to bring such an attempt to application level.

The approach initiates from business and/or production strategies. These are essential, since clear and concise strategic objectives will be interpreted into module drivers: aspects of priority when defining the primary characteristics to be sought after within a module. These may vary, from quality, low-cost, and automated, to high granularity, knowledge transparency, and ease of maintenance. Obviously, a weighting scheme will have to be adopted to classify the priorities/module drivers.

The working procedure given above illustrates the events required when developing the first system (phase 1). Once a system exists, the present architecture is to evolve, hence the working procedure becomes sharper (feedback to product design is based on existing modules) and more focussed on long-term strategies (phase2).

3. APPLICATION ASPECTS

Let us consider the System Features part of the EAS working procedure. The first step is to select a single product type out of a single product class (size, tolerances, no. of parts, complexity). The first stumbling block is that this will require a known taxonomy and ontology. Note that this general classification must be completed and available prior to any analysis. Note also that many products will be of a mixed class nature, such as mini products with micro components: MiniMicro, etc. This precludes that product classes will have to be derived and classified. These classification schemes must then also be applicable to other aspects of the methodology, such as architectures, products, etc.. The main aspect here is to first find a classification scheme that may be applied throughout the product classes and to control, economic and social aspects as well. The zoological classification system[1] has therefore been applied to the proposed manufacturing classification system, which in standard (unexpanded) form may give:

Zoological	Proposed Manufacturing
Kingdom:	Production.
Branch or Subkingdom:	Product Assembly.
Class:	Mega, Macro, Mini, Micro, Nano-Assembly
Order,	Micro-Macro, Micro-Micro, Micro-Nano Assembly
Sub-Order	µClass1, µClass2, etc.
Famil	Assembly, Joining, Handling, Transport, etc.
Genus,	Assembly Processes, Control Processes, etc
Specie	Assembly Sub-Processes, Control Sub-Processes, etc
Individual.	Assembly Modules, Control Modules, etc

The second stage of events in the EAS working procedure requires, for each class, the definition of the processes & sub-processes (from the operations required and other input channels). This may be assumed to be the heart of the System Features part of the approach, since the particular sub-order of product class gives a distinct and unique set of assembly sub-processes.

Main Process Class	Workobject	Assembly Process	Sub-Process Class	Sub-Process	Constraint
Assembly	Part(s)	Assembly	Fit, Type 1	Placement	Always vertical
			Fit, Type 2	Short Insertion	Vertical
					Non-vertical
			Fit, Type 3	Long Insertion	Vertical
					Non-vertical
			Fit, Type 4	Press	Vertical
					Non-vertical
			Connection, Type 1	Side-Fit, stiff component	Non-vertical
			Connection, Type 2	Side-Fit, soft component	Non-vertical
		Drop	Drop	Drop	Always vertical
Joining	Part(s)	Joining	Glue, Type 1	Spot Glueing	
			Glue, Type 2	Seam Glueing	
			Rivet	Riveting	
			Snap-Fit	Snap-Fit	
			Solder, Type 1	Spot Soldering	
			Solder, Type 2	Joint Soldering	
			Weld, Type 1	Friction Welding	
			Weld, Type 2	Laser Welding	
Handling	Part(s)	Grasping	Grasp, Type 1	External Grasp	
			Grasp, Type 2	Internal Grasp	
			Grasp, Type 3	Surface Grasp	
		Feeding	Single Part Feed, Type 1	Mechanical; Vertical	Position & Orientation
			Single Part Feed, Type 2	Mechanical; Non-Vertical	Position & Orientation
			Multiple Part Feed, Type 1	Pattern	Position & Orientation
			Multiple Part Feed, Type 2	Free Placement+Vision	Position (& Orientation)
			Multiple Part Feed, Type 3	Tape	Position & Orientation
			Multiple Part Feed, Type 4	Bulk	Position & Orientation
			Flexible Feed	Mechanical+Vision, vertical	Position & Orientation
Transport	Part/Product	Main Flow System	Product Flow	Conveyor	
		Individual Flow Syst.	Product Transport, Type1	Pallets	
		Independent Flow	Product Transport, Type2	AGVs	
		Internal transport	Product Transport, Type3	Robot	
		Product Fixation	Fixation, Type 1	Fixtures without memory	
			Fixation, Type 2	Fixtures with memory	
		Flow Balancing	Re-Flow & Buffers	Elevators	
			Main buffer	Carrousel	
Quality Control	Part/Product	Function Testing	xxxx	yyyy	
			xxxx	yyyy	
			xx	yyyy	
		Process Control	dddd	iiii	
			eeee	jjjj	
			ffff	kkkk	
			gggg	llll	
		Surface Inspection	hhhh	mmmm	
Finalisation	Product	Marking	Laser Marking, Type 1	nnnn	
			Laser Marking, Type 2	oooo	
			Ink-Jet Marking	pppp	
		Packaging	qq	rrrr	

