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Engineering Design in Integrated Product Development
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A REVIEW ON THE RELEVANCE OF DESIGN SCIENCE IN A GLOBAL PRODUCT DEVELOPMENT ARENA

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Abstract: *Much of Industry, whether an OEM or a tiered manufacturing supplier of products, is involved in a global product development operation, where parts can be designed in one part of the World, manufactured in another and assembled in yet another part of the World. This paper reviews the state of the art of academic design research over the past decade and explores the relationship of present academic activities to that of a product development scenario within the wider global industry practices.*

1. INTRODUCTION

Given the rate that high class academic papers are presently being presented in Design journals and conferences, there is every hope that their relevance in general has a significant bearing on the needs and processes that industries in general wish to adopt. In fact, the academic engineering design research should be assisting industries to innovate more creatively, create better and more competitive products successfully, whilst achieving lower cost, higher quality products with shorter times to market – a tall order, but an ideal that academia should be striving to meet as the research sector matures.

There has been an underlying expression of opinion within the industrial community that such design research has, so far, had little applicability to the wealth generating capabilities of global manufacturing industries. Moreover, few industrialists present papers in leading conferences and journals, such is their lack of apparent empathy with the academic design research community. Is this a false impression or reality?

This review paper explores particular published conference and journal papers over the past decade up to 2004 that have a specific relevance to industrial lean product development and the potential benefits that industry has realised resulting from the implementation of the Design research.

The review focuses specifically on the implementation of Design Science research and asks if there is continuous improvement and on what scale? It attempts to cut through the hype and uncertainty and draw conclusions on the "standing" of Design Science within the context of a global manufacturing industry.

The paper attempts to address the attitudes of Industry today towards applying themselves to a) continuously reducing product time to market, b) getting the product more right first time and c) achieving the cost targets of the customer. Whilst it is not easy to generalise, the paper explores what product development processes are adopted and the management attitudes to innovation and bringing designs to the market.

In comparison the review paper looks to assess what research papers are addressing in terms of identifying market needs, effective product development processes, new design tools/ techniques and design management issues.

Finally, the review draws significant conclusions on the strength of correlation between the two product development communities.

2. THE INDUSTRIAL IMPERATIVES

New product development is an absolute imperative for the survival and increasing global competitiveness of manufacturing industries. Without a stream of regular new products or sound variants on existing products, then the lifeblood of the company would be gradually strangled. Various reviews by Hart [1], Aroujo [2] and Fairlie-Clarke [3] on industrial new product development have recognised the importance to corporate and economic prosperity, coupled with the high risk of failure in such endeavours.

The scope of product development is normally recognised in industry as from the time the idea is generated until the product is launch in a production form on to the market. Whilst there are many models, the product development process itself within a manufacturing company has been normally recognised as wholly supported by such activities as marketing, sales, purchasing, distribution, etc. but should be within a management framework that allows a manufacturing company to achieve a competitive profitable position in the market place [4].

In fact in the UK, most mainland European countries and the USA the more successful companies have adopted well defined and consistent product development processes in one form or another. However, many of the small/medium enterprises (SME's) are still fire fighting on a daily basis and struggling to put a consistent product development process in place if the OEM and first tier customer has not "imposed" their practices on the small company [4], [5].

Similarly, Arvidsson [5] has reviewed (using telephone interviews) the practices of Swedish industry over recent years in terms of their use and knowledge of robust design methodologies (RDM) rather than the adoption of product development processes. This RDM framework is primarily to design product insensitivities to variations in product and process.

From some 87 Swedish manufacturing companies, using only 28% showed familiarity and only 17% used robust design methodologies such as SPC, Design of Experiments, FMEA (product & process), DFM/A, Taguchi Methods, FTA, etc. Apparently the likes of Six Sigma programmes, QS 9000 certification (for the automotive industries), etc. have driven on the use of RDM. The 17% industrial users agreed that the use of RDM increased their competitiveness and that management commitment was an essential pre-requisite for an extensive use of RDM.

Of specific importance to this review was that "many representatives in Swedish Industry agreed that they would increase their use of RDM if it had been integrated into their product development process". It was interesting but startling to note by Arvidsson [5] that this implied that a high percentage of the companies had a defined product development process and that integration of RDM in the process would probably increase the awareness and use of RDM.

Another common opinion stated in the Swedish industry survey was that the use of RDM would increase if it had been a customer requirement and that 67% of the Swedish respondents thought that RDM was useful. Inevitably this begs the question, not only on how customer requirements and regulatory bodies may be encouraged to be increasingly the key influencers, but also that of the relevant academic design researchers?

Haque [6] is of the opinion that Concurrent Engineering (CE) practices (also called integrated product development) are now practised widely in manufacturing industry to improve the integration and collaboration within the development process, using a number of formal tools and organisational mechanisms to improve the quality, cost and delivery of a new product. Lean thinking on the other hand is a wider high-level philosophy focussed on waste elimination and flow of value, but does not provide the details needed to improve new product developments per se. I believe that neither in their own right provides the core activities synonymous with product development. However, they do achieve enhancing features that support a more coherent global process.

Stauffer [7] provides a fascinating insight into the product development needs of smaller manufacturing firms in the USA that endorse much of what has been reviewed above. Out of 61 individual smaller manufacturing companies (with 20-200 employees) from across 10 states, it was found that only between 40-50% of the companies considered that they executed product development activities better than their competitors. Clearly a lot depended on the quality of their competitors.

Overall the areas of greatest need were seen to be in the business related activities of product development. Improving marketing, project management and product refinements, as well as reducing the cost of product and processes were seen as the greatest need for improving competitiveness.

Stauffer [7] also identified that engineering design research should be increased in a) the connection between market, consumer and design information, b) support launching products into the marketplace and c) equating product features with customer value to ensure a sustainable rate of return to small companies.

3. THE ACADEMIC DESIGN RESEARCH AGENDA

Given the extensive range of research papers on product development practices in industry, it is opportune to review where academic design research can or has had a bearing on industry. As stated by Blessing [8} Design is a complex activity, involving people, tools, processes, organisations and the micro and macro-economic environment (market, legislation, society) in which it takes place.

Design research aims at understanding design in all its facets that should lead to the validation of knowledge, methods and tools that improve the working practices in design.

Many strands of design research have emerged that are too diverse to include in this review. However, from this extensive range of possibilities I have attempted to break this review down into a limited number of major well defined areas of the product development process. These main "practical" strands of a) Creativity, b) Design Tools, c) Computer Aided Engineering (CAE) and d) Product Life-Cycle Management (PLM) have been chosen as I believe they have the greatest potential to impact on engineering industry practice with significant effect.

3.1. Creativity/concept generation

One of the aspects of engineering design that has been of particular interest to industry, but of less interest, seemingly to academic research to date, would appear to have been related to the process in concept design has been called product styling. Yet shape, surface finish, ergonomics and overall appearance play a critical role in the successful marketing and sales of a product.

Sauer, *et al* [9] have recognised the importance that in order to increase the efficiency of the conceptual design phase, it is important to support the designer in structuring his problem solving process, particularly as the early design phase is especially essential for the success of a company. They have also analysed several development projects and developed a Pyramid Method that overcomes some of the deficiencies of the phase orientated guideline VDI-2221.

Moreover, as Tovey [10] states "decisions made at the concept and styling stage have a very significant influence on the subsequent engineering design activities". The form should be fixed as early as possible so that it can be translated into the hard data that informs downstream engineering processes.

In relation to the car industry, Tovey is clear that key parts of the stylists work has proved incompatible with computer-aidded design (CAD) support, despite its advantages. He identifies techniques that provide effective CAD support and without inhibiting the fluidity and richness of a sketch based approach, proposes a hybrid technique that combines conventional sketches, sketch mapping, sketch modelling and non-contact scanning methods that apply to all product development processes-not just automobiles. Muller [11] also confirms that many designers support themselves with classical handmade sketches before and also during the work with CAD. Using virtual technologies they have devised a first prototype of a digital sketching tool.

Given the fact from above that designers usually work best with sketches or rudimentary objects or models, Vidal *et al* [12] looked seriously at brainstorming as one of the most widely used creative methods. From their studies they took one step further by using in addition to oral expression, 3 variants-writing (sentential), drawings (visual) and objects (objectual) to generate ideas in a group brainstorming session. Their conclusions were particularly interesting as all the forms of expression were of benefit. However, the objectual variant of brainstorming was found to be the most effective of the 3 variants.