Figure 3 - Structured Process & Sub-process Classification

These are the sub-processes that, after analysis and classification, lead to the system modules for this sub-order. The problems associated with this step regard the formalisation of the data. Typical issues of importance regard the <u>stability</u> of the sub-processes being classified, the ability to <u>formalise</u> them into mathematical expression for software exploitation, and the validity of the information being supplied. These are considerable issues that need very structured working procedures in themselves, and clarify that system modularisation is far more complex than simply tagging a name onto a system.

Once the sub-processes and associated parameters are formalised and classified, the following step takes the formalisation procedure a step further. This step is particularly tricky since the specific parameter/attributes of each sub-process class are to be compared with one another. The robustness of the procedures exploited in the previous stage will now be put to their test. Furthermore, a method needs to be developed, by which the functionally similar sub-process classes are aggregated into potentially exploitable modules. The resulting sub-division must also be capable to re-iterate which functionalities are grouped into *modules*, which are set as *resources*, and which *attributes* are left to specific tooling (see fig. 4.0).

In other words, many sub-processes will require similar characteristics when viewed from an operational point of view. These may be grouped, such that the main functionality may be given by a module, whilst the detailed aspects resolved by a specific resource (that can be attached/detached from the module; i.e.-gripper, tool, etc.). This will require a specific software-based tool/method. Constraints and related mechanisms obviously need to be developed.

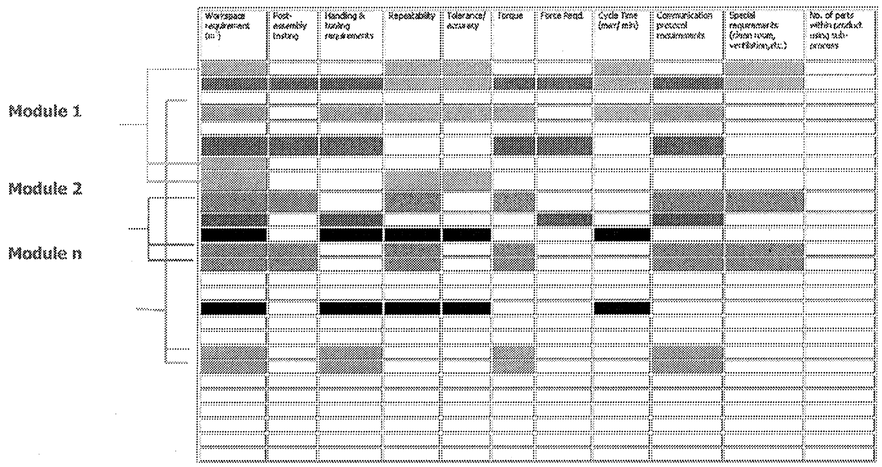

Figure 4 - Sub-division into Potential Modules

The final step in the EAS working procedure, step 5, regards the definition of the Modular Assembly Platform components required: after the first iteration of the EAS procedure, there will be a given system architecture. In this step, the user will pick the modules that correspond to the qualities required by the groupings given in Step 4. However, there may be groups that require entirely new modules. Therefore, there is a need to couple this stage with the final stage in Product Features Analysis: the user/team will have to check whether it is cost-effective to develop a new module, or whether it is better to change the design of the part/product, or even outsource.

Such a Cost Evaluation step may bring new modules to be defined and incorporated into the Module Platform, hence the coupling to a higher-level strategic aspect. Such strategic aspects bring about the issue of having specific "module drivers" set at an early stage in the procedure, an approach already adopted by the Modular Function Deployment product design methodology [5].

4. DISCUSSION & CONCLUSIONS

Figure 2.0 illustrates the potential of fulfilling the requirements given in the EAS working procedure, and also depicts the vital link between processes and modules. However, this is purely theoretical at present.