3.2. Design tools

The range of practical and effective design tools has been quite extensive in academic research terms. From the Author's own UK research [4], it is probably the area of design research that has had the greatest impact on design practice in Industry over recent years. The range of tools extends from Design for "X", tolerancing, costing, assembly/disassembly, recycling, safety, Quality Function Deployment (QFD), TRIZ, etc.

QFD, Design for Manufacture & Assembly (DFMA), Failure Mode & Effect Analysis (FMEA), Fault Tree Analysis (FTA) and 6 SIGMA have been around the academic design research scene for a good number of years and some are continually being refined and implanted into industry practice. Rather than focus on these refinements to what are perceived as important but fairly traditional design tools, the Author has looked at other interesting papers have been published that have made considerable progress in somewhat different directions.

Tolerance analysis tools have raised their profile over the last few of years. In particular, emphasis has been placed by Lindkvist, Wandeback and Soderberg [13],[14],[15] on using as much process knowledge as possible in the early stages of product and production development. Lindkvist [13] highlights a software tool methodology that makes it possible to evaluate tolerance chain "stack-up" and supports the evaluation and detection of geometry and tolerance problems early during concept/detail design, thus minimising problems found later in production. Soderberg [15] provides an interesting application of the Lindkvist [13] software tool in terms of its application to seam variation analysis for automotive body panel design where flushness and gaps between panels take on increasing importance in any quality appearance evaluation.

Wandeback [14] adds further design research knowledge that has practical importance to industry by stressing the importance for industry of learning to use measurement data as a source of information in their development process, thereby increasing confidence in the concept design.

Booker, Swift and Brown [16] have produced an excellent research paper that has reviewed extensively the current assembly-orientated design techniques available to detect potential quality problems and identified the key issues related to assembly, quality, operations and assembly technologies used. It brings out some startling facts in terms of the costs of controlling variability at the design stage, but equally as important an assembly variability analysis has proved to be useful in the identification of potential problems at the design stage. This has addressed a major industry requirement, crucial in the reduction of the quality related costs. Booker *et al* [16] are clearly of the opinion that industry still struggles to execute rigorous strategies for variation reduction. To meet this need, they concur with Wandback [14] that industry must adequately characterise their manufacturing and assembly processes through the introduction of process capability databases – using tools and methods for process characterisation.

In contrast, Ferrao, *et al* [17] have researched into the big issue of how recycling and end of life component processing should be addressed in its own right, rather than be implicit within the design practices of design for disassembly. I believe that so much more design research activity should be developing on this topic to aid industry in establishing clear methods of introducing recyclability into its early design processes.

Whilst still in its formative stages, the research of Ferrao [17] sets the foundations for a new DfR design methodology that incorporates environmental and economic information according to a set of specified parameters.

The integration of safety and risk into the product development process has been a growth area of design research and is well exemplified by P.J.Carkson [18], *et al* who reviewed the effectiveness of design in the UK health service. The objective was to reduce the risk of medical error and improved patient safety across the National Health Service (NHS). I would anticipate the outcome of the design review would also have a significant bearing on other global health services.

From the review the major conclusions were that a) the NHS was seriously out of step with modern thinking and practices with regard to design, b) there were no quick fixes, c) there was cause to question the design of medical devices, products, packaging and information and d) a lack of understanding of customer experience, human factors and user friendliness to the NHS brand.

In contrast Gauthier [19] has focussed on industrial accidents associated with industrial machinery. Despite FMEA, FTA, HAZOP and Risk Analysis tools being available in addition to European legislation on "Safety of Machinery" plus "Certificate of Conformity", this fresh piece of design research, whilst still not yet matured, has proposed relatively new concepts of formal risk analysis and control that should bring about a significant integration of global safety activities into the development process of machinery, rather than the sometimes informal approach of designers at present. Moreover, it builds on the firm foundations of Wang [20] and Stoop [21] who have demonstrated that an efficient integration of safety during design is possible with very effective results.

The activities of Fargnoli and Pighini [22] have addressed safety at the concept design stage in the product development process in a somewhat different manner, bringing in the effects of implementing safety on machinery costs. Using a Safety/Cost Ratio methodology (SCRM) they have identified for machinery design, that they were able to eliminate main risks whilst analysing the increased costs of implementing the safety features. In fact by choosing the correct safety devices using the SCRM, they found a considerable increase in safety with very little increase in costs. The SCR methodology appears to have been positively useful that it is being further validated with an extended range of machinery.

3.3. Computer aided engineering

These range of tools are very extensive and cover Computer Aided Design (CAD), Virtual Reality (VR), Computer Aided Analysis, etc. Again in the opinion of the author, the purpose of the review is to explore the latest research activities that have the potential for a useful and immediate benefit on industrial product development practices.

The question is whether Virtual Reality (VR) is just a design tool that is process that is in a passing phase and/or is only applicable to the large automotive companies? Or is it here to stay as an essential design tool?

Ottosson [23] has put a convincing case in his paper that some applications of VR have already matured, whilst others are still in their infancy. Of particular interest is the fact that in his opinion VR offers new possibilities in the field of product development by speeding up the pace and improving quality and usability, particularly in a distributed or global environment.

Of particular value from his "action research" is that VR is useful for making simulations, for the study of user behaviour, to train personnel skills and for broad-spectrum communication. In particular he emphasises that VR is a tool that enables classical and dynamic product development by providing the means for sharing a vision of the product across a wide range of disciplines.

For example, aesthetic and ergonomic design is assisted by VR tools and be invaluable in the communicating and selling of turnkey products-especially new products not yet in production. I would support the view of Ottosson [23] that whilst VR seems to favour product development practices when many factors have to be taken into account, it would seem that the economic threshold and knowledge to implement VR is very high.

It would probably be applicable to the large global companies where product development continues around the globe over a 24 hour cycle. However, I believe there are VR technological developments that will allow SME's to use the benefits of VR in global product development over the next 5 years.

CAD/CAM systems become ever more comprehensive and easier to use by the designer and manufacturing engineer, that it would seem that there is little academic design research opportunity left in this context that could be relevant to industrial practice. Yet from recent publications in this area, this would appear not to be the case.

The design research of Szewczyk [24] has highlighted the real practical difficulties about the visual representations of interfaces within CAD that can affect users' abilities to comprehend the potential of their CAD tools. Misunderstanding the elements of the graphic user interface such as icons, toolbars, dialogues and cursors can somewhat surprisingly become a barrier to effective design work. Their research found that novices usually want to know all the tools and they actually try to guess their meanings.

Whereas the advanced users have learned to distinguish important tools and the interface context, but they pay no attention to the context if it is not clear. They usually ignore many background tools and this has meant they do not expect to be fully comprehensible. As yet the research has not led to some possible ways forward on this dilemma, but no definite conclusions have emerged as yet.

Boujut [25] has taken a slightly different human interface angle by questioning that CAD systems provide functionalities for sharing models and sometimes even annotations (attached text, images, etc), but these functionalities remain poorly employed. He argues that based on industrial experiences, providing annotation facilities within CAD systems is not enough.

Whilst no design tool developed from the research, the outcomes highlighted the human interactions to global design teams working on CAD systems and the importance of annotative processes when dealing with complex models that involved deeply interwoven process constraints.

At the other end of the CAD/CAM spectrum the complexities of blending complex surfaces and curve optimisation have been researched with practical benefits by Roy *et al* [26] and Prijic & Jennings [27]. Roy *et al* have identified in their research how time consuming and complex is the manual time consuming process of optimising curves and surfaces with a CAD system. They have then addressed the need to find a method to automate this optimisation process within the CAD/CAM environment with minimal intervention from the designer. This is primarily because the CAD/CAM environments used for surface modification provided only limited facilities for such an automatic process.

Whilst undoubtedly there are advanced CAD/CAM tools such as CATIA versions that have significantly improved on their optimisation capability, Roy [26] have provided a framework for surface optimisation within a CAD/CAM environment that requires the Designer to not require any prior knowledge about the internal representation used by CATIA. It has been found to be very convenient to use by the Designer for industrial applications.

In a Similar manner Prijic & Jennings [27] have recognised that a significant amount of end-user time, cost and effort was expended by the designer in the creation of freeform sculptured surface blends in press and mould tooling. Consequently, they have identified an opportunity for utilising a programming and geometrical modelling design tool for the implementation of a free-form feature-based approach to freeform aesthetic design using identified proprietary systems.