In order to achieve the solutions mentioned in this article, major efforts are required on several fronts. First of all, as the article points out, there must be some convergence and agreement on the taxonomies, and an assembly ontology should be created. The whole process of developing the assembly system, which will be software-based in a "Development Toolbox", will rely on the correct priority being selected before starting: the module drivers. That is, the user must decide if the tool is to optimise (set priority) for costs , product design, fast ramp-up, or any other "Module Driver". Weighting schemes are not the only requirement to be applied in order to succeed. Other prerequisites may include:

- Definitions, ontologies.
- New cost models for analysis.
- Impact of Social & Management Issues (see fig.5.0).
- Application of solutions in collaborative networks.
- Standardisation/formalisation of Product Classes.

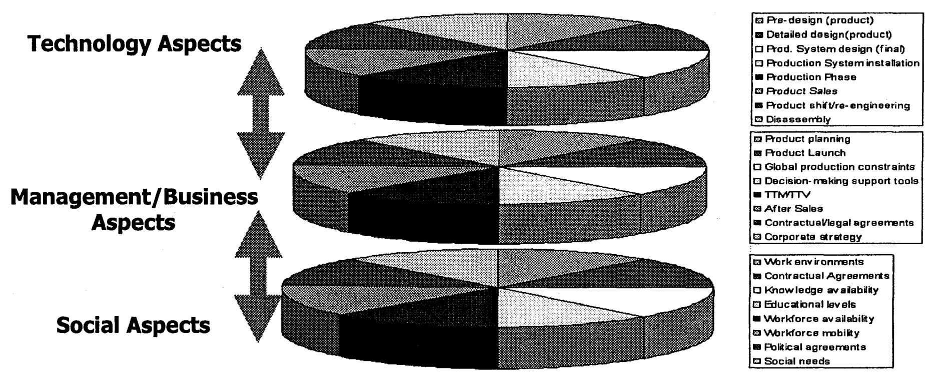

Figure 5 - Concurrent cycles in a product's lifecycle

However, the most important factor remains the collection of the methods required into the so-called working procedure. This includes formalisation procedures, methods, software developments, etc. It is, therefore, important to make absolutely clear that this will not succeed without an appropriate methodology that integrates these issues in an effective manner, a point which was underlined in the Assembly Net Roadmap and other publications ([1],[3]). Note that since the EAS paradigm requires a methodology for successful implementation, it also requires a holistic perspective. This is why social and management issues must also be considered more elaborately. Considering the fact that an eventual implementation may have to recur to multi-agent technology and collaborative networking theories, in which contract management issues arise, these two topics become even more relevant. The article obviously does not present a solution or implementation, but intends to clarify the difficulties behind developing working procedures that result in truly modular system components: the intention is to illustrate the efforts required to achieve evolvable systems, what they represent, and the work that lies ahead. The authors pinpoint that three major initiatives have come together to collaborate around these issues: Assembly Net, E-Race and EUPASS. Assembly Net acts as a dissemination channel and assists the group in finding new collaborating partners.

The E-Race and EUPASS projects are products of such efforts. E-Race is focussed on the software issues related to EAS. EUPASS is an Integrated Project that will attempt to develop EAS systems for two demonstrators at industrial level, and focuses on the architectural, standardisation and hardware issues. The scale of the problem remains significant and the theoretical foundations of many of the issues portrayed in this article will have to be consolidated. Collaboration is also being established with IFIP WG5.5 in order to better incorporate management & social issues. The work described in this article is also detailed in three forthcoming Phd Theses ([6],[7],[8]).

Once again, the point being made is that it is important to clarify that re-configurable, modular, or evolvable systems can only succeed if the processes to be accounted for are classified, stabilised and formalised. Hence, a very focussed approach is strongly recommended: select a well-delimited process for validation/falsification of the ideas. Broad approaches cannot succeed because of the inter-relationships that exist between industrial processes, which complicate the analysis of the core issue, e.g.- re-configurable *production systems* is a doubtful approach since not only manufacturing, assembly, logistic, and sales processes inter-relate on the basis of current solution premises, but sub-contracting, supply-chain, external logistics, marketing and other strategic processes influence the outcome. It is therefore safe to assume that a narrow focus is the only way to scientifically examine, falsify/validate the aspects and potentials behind the EAS paradigm.

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