King *et al* [28] takes a critical design research approach on how computer aided engineering (CAE) analysis tools have grown in their importance, particularly for reducing the level of hardware prototyping during product development and for improving understanding of the system under development.

Their research has been of real significance because it examined the implementation of CAE analysis tools in product developments in a variety of 5 different companies from different industry sectors.

With advanced CAE analysis tools in mind, such as CFD, FEA, multi-body systems dynamic modelling, etc., correlating the results from the 5 companies, King [28] has established points of good global product development practice that integrate CAE analysis tools in a structured manner.

3.4. Product life-cycle management (PLM)

The whole topic of PLM has been around with the designer and the product development process teams for many years. Yet generally with the exception of the global industries, most SME's have not addressed the subject too seriously throughout Europe. This could be a result that the cost of a complete suite of PLM software was prohibitive. Or else it has not been recognised that bespoke PLM software can be introduced on an incremental basis rather than *en block*.

Weber *et al* [29] in their excellent paper are of the opinion that the environment of today's Product Data Management/ Product Life-cycle Management (PDM/PLM) systems is characterised by the coexistence of various independent tools, each based on its own specific product model.

In this environment the PDM/PLM mainly focuses on the administration of computer files generated by these tools without having much access to the actual content of the files. Consequently, such systems do not *know* anything about characteristics and properties of a product, let alone their inter-relationships, so that they cannot really offer a continuous support to the whole product development process.

Whilst they do not as yet offer a robust researched solution, they have proposed the potential of a novel Product –Driven Development/Design (PDD) modelling approach that is of an advanced kind of PDM/PLM system. When introduced it should formally distinguish between properties and characteristics and supports the control and management of the design process itself in a critically important manner.

Moving on to a higher plain, Payne *et al* [30] look at how significant changes within the aerospace industry were required for developing complex products in a globally distributed environment. The trend to globalise product development has increased, with incentives such as lower cost labour in developing countries and shorter development times. In addition, many organisations operate with only a core of full time permanent employees, outsourcing the skills required on a contract basis when specific jobs are required. The authors make the point that integrated product development (IPD) has been effective up to a point in implementing the key features of the design process, but when individuals work collated together. However, present practices do not easily manage product development in a geographically distributed environment.

Within this modern context, Payne *et al* have introduced and are working with industries on researching a new exciting approach known as the Macro Concept that has the potential of working in a distributed environment. It attempts to support the human elements and soft issues of the product development process. The two components of the Macro Concept are the Core Team and the Task Teams which do not depend on the need for collocated teams. The results of further outcomes from the research could have enormous benefits for the way global industries operate on developing new products.

Rouibah & Caskey [31] and Coates *et al* [32] take a different look at similar aspects within a PDM environment and address the coordination of design work within the concurrent engineering environment. Rouibah [31] recognise that managing information workflow processes are critical so that product design in the distributed supply chain is accomplished in less time, with less effort and with superior results. Similarly Coates [32] revues and researches into what effective engineering management coordination requirements are necessary to the successful operation of organisations. There is presently in existence a broad and varied understanding to design coordination.

As a result Rouibah [31] present for industrial practice in a fascinating manner the working concept of an EWF (Engineering Work Flow) method that is more of a generic than specific approach. It links product data and workflow management, whilst defining the control processes to coordinate co-operation and linking the people involved to the activities and data in a CE environment.

In contrast Coates *et al* [32] produce a challenging more comprehensive people-centred approach to operational design coordination than currently exists. It emphasises in some detail that the key elements of operational design coordination to be dependant on knowledge related to coherence, communication, task management, schedule management, resource management and real time support.

4. CONCLUSION

It would be virtually impossible to review comprehensively the full extend of design research that is presently being addressed in academia over the past few years. The topics are far too extensive. So I have focussed specifically on a few areas of critical importance to industry such as Creativity, Design Tools, CAE and PLM.

From the Authors own research in the UK plus others identified in this review across mainland Europe and the USA, I have drawn the conclusion that a lot of "blue sky" intellectual design research continues to be prevalent across academia. However, whilst I have been highly critical in the past, there are now immensely encouraging signs that academic design research in specific areas and specific University design departments are producing intellectually challenging outputs that are being adopted by industry with considerable delight and satisfaction.

This review gives an insight into some of these important outputs and hopefully removes much of the doubt about the usefulness of academic design research to sound industrial practice in the 21st Century.

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